Intermountain West Energy Sustainability & Transitions

On the road to carbon neutrality in the Intermountain West

Phase One Final Report
Detailed Chapters

Version 2.0

Table of Contents

Click on a chapter title to advance to the chapter.

I-WEST

Phase One Final Report | Detailed Chapter

Regional Overview

VERSION 2.0 LOS ALAMOS NATIONAL LABORATORY JUNE 2023

About this chapter

The Intermountain West Energy Sustainability & Transitions (I-WEST) initiative is funded by the U.S. Department of Energy to develop a regional technology roadmap to transition six U.S. states to a carbon-neutral energy economy. I-WEST encompasses Arizona, Colorado, Montana, New Mexico, Utah, and Wyoming. Each state is represented in this initiative by a local college, university, or national laboratory. Additional partners from beyond the region were selected for their expertise in applicable fields. In the first phase of I-WEST, the team built the foundation for a regional roadmap that models various energy transition scenarios, including the intersections between technologies, climate, energy policy, economics, and energy, environmental, and social justice. This chapter presents work led by an I-WEST partner on one or more of these focus areas. A summary of the entire I-WEST phase one effort is published online at www.iwest.org.

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Table of Contents

Introduction

Energy production and distribution are critical components in the state-based economies across the Intermountain West. Collectively, the region contributes to approximately one-fifth of the nation's energy production[1], with regionally abundant fossil resources being dominant contributors. Dependence on fossil-based resources is increasingly becoming a challenge for the region as demand for a carbon-constrained energy economy rises. Economic impacts of this transition are already affecting many energy communities and sovereign nations whose economies are structured around fossil fuel industries. While each Intermountain West state is managing the challenge differently, a regional plan will be critical to achieving an accelerated transition and mitigating regional economic impacts. Furthermore, a place-based approach that leverages the region's strengths and considers its constraints and challenges must be part of the strategy to deploy and implement a regional energy transition plan on an accelerated timeline.

Place-based approach

A place-based approach focuses on effectively utilizing regional resources. A collaborative approach is required, along with coordinated efforts by regional stakeholders, including sovereign nations, federal and state governments, private industries, policy makers, educational entities, non-governmental organizations, and the general public. The two fundamental tenets of a place-based approach are:

1) Geographical context of a region, including its social, cultural, and environmental characteristics.
2) Interactions between industry, local communities, and government with information and knowledge sharing.

A place-based approach leverages existing physical advantages, specialties, and capabilities to develop new industries and economies. This inherently builds on the region's geography, culture, and history— emphasizing societal readiness first and technologies second. A place-based approach uses local characteristics, complexities, and partnerships to spur inclusive technology deployment and industrial growth. Most of the knowledge needed to fully realize the true growth potential of a region is not readily available to large industries; federal, state, and local governments; or policy makers. Rather, it must be developed through a deliberate dialogue and

[1] EIA's State Profile and Energy Estimates website (eia.gov/state last accessed 01/30/2022).

interactions among internal and external stakeholders. The place-based approach combines key theories that highlight the characteristics of a location, available resources and institutions, and additional elements such as collaboration, adaptability, resource management capability, and the interactions of various local elements. As local conditions determine the competitiveness of resources and ensure its persistence over time, space becomes an active factor in development. Thus, the specificity, complexity, and interconnectedness of a territory are essential parts of a place-based strategy. In this sense, place-based strategies are different from top-down approaches—often identified as place-neutral approaches—that prioritize technologies.

There are three key elements of a successful place-based approach:

Define local comparative advantages. This involves defining the technology development and deployment pathways based on the existing and potential new comparative advantages of a region. According to the place-based approach, each region has unique industries that provide the local economy with different comparative advantages. Determining the comparative advantages means identifying which specific industries need to be deployed. These, in turn, are dependent on human and physical capital, which are related to workforce, raw materials, and energy resources. A place-based approach aims to improve the quality of the local workforce as well as investments in research, development, and innovation. Without investing in local human capital and research and development, investment in infrastructure may be useless, although such investments increase accessibility, especially for remote areas. While the effects of these may not be evident over the short term, they can create conditions for sustained long-term growth.

Identify regionally applicable technologies and industries. There is no one-size-fits-all approach for a place-based strategy. Local specificity is highly desirable to develop the strength of an industry within a region. What works in one place cannot be transferred context-free to another, regardless of the similarities. Therefore, a place-based regional strategy for industries requires the understanding of the specific sectoral constraints and capabilities in a particular area. An industrial regional strategy identifies the path for industrial technology deployment based on the existing comparative advantages. On one hand, place-based regional strategies can foster industrial specialization by enhancing traditional sectors where local industry already has a comparative advantage and existing strengths. On the other hand, they strive for supporting enterprises to move toward more dynamic technology sectors.

Identify effective policies to facilitate regional deployment. The place-based approach assumes that each territory has different resources and institutional settings to develop. Thus, no single policy setting can be applied. Delivering policy change is highly context-specific and depends on institutional, administrative, legal, and organizational conditions. Institutional weaknesses at the federal, state, and local levels can act as barriers to the successful realization of each region's potential.

A place-based approach to facilitate accelerated transition of the Intermountain West region toward carbon-neutral energy systems will have to take into consideration the regional geography, existing energy economies, policies, and stakeholders' perspectives on energy transition. The subsequent part of this report focuses on the regional geography and stakeholder perspectives based on extensive outreach efforts.

Regional attributes

The Intermountain West has a unique mix of extremely diverse geography that includes high mountain ranges (e.g., the Rocky Mountains), spectacular canyons (e.g., the Grand Canyon), river valleys, forests, plains and grasslands, large salt flats (e.g., Bonneville Salt Flats) and deserts (e.g., the Great Salt Lake and Sonoran Desert). The six states are among the 13 largest in the country by land area (Figure 1).

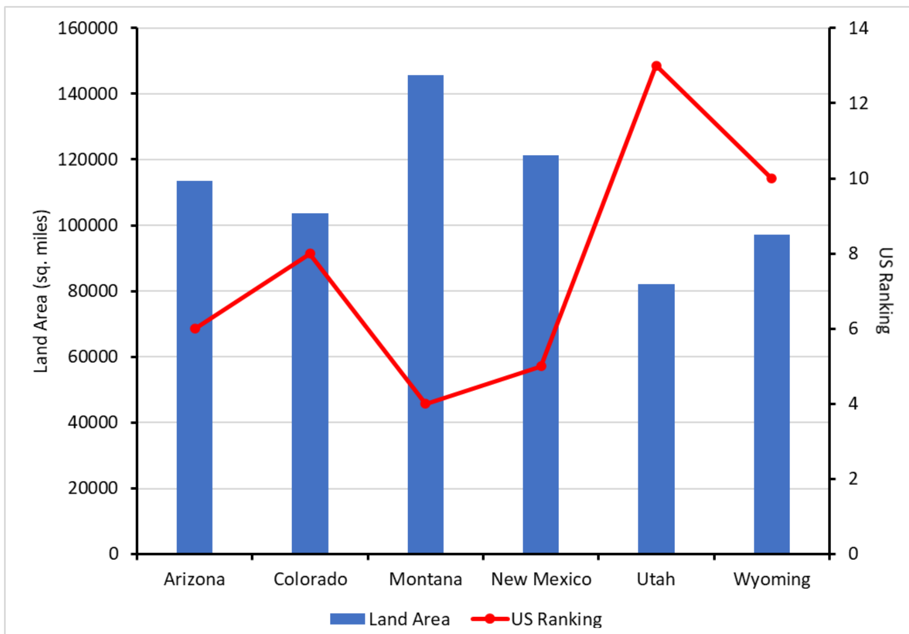

Figure 1. Land area of the states and their U.S. rankings.

Despite this large land area, most of the population is concentrated in four major urban corridors in Arizona (Phoenix-Tucson), Colorado (Fort Collins-Denver-Colorado Springs), New Mexico (Albuquerque-Santa Fe), and Utah (Ogden-Salt Lake City-Provo). This leaves a large portion of the region with some of the lowest population densities in the US (Figures 2 and 3). One unique aspect of the region is the presence of approximately 60 federally recognized tribal nations (Figure 4), the majority of which are located in Arizona and New Mexico, with a combined population of around 470,000.

Land ownership in the Intermountain West is complex, with various combinations of federal and state government, tribal government, and private ownership (Figure 5). On one end of the spectrum are states such as Arizona and Utah where almost 80 percent of the land is non-private and is owned by state or federal governments or tribal nations. On the other end of the spectrum are states such as Wyoming and Colorado where about 60 percent of the land is privately owned. Tribal nations own close to 30 percent of the land in Arizona and approximately 10 percent of the land in New Mexico.

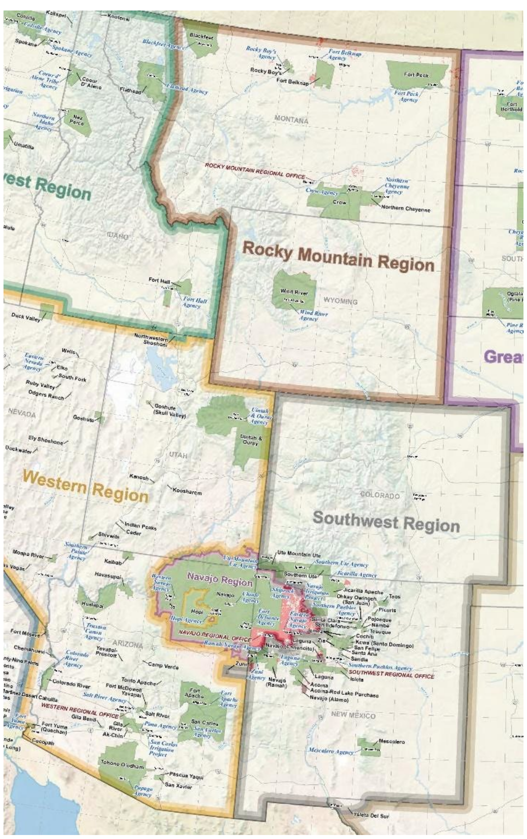

Figure 2. Urban and rural population.

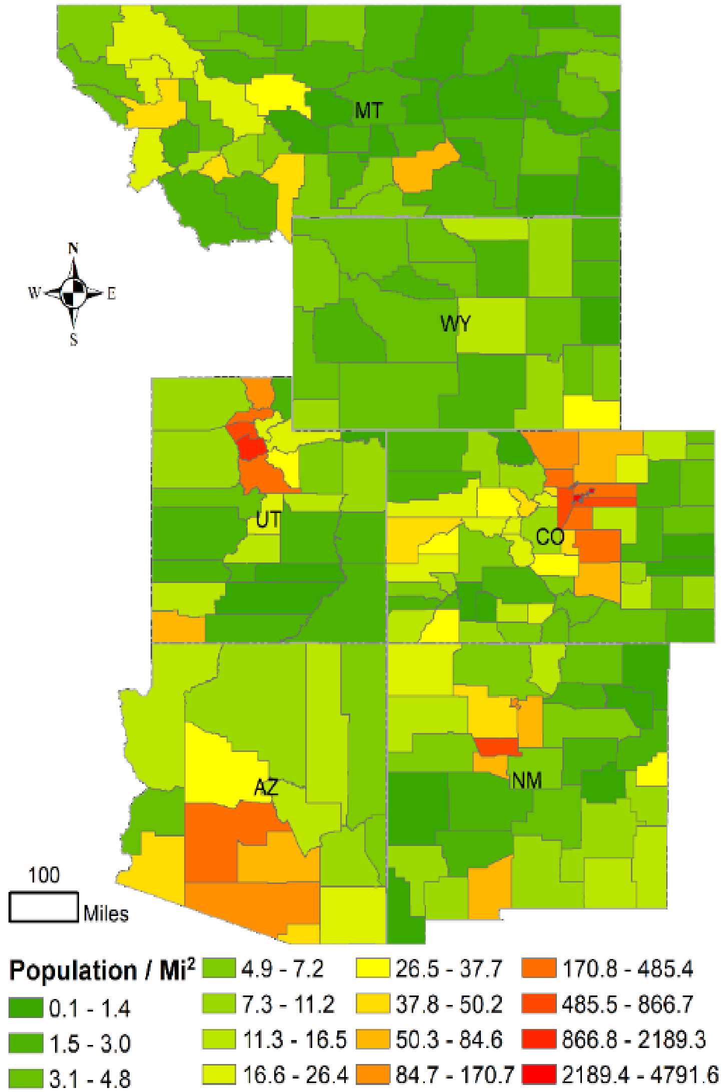

Figure 3. Population density.

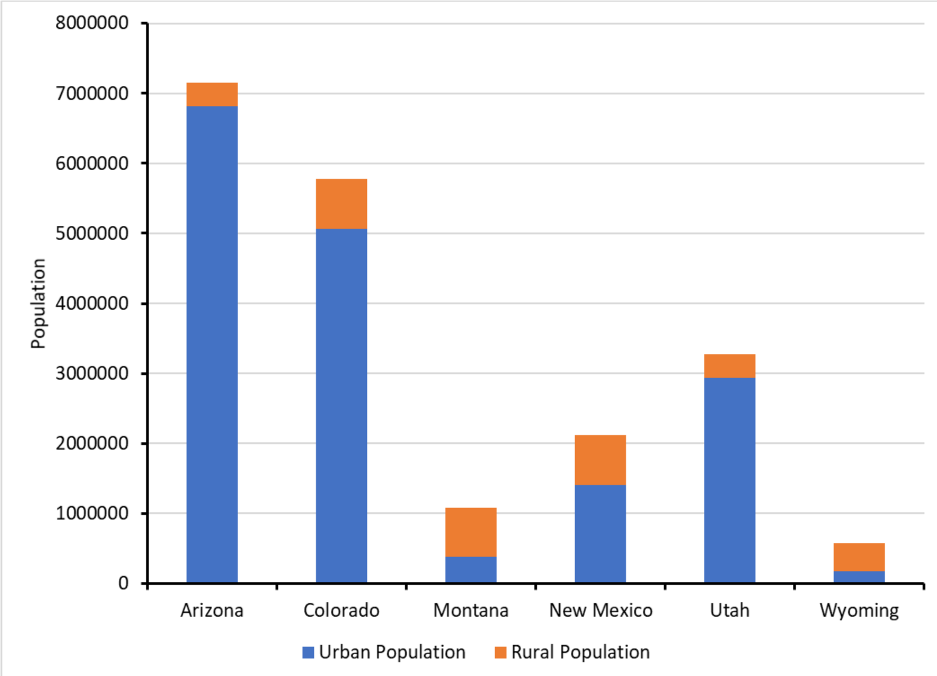

Figure 4. Native American lands of federally recognized tribes located in the region.

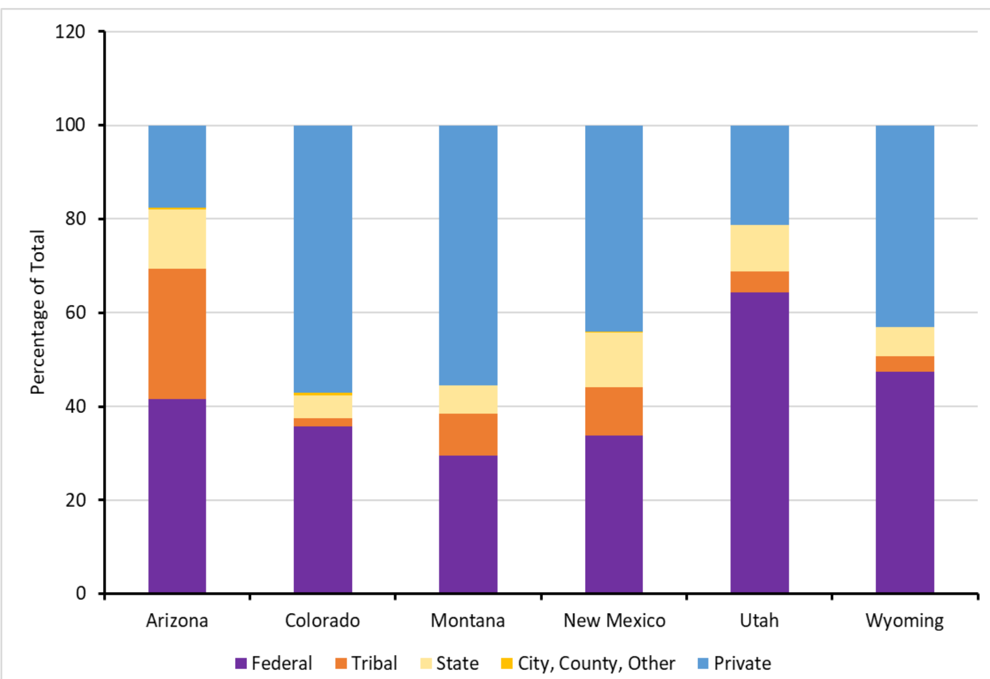

Figure 5. Make up of land ownership.

Regional climate

The climate in the Intermountain West ranges from cold, semi-arid in the northern states to hot desert in the southern states. The regional climate varies within each state due to variations in topography and geography. For example, eastern and central Montana are part of the Great Plains and have warm summers and cold winters, while the western side of the state is part of the Rocky Mountains and has snowy and cold winters. Arizona, however, has some of the hottest and driest climates in the country in its southern deserts, a cooler climate in the northeast, which includes part of the Colorado Plateau, and heavier precipitation and significant temperature variations in the mountain ranges that extend from northwest to southeast. The mountains of the Intermountain West are home to the headwaters of major rivers that supply water to numerous states, including the Colorado River, Missouri River, Rio Grande, Arkansas River, and Platte River.

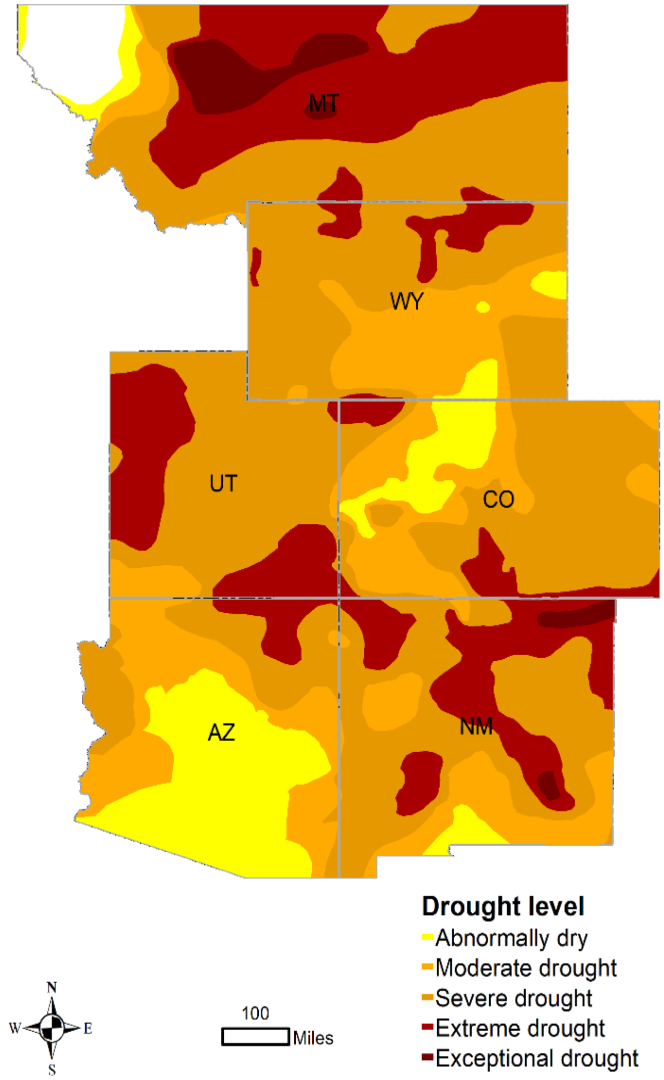

Figure 6. Current drought levels. From droughtmonitor.unl.edu.

Climate change has shifted the Intermountain West's regional climate. Temperatures in the region have increased by 2–2.5 °F since the beginning of the 20th century. Almost the entire region is extremely dry or in moderate to extreme drought (Figure 6). The latest long-term climate predictions for the region indicate severe impacts of climate change, including 1) historically unprecedented increases in annual average temperature during this century, 2) potential for more extended droughts posing major challenges to environmental, agricultural, and human systems, 3) high risk of very large wildfires, 4) high variability in monsoon rainfall, 5) decreased winter snowfall leading to reduced water in major rivers, 6) increased potential for flooding due to heavier spring precipitation combined with a shift from snow to rain, and 7) increased rate of soil moisture loss due to higher temperatures and decreased summer precipitation leading to increased intensity of naturally occurring droughts[2,3,4,5,6,7].

Regional geology

The geology of the Intermountain West is marked with sedimentary basins, mountain ranges, rift valleys, volcanic cones, and basaltic deposits. A number of major sedimentary basins in the region are rich in fossil-based resources including coal, oil, and natural gas (Figure 7). Additionally, the region has other mining resources such as gold, copper, silver, and a number of rare earth elements. In fact, nine of the top ten US copper mines—including the largest—are located in either Arizona, Utah, or New Mexico. One unique feature of the region is the presence of numerous natural CO_2 reservoirs (Figure 8), which are primarily located on the Colorado Plateau. These reservoirs have been used to supply CO_2 primarily for enhanced oil recovery operations in the Permian Basin in New Mexico and Texas. The regional sedimentary basins also contain major saline formations that have been identified as potential targets for geologic storage of CO_2.

Regional energy resources, production and infrastructure

The Intermountain West encompasses some of the biggest energy-producing states in the nation (Figure 9), primarily due to abundant fossil resources in the region. Five of the six states (excluding Arizona) are in the top 15 for coal, oil, and gas production, with Wyoming being the top coal producing state in the country. In terms of electricity generation, all but Arizona rank in the bottom half of state rankings. However, five of the six states (all but Colorado) are net exporters of electricity, primarily to the more populous western states. Arizona and Wyoming rank in the top seven of the net electricity exporting states, while New Mexico (18), Montana (21), and Utah (25) rank in the top 25. Almost 68 percent of the electricity generated in the region is derived from fossil fuels, primarily coal and natural gas (Figure 10). **The reliance on fossil fuels for electricity**

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[2] Frankson, R., K.E. Kunkel, L.E. Stevens, D.R. Easterling, T. Brown, N. Selover, and E. Saffell, 2022: Arizona State Climate Summary 2022. NOAA Technical Report NESDIS 150-AZ. NOAA/NESDIS, Silver Spring, MD, 5 pp.

[3] Frankson, R., K.E. Kunkel, L.E. Stevens, D.R. Easterling, N.A. Umphlett, C.J. Stiles, R. Schumacher, and P.E. Goble, 2022: Colorado State Climate Summary 2022. NOAA Technical Report NESDIS 150-CO. NOAA/NESDIS, Silver Spring, MD, 5 pp.

[4] Frankson, R., K.E. Kunkel, S.M. Champion, D.R. Easterling, K. Jencso, 2022: Montana State Climate Summary 2022. NOAA Technical Report NESDIS 150-MT. NOAA/NESDIS, Silver Spring, MD, 5 pp.

[5] Frankson, R., K.E. Kunkel, L.E. Stevens, and D.R. Easterling, 2022: New Mexico State Climate Summary 2022. NOAA Technical Report NESDIS 150-NM. NOAA/NESDIS, Silver Spring, MD, 5 pp.

[6] Frankson, R., K.E. Kunkel, L.E. Stevens, and D.R. Easterling, 2022: Utah State Climate Summary 2022. NOAA Technical Report NESDIS 150-UT. NOAA/NESDIS, Silver Spring, MD, 5 pp.

[7] Frankson, R., K.E. Kunkel, L.E. Stevens, D.R. Easterling, B.C. Stewart, N.A. Umphlett, and C.J. Stiles, 2022: Wyoming State Climate Summary 2022. NOAA Technical Report NESDIS 150-WY. NOAA/NESDIS, Silver Spring, MD, 5 pp.

generation may have future implications for Intermountain West states exporting electricity to other western states that are increasingly demanding carbon-neutral electricity. The share of renewable resource-based electricity is currently at 28 percent, with Arizona ranking fourth in the nation in terms of solar electricity generation capacity and Colorado ranking ninth for wind electricity generation capacity. Given the abundance of wind (Figure 11) and solar (Figure 12) resources in the northern and southern Intermountain West states, respectively, the share of regional electricity generated from renewable resources is expected to grow in the future. In addition to the traditional renewable energy resources such as wind and solar, the region has geothermal energy potential that has not been fully exploited (Figure 13).

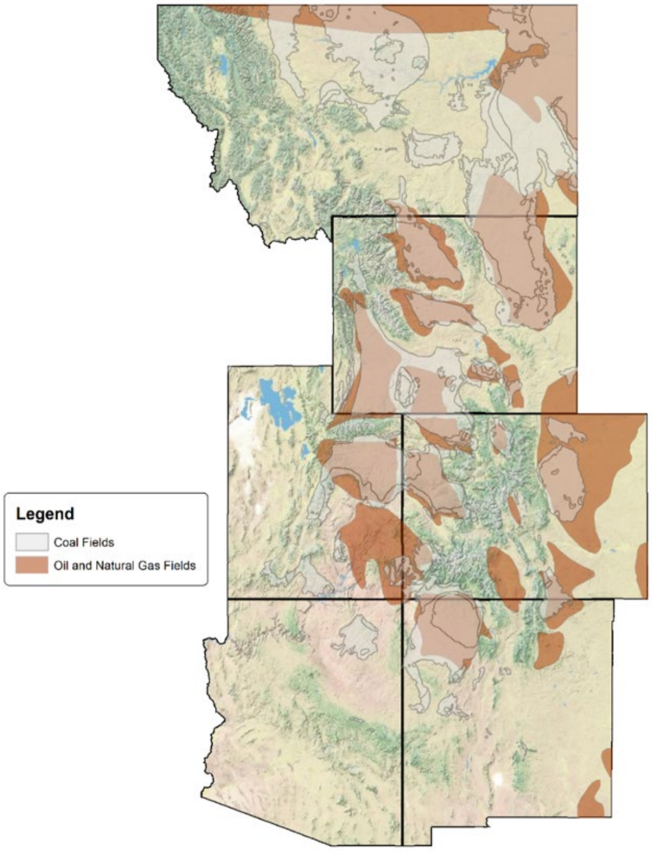

Figure 7. Coal, oil, and natural gas fields.

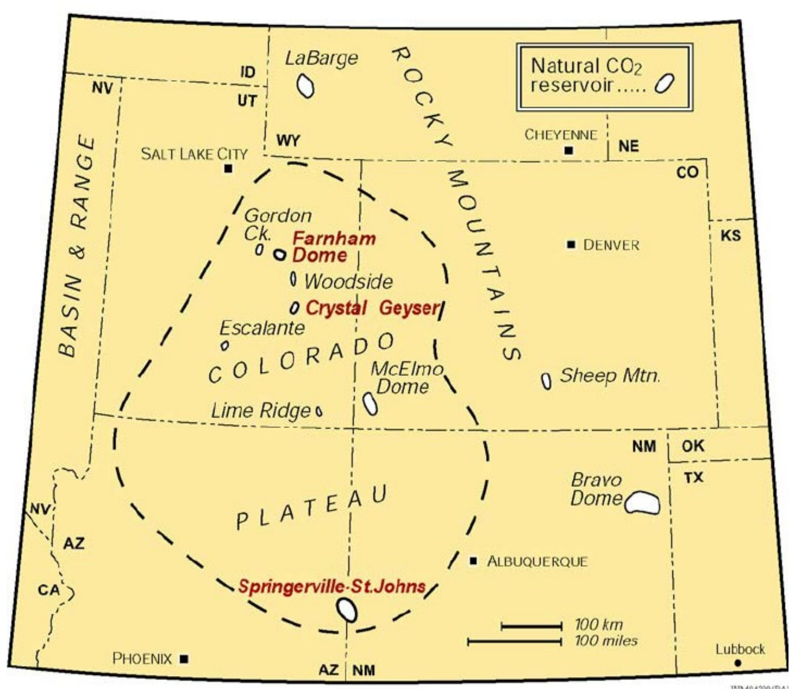

Figure 8. Natural CO_2 reservoirs on Colorado Plateau[8].

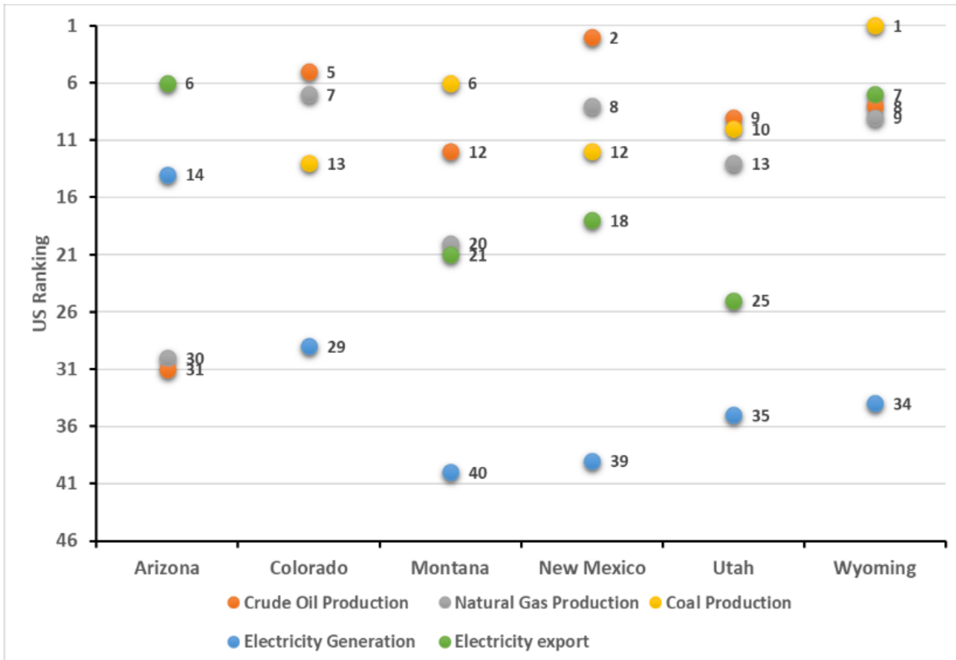

Figure 9. State rankings in terms of production of fossil fuels, electricity generation, and electricity export. Data: eia.gov.

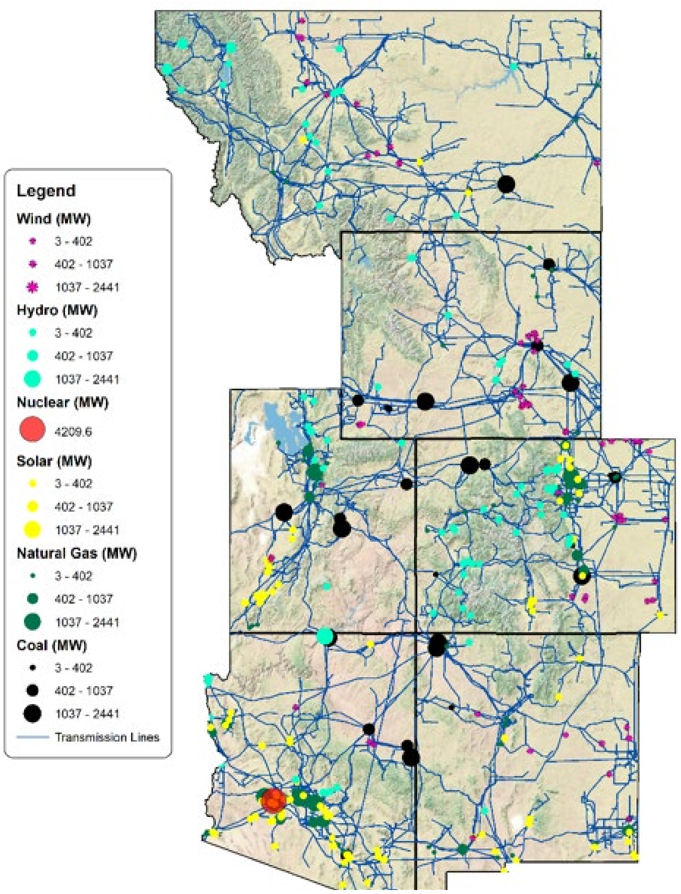

Figure 10. Locations of power plants and electricity transmission lines. Data: eia.gov.

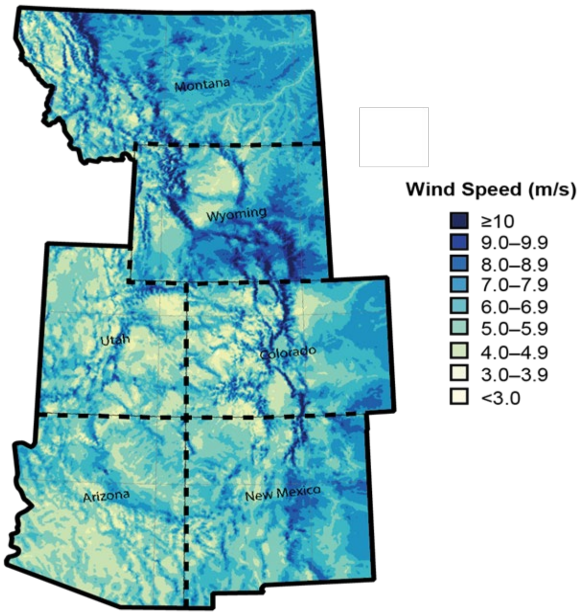

Figure 11. Wind potential in terms of wind speed. (Source: NREL)

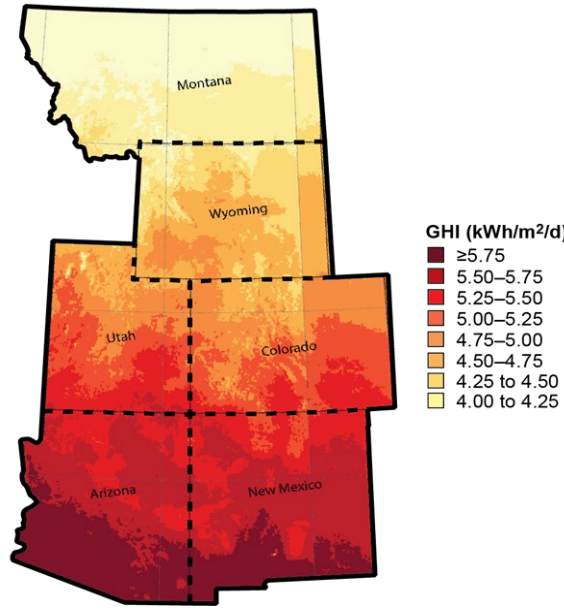

Figure 12. Solar potential in terms of global horizontal solar irradiance (GHI). (Source: NREL)

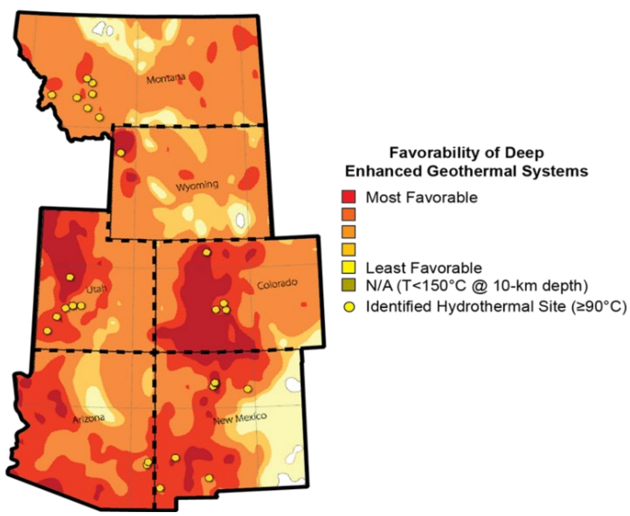

Figure 13. Geothermal energy resources. (Source: NREL).

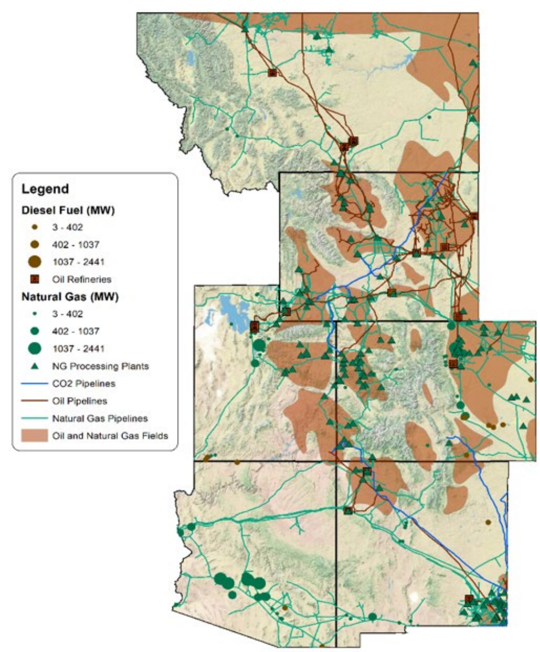

Figure 14. Locations of oil- and gas-related infrastructure. Data: eia.gov.

Regional fossil-fuel based energy production has led to the development of significant regional infrastructure for conversion and transport of energy products, including oil refineries; gas processing plants; and oil, gas, and CO_2 transport pipelines (Figure 14). **The fossil and non-fossil**

energy resources—combined with a) existing energy extraction, conversion, processing, and transportation infrastructure and b) growing future low-carbon energy economies—indicate that there is potential for deploying multiple regionally relevant energy technologies to transition the Intermountain West to carbon neutrality.

Stakeholder perspectives on energy transition

As indicated earlier, a place-based approach necessitates knowledge sharing among the regional communities, industries, government, and non-governmental organizations to identify regionally relevant context and considerations to develop an effective technology deployment plan. To facilitate development of a regionally relevant technology roadmap and its implementation, the I-WEST team performed extensive outreach to regional stakeholders to identify their needs, goals, and expectations related to energy transition. We utilized various outreach approaches, including eight state-based workshops (one exclusively focused on the sovereign nations), multiple public surveys, and focus group discussions. Through these efforts, we engaged with more than 1400 regional stakeholders representing local communities, the public, non-governmental organizations (NGOs), and educational institutions. Our outreach efforts led to several key insights into regional stakeholders' perspectives on issues associated with energy transition and carbon neutrality.

There are diverse motivations for energy transition among regional stakeholders.

- Enthusiasm for energy transition depends on numerous things, including how permanent or temporary a community perceives it to be, and whether or not it believes energy transition will present opportunities or barriers for economic growth.
- Energy transition means different things to different people, and decarbonization is often thought of on a spectrum—carbon neutral, net zero, absolute zero, climate positive, etc. There is support for various scenarios across the region, and all stakeholders are wary of what each scenario will equate to in terms of impact on environment, economies, workforce, and revenues.
- Within the Intermountain West region, there are diverse motivations for energy transition, which impact the attitudes, enthusiasm, and acceptance for energy transition. This emphasizes the importance of communication among local governments, technology developers, technology deployers, and communities. Ultimately, all stakeholders across the region are interested in new energy economies that can represent opportunities.

Stakeholders identify with energy transition opportunities but are concerned with risks

- New energy economies have the potential to help reduce regional carbon emissions and create new opportunities. The impact of energy transition is already being felt across the region and a desire to stay competitive in changing markets is a unifying motivation for energy transition acceptance—the region does not want to get left behind. But the new opportunities need to be weighed against the risks.
- The energy transition will lead to increased economic and job opportunities but there are risks associated with the viability of new energy technologies over the long term. Past experience with boom or bust cycles, especially those associated with fossil fuels, have made regional communities cautious about adopting new technologies. Additionally, local communities are skeptical about the long-term commitment of “out of region” project developers given past negative experiences. Deployers of new technologies will be expected to build relationships with local communities and work with them over the long term to overcome the skepticism and ensure community buy-in and support.
- The energy transition has the potential to positively impact the environment and public health, but there are concerns of unforeseen impacts new energy technologies might have within the region and beyond.

Regional perspectives on future energy technologies

- Motivations for energy transition impact attitudes toward energy technologies, which emphasizes the importance of communication among technology developers, technology deployers, and communities. Traditionally, technology adoption and community acceptance are afterthoughts, but I-WEST has found that doing things in parallel will help accelerate deployment.
- Technologies must be regionally relevant and conducive to the geological, environmental, and natural resources available, as well as considerate of existing economies, infrastructure, and workforce.
- Communities are more likely to accept technologies that leverage existing frameworks and/or present viable and realistic options for building new economic frameworks.
- Overall, there is a high level of support for renewable energy, while technologies for hydrogen and CCUS require more explanation and assessment to address questions

and concerns about environmental impacts and if these pathways extend the use of fossil fuels.

- Existing infrastructure may be limited to accommodate the new energy technologies; significant investments will be required to develop required infrastructure.
- Risks associated with new energy technologies are not things that communities ignore, and technology developers and deployers should not assume that communities are ignorant about potential impacts to water, ground, air, and health; in fact, many regional stakeholders prioritize these issues over economic opportunities.

Sustained pursuit of energy justice within the region is important to stakeholders

- Energy justice is multi-pronged and involves ensuring affordable energy for all, protecting natural resources, ensuring job security, and mitigating the impacts of climate change for disadvantaged communities that most suffer from a combination of economic, health, and environmental burdens.
- The Intermountain West region is especially critical due to the high number of sovereign nations who have a long history of dealing with environmental and economic impacts as a result of unjust energy decisions. Across the board, governments at all levels and technology deployers must build trust with tribal stakeholders and make decisions that inspire their confidence.
- A just energy transition is something that must be pursued in a sustained manner. Stakeholders from sovereign nations emphasized that there must be an ongoing dialog and not a one-time “check the box” exercise.
- Opportunities related to new energy technologies may increase regional population and temporarily stress infrastructure, but could also lead to better education and services in the long term.

Government’s role in energy transition

- Regional stakeholders want state and local governments to take a more proactive and holistic approach to facilitate effective energy transition. The lack of coordination across state-based approaches, policies, and regulations related to reducing CO_2 emissions and strategizing for energy transition is slowing the pace for an effective transition.
- To facilitate deployment of new energy technologies, gaps in policies and regulations need to be addressed immediately. Furthermore, timelines to obtain permits need to be

shortened drastically. New and existing energy technologies fall under the jurisdictions of multiple federal and state agencies that are not necessarily on the same page in terms of what is needed to facilitate rapid energy transition. Certain agencies may have limited or no flexibility to modify the existing regulations in the near future.

- On average, local communities and sovereign nations are typically unfamiliar with the process required to pursue various funding and financial assistance opportunities related to energy transition. Due limited in-house technical expertise, and limited resources for grant/proposal writing, they need assistance to pursue federal and state opportunities.

Workforce needs for future energy technologies

- While future energy technologies may result in job opportunities, the current regional workforce may not be able to meet the needs of new industries for various reasons, including lack of technical expertise. This may limit timely deployment of new energy technologies.
- Historically, energy-related jobs have paid well and offered good benefits. Similar financial benefits will be needed from future energy pathways in order to maintain a normal standard of living for energy communities—this will also help drive the desire to develop the required technical skills through training.
- Local communities want regional educational and vocational institutes to create and offer curricula to develop the technical skills needed for jobs associated with new energy technologies.

Stakeholders expect to have a voice in the transition, be engaged in the decision-making process, and remain informed

- The public expects greater transparency in the deployment of new energy technologies than it has had in the past. Members of the public also expect to be better educated about the positive and negative aspects of new energy technologies so they can make informed decisions. Numerous public debates over challenging issues have shown that concerned members of the public are proactive in gathering information from public domain resources. Overcoming unfavorable public opinions will be a significant challenge and will require a transparent approach.

Outreach efforts help provide a comprehensive understanding of the regional stakeholders' mindsets related to energy transition, their expectations, and their values associated with a range of related issues that are important to consider while developing a technology roadmap.

Summary

Transitioning the Intermountain West to carbon-neutral energy systems within a 15-year timeframe is a tall order. Successful transition will require a nontraditional approach that is both just and effective in meeting the regional carbon emission reduction goals. A traditional technology-centric approach may be effective in meeting emission reduction goals but likely will not be effective in meeting the regional stakeholders' expectations and buy-in, which in turn may delay technology deployment. A place-based approach, which emphasizes leveraging regional physical and human capital, engaging regional stakeholders to inform decision making, and forming regional coalitions can be an effective alternative to facilitate accelerated energy transition.

Given the range of natural resources—fossil and non-fossil alike— combined with significant energy generation and distribution infrastructure, there is significant potential to deploy multiple low-carbon or carbon-neutral energy technologies in the Intermountain West. Insights gained from I-WEST outreach efforts demonstrate that regional stakeholders expect energy transition to meet diverse motivations by prioritizing regionally applicable technologies, reducing economic hardships faced by energy-dependent communities, offering new sustainable economic opportunities, and ensuring energy justice.

I-WEST

Phase One Final Report | Detailed Chapter

CO_2 Point Source Management

VERSION 2.0 LOS ALAMOS NATIONAL LABORATORY JUNE 2023

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Table of Contents

Introduction

A carbon dioxide (CO_2) point source is a facility with a significant and concentrated output of CO_2. The dominant source for point source CO_2 emissions is fossil fuel combustion for electricity or heat, but other significant sources include the industrial production of hydrogen and hydrogen products (e.g., ammonia, lime, and cement), and fossil fuel processing and refining.

The threshold for defining a process CO_2 emission as a point source can vary. Historically, industry facilities were tracked given their function. More recently, the definitions in the federal Sequestration Tax Credit (45Q) dominate, as they define the likely economics of point source treatment. The sequestration credit can apply to electricity generation point sources at a scale of 18,750 t/y (metric tons per year), and industrial facilities at a scale of 12,500 t/y, of CO_2 emissions abatement. This report uses the Environmental Protection Agency (EPA) eGRID database for electricity generation, which is a complete inventory of grid-connected generation, and the EPA Greenhouse Gas Reporting Program (GHGRP) data for other point sources, which is an inventory of all emitters greater than 25 kt/y and many with smaller emissions.

Point source management considers the overall picture of existing point source emissions and how they might change. This report details the current point sources in the Intermountain West and what changes and treatments could make an impact on their emissions.

There are two main strategies for point-source emission abatement. First, point source capture (PSC) technologies separate, purify, and compress the CO_2 from point sources into concentrated streams. The PSC strategy goes hand-in-hand with carbon utilization and sequestration. Second, retiring point sources and potentially replacing their function with other technologies eliminates the emissions. In the near term, this strategy is closely tied with the transition to non-fossil electricity generation, and in the longer term it is connected with maturation of efficiency improvements and new technologies for industrial processes. A third strategy involves changing the fossil fuel that is used, which is quite significant. Natural gas generates less (roughly half of) CO_2 emissions than coal for the same energy output; therefore, continuing to transition from coal to natural gas for electricity generation would result in a significant change to emissions.

In an overall outlook, treating point sources is an available and impactful pathway for near-term CO_2 emissions reductions, and a significant aspect of the long-term outlook for emissions. Commercial at-scale deployment is available today for flue-gas emissions from electricity generation and industrial heat sources, and natural gas processing is inherently a CO_2 separation. Experimental technologies are being deployed at pilot scale or developed at lower technology readiness levels (TRLs) for CO_2 separation in other industrial processes.

The goal of this report is to provide an estimate and explanation of the potential for CO_2 emissions reduction with point source management in a low-medium-high adoption scenario format. Outcomes depend strongly on qualitative conditions like public acceptance and investment, which are largely unpredictable. The primary focus is the electricity sector, which is responsible for most CO_2 point source emissions, based on established estimates of future energy mix and qualitative underlying adoption scenarios. Remaining sources, given the lack of demonstration and low TRL, have more uncertainty in their scenarios. The intent of a coarse low-medium-high adoption analysis is to provide insight into possible outcomes, rather than to make predictions.

Point sources in the Intermountain West

Point sources in the Intermountain West are shown in Figure 1. As the legend shows, the dominant emissions are electricity production from coal, as well as natural gas (NG) electricity generation plants. The emissions by major category are shown in Figure 2.

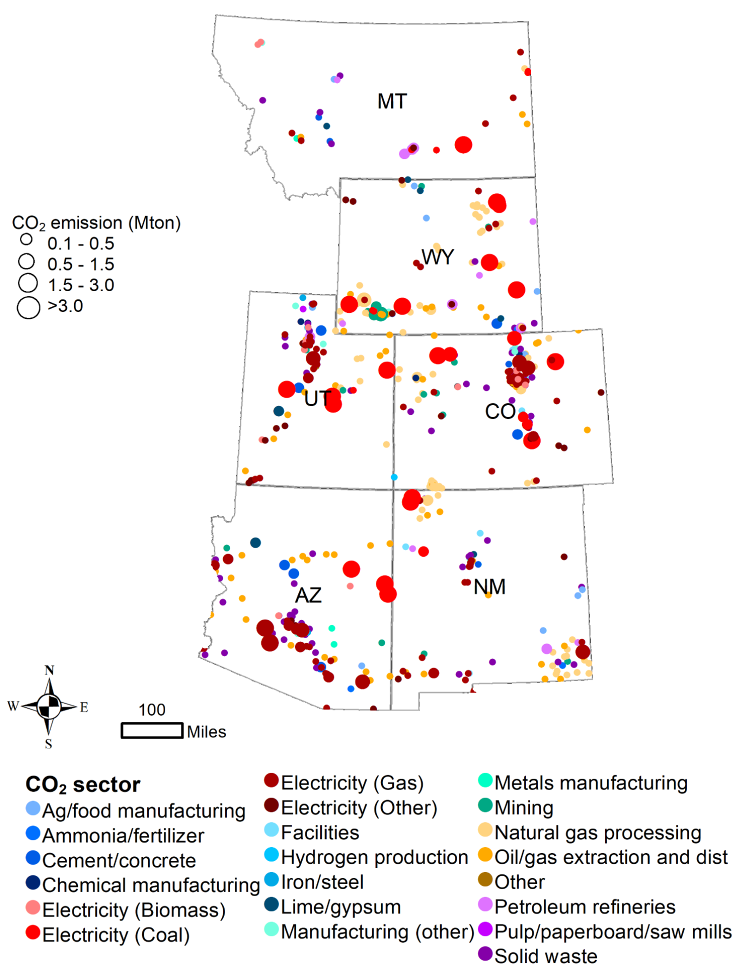

Figure 1. Map of CO_2 emissions in the Intermountain West by category.

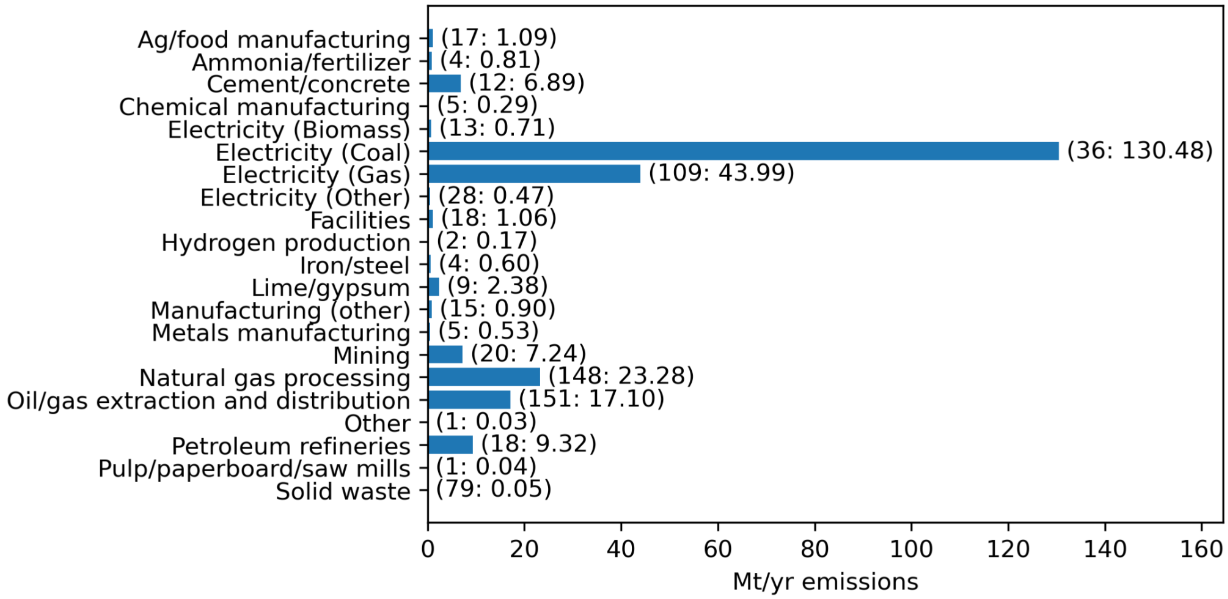

Figure 2. Emissions by facility types of point sources. Bar labels are number of facilities: total emissions of sector in kt/y.

Like all regions, the Intermountain West has a unique fingerprint of emissions types. It is a producer and net exporter of fossil energy, in particular coal and NG electricity generation, NG production and processing, and oil and gas refining. Industrial sources not related to fossil production are a relatively small part of total point source emissions, including mining, cement and lime production, and ammonia (fertilizer) production and agriculture. This analysis emphasizes the potential emissions reduction pathways associated with electricity production, given its dominance in regional point sources.

Emissions are driven by relatively large sources. Figure 3a shows the individual facility emissions sorted by emissions, and the corresponding cumulative emission amount for point sources in the region. The 90% and 95% of total point-source emissions levels are plotted. Figure 3a shows that there is a long tail of very small sources.

The small sources shown in Figure 3a are difficult to treat with PSC for a number of reasons. First, the CO_2 capture becomes a less efficient and economical process as the scale reduces, where absolute costs vary with source purity but generally start to grow exponentially as the capture capacity goes below approximately 300 kt/yr with currently mature technologies [1]. Second, the disposition of the CO_2 is such that, for any source in the tens of kt/yr range and up, transport via pipeline to CO_2 sequestration sites is required. Transportation for smaller capture would be even more expensive. Grouping industry into pipeline-accessible sites would be advantageous, but transitioning industrial locations is a long-term prospect requiring further analysis. Finally, smaller sources represent smaller industries, likely much more sensitive to capital investment costs.

For these reasons, it is worth considering the 22% of facilities that constitute 90% of point source emissions, which emit over 250 kt/yr. Figure 3b shows these facilities broken down by sectors. The small sectors may be considered negligible for some purposes, either because they are single facilities or their total emissions are relatively small.

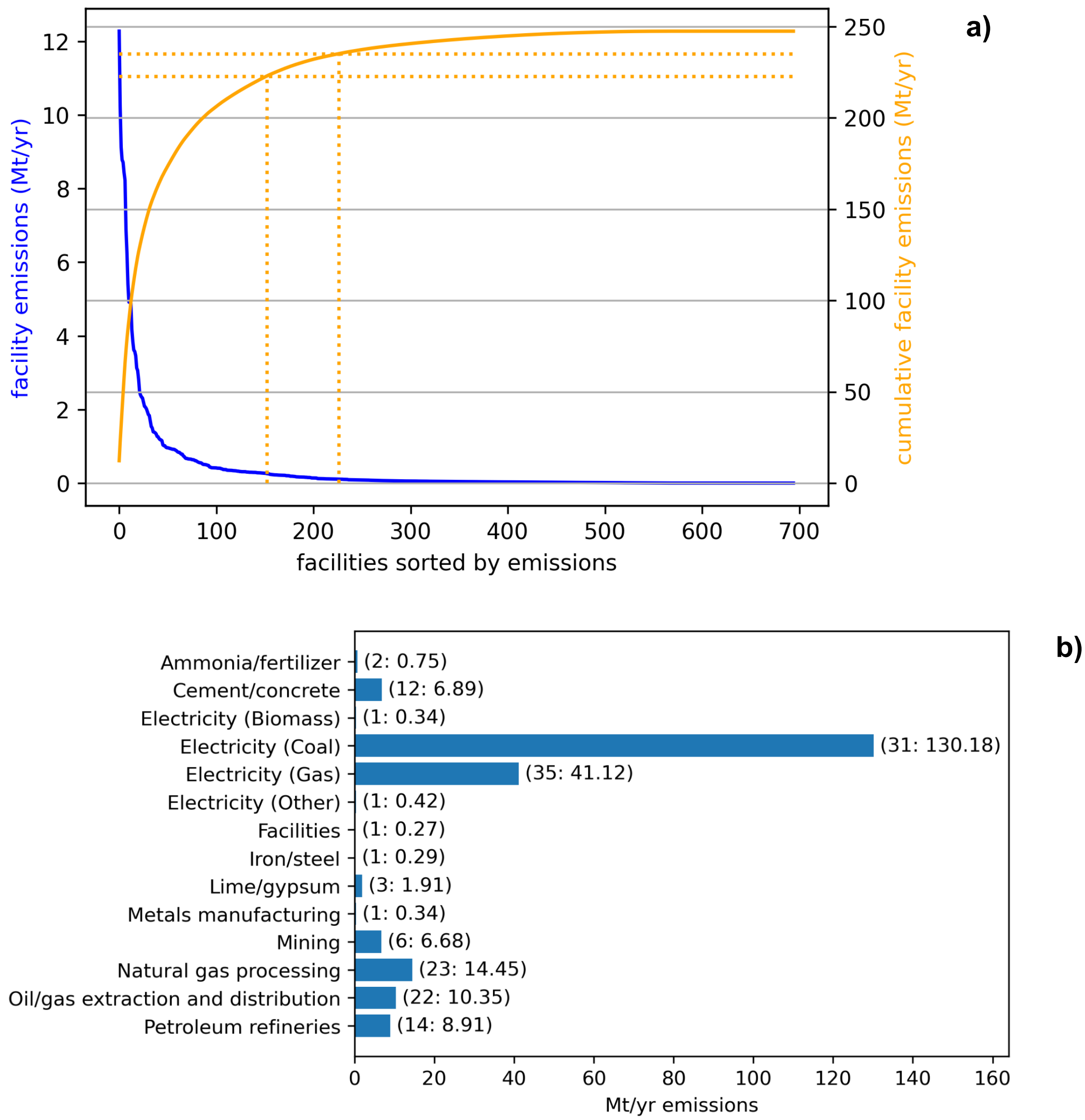

Figure 3. a: Individual and cumulative emissions for regional point sources, sorted by emissions magnitude. The dotted lines are at the 90% and 95% of cumulative, corresponding to 153 and 227 facilities, respectively. b: Emissions constituting the largest emitters constituting 90% of all point source emissions by sector. This represents 22% of facilities, which are all above approximately 250 kt/yr. Bar labels are (number of facilities: total emissions of sector) of the selected facilities.

A few key observations can be made by comparing the threshold emissions by sector to the complete emissions by sector. Sector distributions have differing characteristics. In electricity, most coal facilities are large emitters and are virtually 100% of sector emissions; with NG, two-thirds of facilities fall below the 250 kt/yr, while the remainder still account for 93.5% of emissions. In NG processing, 85% are below the threshold while the remaining 15% of facilities produce 65% of emissions. On the other hand, in cement/concrete there are no emitters below the threshold (emphasizing the economy of scale for this sector). However, the general character of smaller emitters in the Intermountain West is such that electricity production remains the dominating source of CO_2 emissions, whether looking at all facilities or just those with the largest emissions.

There is a grey area about the economics and pragmatics of capturing and disposing of the CO_2 from smaller sources, but it is clear that initiating capture in fossil electricity generation will optimize the potential reductions, both in near-term potential and in the magnitude of CO_2 stream separations. This issue of the pragmatic options for capture and disposal will be implicitly captured in the projection scenarios described below.

Point source capture technology and economics

Summary of point source capture technical considerations

There are three main avenues for treating point sources. The first is to retrofit a facility with PSC technology to flue gas streams. Detailed later in this report, PSC is a mature technical solution that can be fielded in the short term for fossil electricity generation, as well as the significant proportion of industrial emissions from flue streams coming from combustion of NG for heat. Using existing CO_2 separation techniques, NG processing is generally an easily captured, pure CO_2 stream, as are some of the streams from fossil refineries. The second avenue is replacement with new technology. New technologies for replacing existing sources can vary in technology readiness. In electricity production, this can be a new fossil facility that includes PSC, new technology that uses combustion in oxygen resulting in pure CO_2 output, or as simple as transitioning from coal to NG fuel, which will result in ca. 60% reduction in CO_2 emissions. Capture of non-heat CO_2 streams from industry is relatively low TRL and specialized in application. The third avenue is to retire a facility, which happens as fossil electricity generation is supplanted by non-fossil electricity generation.

Point source capture technical overview

There is a large body of literature on PSC technologies, from basic science on materials to systems techno-economic analyses. The technology to separate CO_2 has three main approaches: (1) a dry sorbent to chemically bind and release CO_2, (2) a liquid solvent (e.g., Monoethanol amine [MEATM] process) to selectively dissolve and release CO_2, and (3) membranes (e.g. MTR Inc. Polaris membranes) that selectively allow gasses to penetrate at different rates. All three solutions have deployment in commercial separations; for example, in NG processing, separating methane from CO_2. All of these are being tested at pilot scale for deployment in flue-gas capture. Currently, liquid solvents in the amine family are the dominant choice when considering commercial deployment because of economics and a track record of at-scale deployment. It might be expected that the technology will transition over time with maturation, or that different solutions might be best in different settings. For example, coal flue gas has 14 volume percent CO_2 and perhaps substantial sulfur, while natural gas flue has 5 vol.% with very low impurities - a substantial difference in operating requirements.

Liquid solvent CO_2 separation is a well-understood industrial process. Flue gas is passed through an absorber exchange column that maximizes contact between the solvent liquid and the gas. The “rich” (high in CO_2 content) solvent is then heated in the stripper to release the CO_2. The flue gas and the lean solvent are contacting in the absorber exchange column, cooled to a temperature range amenable for the solvent to take up CO_2 removing both heat from flue gas and the exothermic reaction. Substantial energy is used in this heating and cooling cycle. In fossil electricity generation treating the capture process can require 20-30% of the system energy as a ‘parasitic load’, i.e., reduction in generation capacity. In an industrial heat setting, an equivalent amount of energy must be supplied.

To achieve PSC targets in the short to medium term, deploying PSC (and sequestration) will be a necessary and major industrial sector. Each instance is a substantial facility representing a major construction project, and substantial management, maintenance, and material operating support.

Results and outcomes from low, medium, and high scenarios

The estimates of low, medium, and high scenarios have some different implications depending on the sector and technology. The main consideration will be PSC technology adoption (and associated transport and sequestration) for electricity generation, which in principle is commercially available. There are projects already online or in process, so a low adoption scenario isn't necessarily zero, although there is no trend yet to demonstrate that widespread commercial adoption is inevitable. We will only note here that adoption is a combination of permitting and legal status, economics and incentives, transport and storage availability, and sentiment. High adoption in the electricity sector is in principle achievable. On the other hand, industrial sector applications include lower-TRL methods, so the scenarios are a combination of development outcomes and adoption. Although high achievement of industrial PSC is possible, it is less likely even in a high scenario.

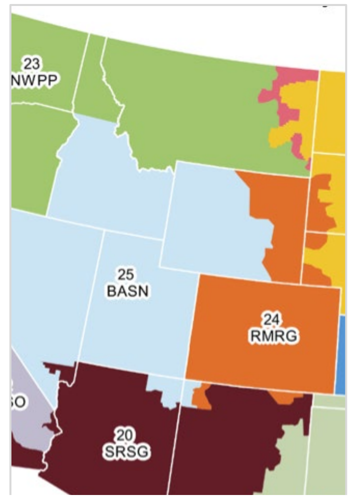

Figure 4. WECC regions relevant to I-WEST, with designations 20: Southwest, 23: Northwest, 24: Rockies, 25: Basin.

Electricity generation point sources

With the large proportion of electricity generated from fossil fuel, the focus of this analysis is on electricity generation. Currently, there are 145 listed electricity generation facilities–36 coal and 109 NG—together they comprise 175 Mt/yr CO_2 emitted. Although there is some small capacity from petroleum, these are largely backup and emergency generators, and not a focus.

To estimate the future of electricity generation, the Energy Information Agency's (EIA) Annual Energy Outlook (AEO) analysis was adopted. The region's facilities are in four of the Western Electricity Coordinating Council (WECC) sub-regions, as shown in the map in Figure 4.

The AEO makes projections at a sub-region level, as well as under different scenarios, including a reference scenario for nominal assumptions, and particularly relevant to this analysis, high and low renewable cost and high and low economic growth. The variation of the scenarios from the reference case is a few percent at most. The projections of the WECC sub-regions are shown in Figure 5.

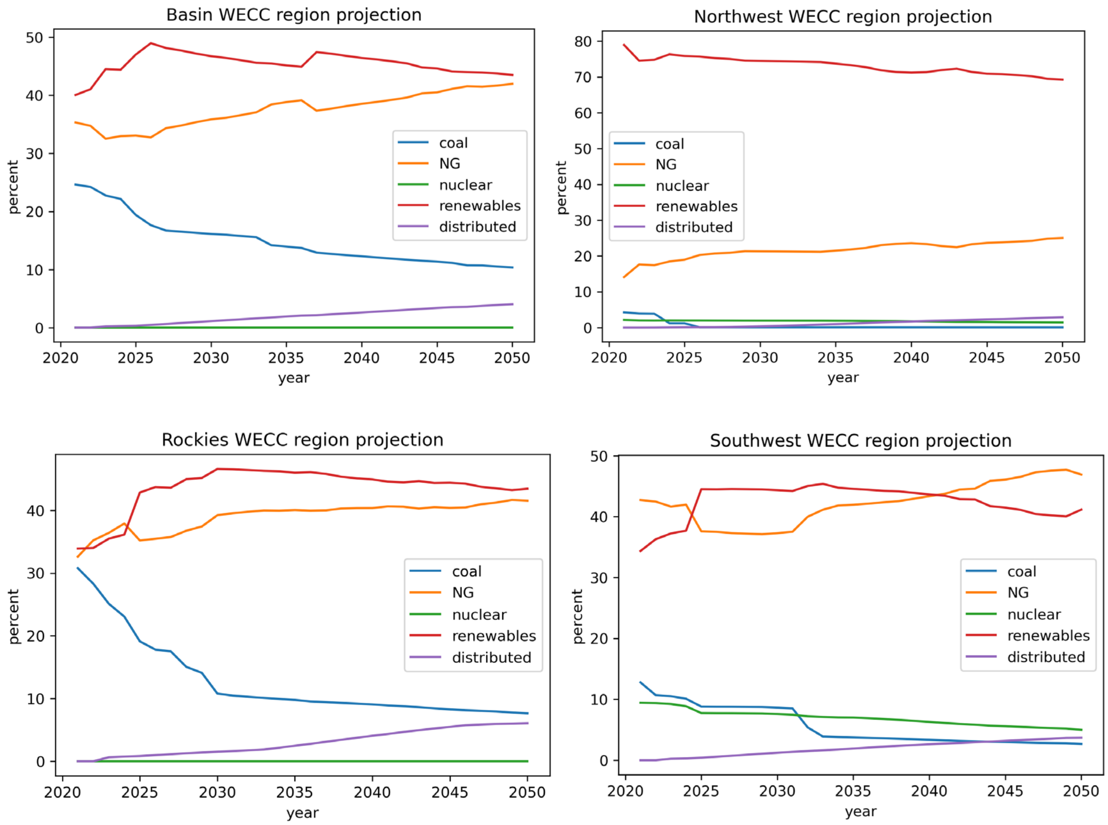

Figure 5. WECC sub-region AEO forecasts relevant to the Intermountain West.

In this analysis, electricity from biomass, and electricity storage in pumped hydro and traditional batteries, are negligible (sub-percent) and not tracked. The projected regional characteristics vary considerably. To estimate the future energy mix for the region, a correspondence is made between emissions and power production: coal electricity production is approximately 1MWh/t (one megawatt-hour per ton of CO_2), and NG production 2.5 MWh/t. These conversion factors can vary depending on plant type, particularly for NG steam combustion vs. combined cycle generation, and should be refined as finer detail regarding power generation is collected about regional facilities. With these conversion factors from CO_2 emissions to generation, and knowing the location of the facilities, the relevant regions are assigned a weight according to production for their relevance to the Intermountain West, resulting in a synthesized AEO for the region. This is shown in Figure 6.

Following this mix projection, we can estimate the changes to emissions in the Intermountain West for coal and NG fossil generation, as shown in Figure 7.

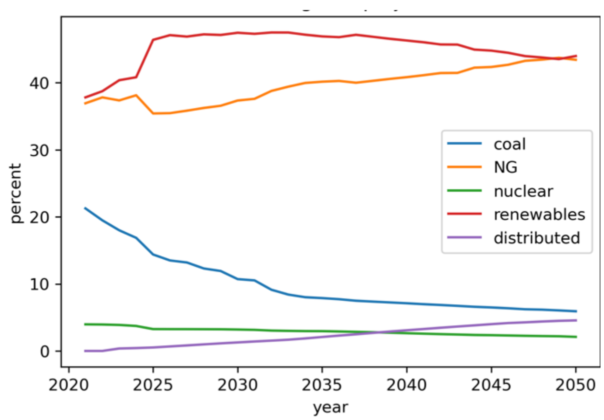

Figure 6. Weighted AEO for electricity generation reference projection for the Intermountain West region.

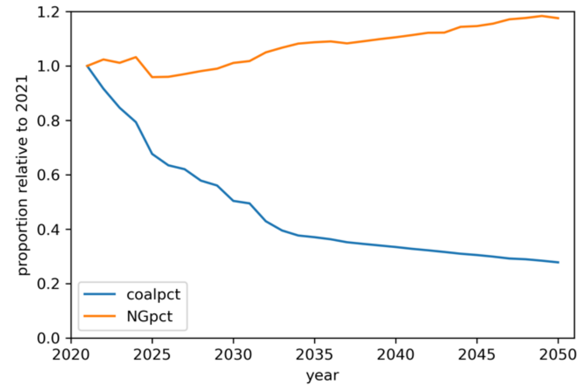

Figure 7. Change in fossil electricity generation, proportion relative to 2021.

Finally, by multiplying these profiles by their current levels, a projection of regional fossil electricity generation emissions is calculated and shown in Figure 8; this result includes the expected change in energy mix due to changing generation, including growth and replacement of fossil generation by renewables. The decrease is primarily driven by reduction in coal generation. It does not include the potential impact of point source capture technologies. The emissions can be further modified given assumptions about point-source capture adoption.

Adoption of PSC will be linear over time, as more complex alternatives have low impact to the outcome given other uncertainties. The low-adoption case will be greater than zero, as there are already capture and sequestration projects underway. PSC efficiency has historically had a goal of 90% capture, but is demonstrated to be possible at much higher rates, up to achieving net-zero emissions. There is a trade-off of diminishing returns in capture proportion to energy invested. Here, we will assume a nominal 98% capture at 30% parasitic power loss by the PSC process. If the electricity mix is to remain at projections through increasing system capacity, this implies a net capture of 97.5% of adoption. The low, medium, and high adoption cases are 10%, 50%, and 90% adoption by 2050. The modified curves are shown in Figure 9.

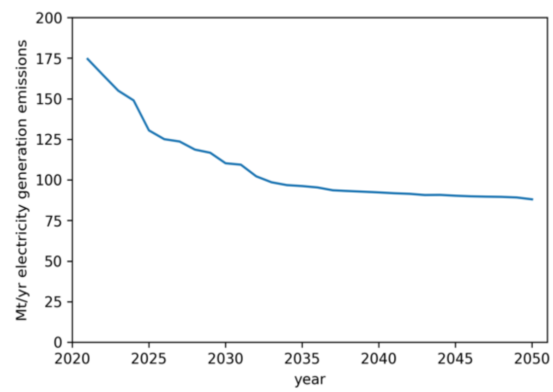

Figure 8. Total projected fossil emissions from electricity generation.

Please see the Appendix for regional project examples, featuring the San Juan Generating Station (SJGS), Dry Fork Station Complex, and Coyote Clean Power Project.

Industrial point sources

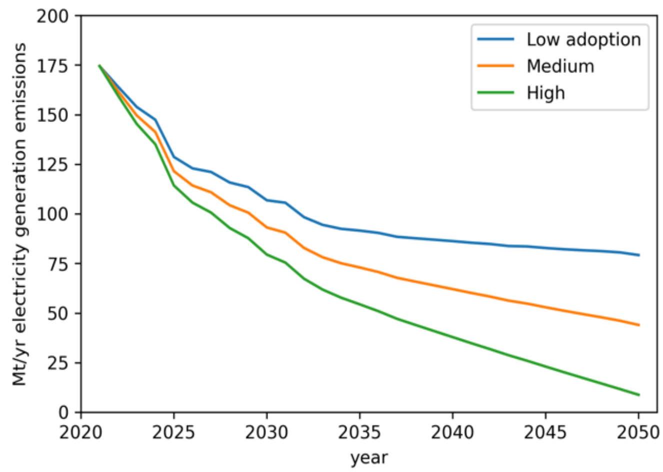

Figure 9. Projected emissions with linear adoption scenarios from present (zero) to 2050: low = 10% adoption, medium = 50% adoption, high = 90% adoption.

This section discusses point sources that are not related to coal and NG electricity generation. Industrial capture has many more facets than electricity production, due to the nature of the industrial sources and in terms of the technology readiness to address the emissions. Here, industrial processes are split into three main categories: fossil fuel production related, industrial heat streams, and other industrial CO_2.

Fossil fuel production is broken down in a more detailed discussion, due to the significance of the streams associated with region's fossil energy economy. Other industries of significance for regional point sources include cement/concrete/lime/gypsum (9.26 Mt.yr) (grouped here for similarity in production through calcination), and mining (7.25 Mt/yr).

In industrial processes, a significant portion of emissions is associated with industrial heat production, effectively all associated with combustion of NG (as opposed to other fossil fuels, light industry can also use electricity). Separating this in processes will be industry and facility dependent, but this is a significant portion of cement/concrete/lime production (calcination), petroleum refining, metals production, ammonia production, and potentially future blue hydrogen production. In these cases, the heat component generates a flue stream that is a straightforward candidate for PSC. Other components of the industrial processes may also release significant CO_2 and be amenable to capture, although this is at a lower TRL, notably the calcination in cement/concrete/lime production or the process output from ammonia production and future blue hydrogen production. Finally, there are industrial processes where the emissions are not pure CO_2 and PSC treatment is experimental; for example, in refining process waste flares, agriculture/food, and oil and gas extraction. Many of these sources are also smaller, and may be better candidates for migrating the point source to replacement technology rather than a simple retrofit-style application of point source capture.

The estimates in this section are more speculative than in the electricity sector, and are open to future refinement as cataloging and analysis of the regional point sources become available in more detail.

Fossil fuel production

As shown in the chart in Figure 2, fossil fuel production sources include: NG processing (23.28 Mt/yr), oil and gas extraction (17.1 Mt/yr), and petroleum refineries (9.32 Mt.yr).

The low, medium, and high scenarios in this area are a combination of change in fossil fuels, and PSC adoption. At this time, we do not have an estimate of the change to oil and gas production, although we may expect this to decline significantly and further contribute to CO_2 point source reductions in this sector.

Natural gas processing

Natural gas processing is an existing separation process, which involves separating hydrocarbons as in petroleum refining, in addition to separating varying but significant CO_2 streams (with CO_2 concentration depending on the well). This is a high-TRL application, with existing operational facilities and application projects in progress within the region. In a scenario, the potential for adoption can be taken as relatively high, as the application requires low technology development and low adoption costs. A low-adoption scenario may still be low for a number of pragmatic reasons, at 10% by 2050; medium will be relatively higher at 70%; and high adoption is 95%.

See the Appendix for a regional example featuring the Piñon Midstream NG Processing project.

Petroleum refining

Petroleum refining has a total of 9.32 Mt/yr emissions and represents varied sources associated with the refining process, from large to small, and various considerations of associated capture. Emissions include sources such as gas flaring (combustion of waste gasses), and process heat (see industrial heat, below). These sources also have a range of sizes, with the small scale sources making capture and storage challenging. Petroleum refining is difficult to address technically, so the estimates of adoption are relatively conservative. We adopted a low scenario of 10% capture by 2050, medium of 40%, and high of 75%.

Oil and gas extraction

For oil and gas extraction, the range of TRLs lead to a relatively low adoption pathway for the various components. We adopted a low scenario of 10% adoption by 2050, medium 35% adoption, and high 60% adoption.

Other major industrial sources

As discussed above, other significant sources in sectors cement/concrete and lime/gypsum currently exist in the Intermountain West. A significant portion of emissions are from heat generation in combustion of NG for heat, while the calcination process of producing CaO from $CaCO_3$ also releases significant CO_2. In these cases, capturing CO_2 from the NG combustion flue is an available technology, but capturing the process CO_2 stream is a lower-TRL that is understood in principle but is at the technology evaluation level. There is a similar situation for ammonia where NG combustion supplies heat and an associated CO_2 flue stream, and the process of producing NH_3 (ammonia) from CH_4 (methane) releases CO_2. As with other NG combustion, the flue stream is available, and with ammonia the ability to easily generate a nearly pure CO_2 process output stream is also well understood and high-TRL; capture from ammonia generation is an available technology. All of these industry sectors have a very high potential for adoption of PSC and management for CO_2 abatement, as high as 95% in the long term, but with some challenges in investment of significant process changes.

In mining, a variety of sources lead to difficult capture scenarios. The potential to address these with capture has challenges, but the potential to address these with process changes is moderate.

See the Appendix for a regional example featuring the Lafarge / Holcim Cement project.

Other sources

The remaining small sectors not discussed are shown in Figure 1, with labels: ag/food manufacturing, chemical manufacturing, electricity (biomass), electricity (other), facilities, hydrogen production, iron/steel, manufacturing (other), metals manufacturing, other, pulp/paperboard/saw mills, and solid waste. These sectors are either composed of small facilities or are not a single clear source to treat. However, collectively they make up 6 Mt/y of emissions. With a combination of technology updates and efficiency improvements, a conservative estimate of treatment is between 10% and 50%.

Industrial sources emissions summary

Table 1 shows the scenario assumptions by emissions type. These estimates are round numbers considered appropriate to the sectors with some reasoning given above. These are general estimates consistent with available literature and will be a topic for future revision and detailed analysis. Putting these together, the summary CO_2 reduction, with regional sector emissions weighting, is shown in Table 2. The summary reduction is the amount below the current total for the selected industry sectors of 67 Mt/yr.

Table 1. Scenario assumptions by emission type

	low % by 2050	medium % by 2050	high % by 2050
Oil and gas extraction	10	35	60
NG processing	10	70	95
Petroleum refineries	10	40	75
Cement/concrete/lime	10	60	95
Ammonia production	10	80	95
Mining	10	50	70
Other	10	30	50

Table 2. Summary of industrial emission sources reduction

	low % by 2050	medium % by 2050	high % by 2050
Summary CO_2 emissions reduction	10%	51.6%	78.1%
Summary Reduction (Mt/yr)	7.3	37.6	57

New sources

New point sources may include industrial growth in the region, new sources related to a hydrogen economy, including blue hydrogen (hydrogen from methane) and carriers like ammonia, and the sources coming from direct air capture. In a future targeting zero emissions, new sources would be born with appropriate technologies that integrate CO_2 capture as part of the process. Future development of significant sources of CO_2 will connect directly with CO_2 utilization and sequestration. Here, we will not consider these sources, although in the future, their development and deployment will be a key part of eliminating CO_2 emissions from what are currently typical point sources.

Summary and outlook

Summarizing the projections above for point sources from electricity generation and industry, the emission reduction potentials for the three scenarios are shown in Figure 10.

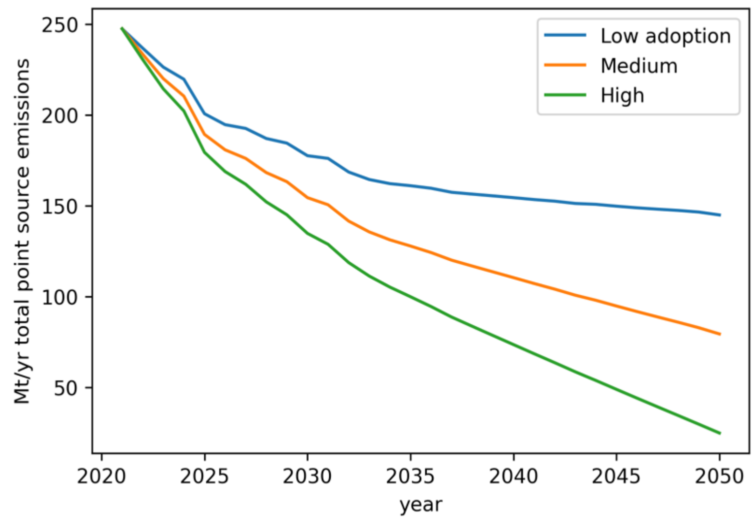

Figure 10. Emissions reduction potential including electricity generation projected mix change and low, medium, high adoption of PSC; plus, a low, medium, high estimate of industrial emissions potential change including PSC, technology changes, and efficiency changes.

There are a variety of point sources in the Intermountain West, and understanding their outlook and potential treatment outcomes is a critical part of reducing emissions, while providing economic energy and growth. PSC is an available technology with significant potential in the region.

PSC adoption in fossil electricity generation is a path to near-term emissions reductions, with commercially available technology. A likely future technical pathway through at least the medium term (10-20 years) is the requirement to match adoption of wind and solar renewables with NG baseload to provide electricity when renewables are not active—the key to addressing the corresponding emissions in that timeframe is point source capture. This report used the EIA's Annual Energy Outlook study as a baseline for electricity generation projections and associated emissions estimates, which is consistent with that scenario. Overall reduction in emissions due to reductions in coal as a fossil fuel, PSC adoption low, medium, and high scenarios reflect a range of outcomes for emissions.

Industry emissions in the Intermountain West are relatively small compared to current electricity generation, but are significant and potentially growing, although here the emissions are taken as not changing over the study period. The disposition of these sources in terms of technology change are difficult to project, and the potential for adoption of PSC is also unclear due to low TRL and small emissions sources that are expensive to treat (both in PSC economies of scale and in disposition of the CO_2 through pipelines and sequestration). Major industrial processes using NG combustion for heat are potentially addressable in the near term. This report gives low, medium, and high capture scenarios by industry sector, showing a potential range of outcomes.

It is important to recognize that possible energy transition scenarios may rely on the growth of calcination, ammonia production, and blue hydrogen. If the driver for the adoption of these technologies is CO_2 emissions reduction, we can expect that new sources will be equipped inherently with managed point source capture technologies and will not contribute significantly to emissions. However, in these scenarios there remain significant CO_2 streams for transport and sequestration.

In summary, of the approximately 250 Mt/yr of emissions from point sources, a low adoption scenario for PSC technology combined with expected electricity generation changes may reduce emissions by approximately 100 Mt/yr. The low adoption scenario would include a relatively modest change from the current trajectory of carbon capture projects, and incentivized technology and efficiency changes. A medium adoption scenario represents a significant increase in adoption and technology alternatives from current trajectory, and may be more in the range of an overall decrease of emissions of approximately two-thirds, or 165 Mt/yr. The high scenario combines an aggressive adoption of PSC technology in electricity generation, and an aggressive combination of PSC, and maturation and adoption of process change in industry, which combine for emissions reductions of 90%.

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Appendix: Regional Projects

This appendix summarizes some of the projects in the Intermountain West, both planned and in process, demonstrating potential paths for PSC in electricity, energy, and industrial processes.

San Juan Generating Station

The San Juan Generating Station (SJGS) is a coal-fired facility that began operating in the 1970s with four coal-burning stacks generating a capacity of 1,684 megawatts. As of the writing of this report, there are two coal-burning stacks still in operation, generating 847 megawatts. There are plans to sell the facility to Enchant Energy Corp. in 2022. Under Enchant, the SJGS would be retrofitted with carbon capture and storage (CCS) to a projected 95% capture rate using Mitsubishi's demonstrated amine-based carbon capture system. The amine solvent which was jointly developed by MHI and Kansai Electric Power Co. is used for CO_2 absorption and desorption.

This project could lead to the capture and potential sequestration of 6 million metric tons of CO_2 annually. To store the captured carbon, Enchant plans to drill 10 carbon injection wells near the power plant, which would have dedicated storage in saline formations. Enchant could also sell the CO_2 for enhanced-oil recovery through the Cortez Pipeline, located 20 miles away, which is a connecting link to EPA-certified storage. The capture facility would utilize approximately 29% of electricity generated from SJGS. The planned project could potentially go online by 2025.

Dry Fork Station Complex

Globally, coal plants generate around 2,000 gigawatts, which is over one-third of global electricity demand. In the electricity sector, coal produces more than one-fifth of global greenhouse gas emissions. On average, a coal-based power plant emits 915 grams of CO_2 power per kilowatt hour of electricity produced.

The Dry Fork Generating Station is a single unit 420 MW capacity generating facility using subbituminous coal. The $1.35 billion facility began operating commercially in 2011 and is currently one the most efficient and cost effective coal fired generating facilities in the United States. The facility's emissions levels are currently below both federal and state requirements, and the water consumption is minimal as it is a zero- liquid discharge facility. In 2014, Dry Fork Station became a test center for carbon capture, utilization and sequestration technologies. The Wyoming Integrated Test Center has used the site to test viable technologies using the site's flue gas. More than $336 million have been invested into advancing Dry Fork's environmental technologies. Dry Fork Station is part of the Basin Electric power cooperative.

These technologies include a reflux circulating fluid bed scrubber, air condenser, CCS, etc. The reflux circulating fluid bed scrubber uses lime to capture and remove more than 95% of sulfur dioxide emissions, and mercury emissions. The Dry Fork Station's scrubber is the largest of this design. An air-cooled condenser uses outside air to condense steam back to water, reducing the amount of water required for plant operations. It is the largest air-cooled condenser in North America and the first application of this kind of cooling technology in Basin Electric's generating fleet.

Coyote Clean Power Project

Gas-fired power generation supplies 20% of the global electricity production capacity. These facilities have low installation costs, high efficiency and are a reliable source of electricity.

Increasing the efficiency of existing fossil fuel-fired power plants is possible using advanced technologies, substituting less carbon-intensive fuels, and shifting generation from higher-emitting to lower-emitting power plants. Natural gas facilities emit an average of 549 grams of CO_2 per kilowatt hour.

The Coyote Clean Power Project will be a 280 MW gas-fired power plant, using NET Power technology for zero-emissions electricity generation. The company 8 Rivers is working with the Southern Ute Indian Reservation to build the carbon capture facility. The Southern Ute Indian Reservation implemented one of the first utility solar projects in Colorado and has promoted alternative energy projects. The NET Power system uses the Allam-Fetvedt Cycle, which combusts natural gas with oxygen and uses CO_2 as a working fluid to drive a turbine instead of steam. This eliminates all air emissions from combustion, including traditional pollutants and CO_2, and inherently produces pipeline-quality CO_2 that can be sequestered. This facility will also be water free by using air cooling, which does not consume or produce wastewater

With an investment decision for the Coyote Clean Power project in 2022, production could begin by 2025. The project is projected to cost $500 million prior to federal tax credits. This project is expected to add 1,000 jobs both on and off the Reservation during peak construction.

Piñon Midstream NG Processing

Sour gas refers to natural gas that contains a significant amount of hydrogen sulfide and CO_2. High levels of these contaminants are removed from natural gas before entering a pipeline due to the environmental harm and the possibility of it affecting down-stream technology. Piñon Midstream NG Processing was created in December 2020, to provide a solution for sour gas that is long-term, economic, and environmentally responsible. Sour gas has been a problem in the Northeastern Delaware Basin since it limits the ability to deliver gas to processing plants due to extreme concentrations of hydrogen sulfide (H_2S) in the gas stream. This has forced operators to flare sour gas, shut-in wells, or delay drilling activity, affecting the resource development opportunities and revenue streams.

Piñon uses the Dark Horse Facility to remove and sequester H_2S and CO_2, which allows companies to drill and produce high levels of sour gas. By removing these contaminants, Piñon is sweetening the gas to be able to transport by pipeline. Piñon Midstream's Dark Horse facility removes the CO_2 from the natural gas and permanently sequesters it more than 17,000 feet below the surface in geologic formations that are highly suitable for this purpose. The CO_2 never has to enter pipelines for further transport once it enters the Dark Horse facility for geologic sequestration. Piñon's total sour gas treating capacity is approximately 170 million cubic feet per day.

Lafarge/ Holcim Cement Project

The cement industry contributes 5-7% of global CO_2 emissions. Around half of those emissions occur from calcination, which occurs when calcium carbonate is heated and the calcium oxide and CO_2 separate. Research and pilot programs for carbon capture in the cement sector are increasing, and studies have shown that there is too much CO_2 for the facility to reuse; instead, it needs to be sent to a sequestration site. To drive the circular economy, Lafarge Canada is also working on various other methods to reuse the captured CO_2, including investment into other products such as concrete and aggregates.

The LafargeHolcim Cement Project is designed to improve carbon-efficiency in cement production through a full-cycle solution of capturing and reusing the CO_2 to limit emissions. The LafargeHolcim Cement plant in Colorado is a dry process cement plant that became operational in 1996. The facility has previously invested in environmental technologies including a flue gas desulfurization scrubber and a low nitrogen oxide calciner. LafargeHolcim received a $1.5 million grant from the U.S. Department of Energy for design and development of a carbon capture technology on a commercial scale. The project is currently in the feasibility phase to assess the Svante technology at LafargeHolcim cement plant. The Svante system captures a portion of the flue gas and scrubs it through an amine system. Svante's carbon capture technology consists of a patented architecture of structured adsorbent laminate (spaced sheets), proprietary process cycle design, and a rotary mechanical contactor to capture, release and regenerate the adsorbent in a single unit. Once the CO_2 is captured in a proprietary filter, steam is used to release it for storage or industrial use. The system has the potential to capture more than 700,000 tons per year, which can either be sold for enhanced oil recovery or sequestered. The LafargeHolcim Cement plant is near the Sheep Mountain CO_2 pipeline that runs south to Texas.

Appendix sources

Lafarge / Holcim Cement Project, retrieved from:
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I-WEST

Phase One Final Report | Detailed Chapter

Direct Air Capture

VERSION 2.0 ARIZONA STATE UNIVERSITY JUNE 2023

About this chapter

The Intermountain West Energy Sustainability & Transitions (I-WEST) initiative is funded by the U.S. Department of Energy to develop a regional technology roadmap to transition six U.S. states to a carbon-neutral energy economy. I-WEST encompasses Arizona, Colorado, Montana, New Mexico, Utah, and Wyoming. Each state is represented in this initiative by a local college, university, or national laboratory. Additional partners from beyond the region were selected for their expertise in applicable fields. In the first phase of I-WEST, the team built the foundation for a regional roadmap that models various energy transition scenarios, including the intersections between technologies, climate, energy policy, economics, and energy, environmental, and social justice. This chapter presents work led by an I-WEST partner on one or more of these focus areas. A summary of the entire I-WEST phase one effort is published online at www.iwest.org.

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Table of Contents

Key messages

- Direct Air Capture (DAC) offers two significant benefits: it can efficiently lower the atmospheric concentrations of CO_2 when combined with permanent sequestration in geologic reservoirs and the CO_2 captured can be used to produce a range of sustainable fuels.
- Bringing down the cost of DAC with the accompanying increasing deployment requires the creation of a market.
- Three DAC technologies are tied to the Intermountain West, and two are currently being demonstrated. The region is well suited for DAC in terms of available land, renewable energy, sequestration potential, and a large workforce already trained in the mining and energy sectors.

"Make no little plans. They have no magic to stir our blood and probably themselves will not be realized. Make big plans; aim high in hope and work." Daniel Burnham, Architect.

Introduction

Since the 1850s, atmospheric CO_2 concentrations have increased to reach their highest level in at least 800,000 years[1]. Part of transitioning to a sustainable energy system is dealing with CO_2[2], including reducing the generation of CO_2. The other part of the solution will be to capture the excess CO_2 that is already in the atmosphere and oceans and to capture what is released during the transition to a future based on renewable energy.

The work to build a new carbon management industry depends on the development and implementation of technologies to eliminate carbon pollution and draw down what is already in the atmosphere. Of the solutions that could be implemented, carbon capture will directly affect millions of people with the goods and services it provides. By the end of this decade, Direct Air Capture of CO_2 (DAC) will have to grow from kilotons per year to hundreds of megatons per year. By harvesting carbon from the atmosphere for sequestration and carbon products, a new industry will be born. The benefits will include the permanent storage of carbon and the development of renewable energy through recycled synthetic fuels. By recycling CO_2, it becomes possible to have renewable energy penetrate through the entire market. For emissions that cannot be avoided and the legacy of past emissions, DAC and carbon disposal stand ready to balance the carbon budget.

The world needs to sequester about 1.5 trillion tons of CO_2 to lower its concentration in the atmosphere by 100 ppm relative to where it would end up otherwise. Minimizing emissions will not be sufficient to stabilize climate below 2°C warming. A plausible solution is to combine emission reductions with “negative-emission” or “drawdown” technologies. DAC represents a technology for such a drawdown. It also could play a major role in a closed carbon cycle, where fuels and plastics are produced from CO_2 from the air using renewable or recycled fueled electric power for the production.

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[1] IPCC, 2021: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change[Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, In press, doi:10.1017/9781009157896.

[2] Lackner, K.S., Jospe, C., 2017. Climate Change is a Waste Management Problem. Issues in Science and Technology 33, 83–88.

Once mobilized, carbon stays in the atmosphere/hydrosphere/biosphere system for tens of millennia[3]. For the first hundred years half of the carbon remains in the atmosphere[4]. The rest acidifies the ocean and leads to the eutrophication of the biosphere[5].. In the end, for every ton of carbon produced, another ton will have to be disposed of [6,7], and the emissions from the waste burned over the past two centuries will need to be cleaned up as well.

Can DAC be implemented in time? Analogs with other technologies suggest that after invention there typically is a latency time, which is followed by rapid growth that results in ubiquitous deployment, maybe a decade or two later. If we optimistically assume the start time as 20 years ago, that the latency time is over and that growth starts now, we will take maybe around 20 years to reach scale. Then it still takes 40 years to draw down the carbon, so one could reach the end of the overshoot near the end of the century.

The really difficult question is, “How to get started?” By the time we have grown our capture capacity to its fullest, the amount of CO_2 to be removed will be well above current estimates.

Intergovernmental Panel on Climate Change (IPCC) finds “unequivocal” evidence that any more delays “will miss a brief and rapidly closing window of opportunity” for a globally livable future[8]. UN Secretary-General António Guterres called the report “an atlas of human suffering,” because it is a comprehensive look at both recent and projected extreme weather events, lacerated ecosystems, and their human toll. “The facts are undeniable. This abdication of leadership is criminal", Guterres said in a statement. "The world's biggest polluters are guilty of arson of our only home"[9].

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[3] Archer, D., Eby, M., Brovkin, V., Ridgwell, A., Cao, L., Mikolajewicz, U., Caldeira, K., Matsumoto, K., Munhoven, G., Montenegro, A., Tokos, K., 2009. Atmospheric lifetime of fossil-fuel carbon dioxide. Annual Reviews of Earth and Planetary Sciences 37.

[4] Archer, D., Kheshgi, H., Maier-Reimer, E., 1997. Multiple timescales for neutralization of fossil fuel CO. Geophys. Res. Lett. 24, 405–408. https://doi.org/10.1029/97GL00168

[5] Archer, D., Kheshgi, H., Maier-Reimer, E., 1998. Dynamics of fossil fuel CO2 neutralization by marine CaCO3. Global Biogeochemical Cycles 12, 259–276. https://doi.org/10.1029/98GB00744

[6] Lackner, K.S., Wilson, R., Ziock, H.-J., 2000. Free-Market Approaches to Controlling Carbon Dioxide Emissions to the Atmosphere. Global Warming and Energy Policy 31–46. https://doi.org/10.1007/978-1-4615-1323-0_3

[7] Allen, M.R., Frame, D.J., Mason, C.F., 2009. The case for mandatory sequestration. Nature Geoscience 2, 813–814. https://doi.org/10.1038/ngeo709

[8] IPCC, 2022: *Climate Change 2022: Impacts, Adaptation, and Vulnerability.* Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge University Press.

[9] Press Release Secretary General. Secretary-General Calls Latest IPCC Climate Report ‘Code Red for Humanity’, Stressing ‘Irrefutable’ Evidence of Human Influence. SG/SM/20847. 9 AUGUST 2021. Available at:

How does direct air capture work?

DAC uses a nature-inspired design to absorb CO_2 directly from the air (Figure 1). The capture process may be driven by mechanical means (fans) or passive (relying on natural air movement). DAC uses a chemical compound (sorbent) to "catch" the CO_2 out of the air. Following capture, the sorbent is exposed to heat, moisture, or some combination that releases the CO_2 into an enclosed space that serves as a harvest chamber. This capture and harvest sequence is then repeated. Following the capture phase, except in a few applications, the CO_2-enriched air is fed to a compression and purification unit to produce CO_2 in varying concentrations, generally in the 90+ percent range. The basic operation relies on a sorbent cycle to bind CO_2 from the atmosphere and release it in an enriched form (Figure 2).

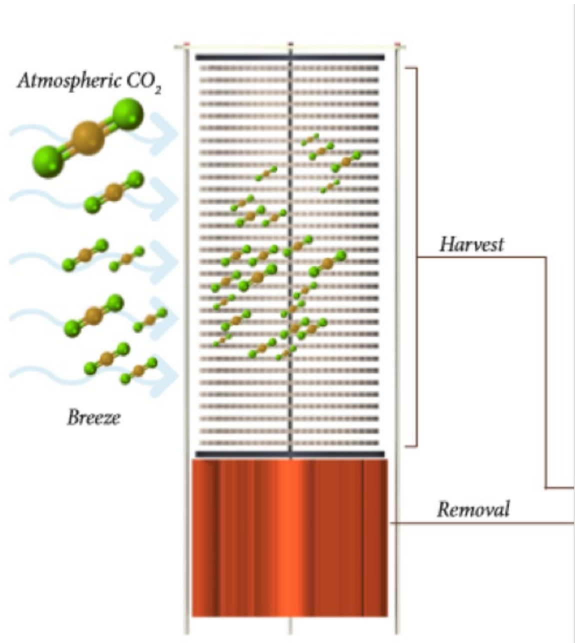

Figure 1. A rendition of the ASU Tiburio design. Credit ASU/CNCE SRP Project 2017.

https://press.un.org/en/2021/sgsm20847.doc.htm#:~:text=Today's%20IPCC%20Working%20Group%201,of%20people%20at%20immediate%20risk.

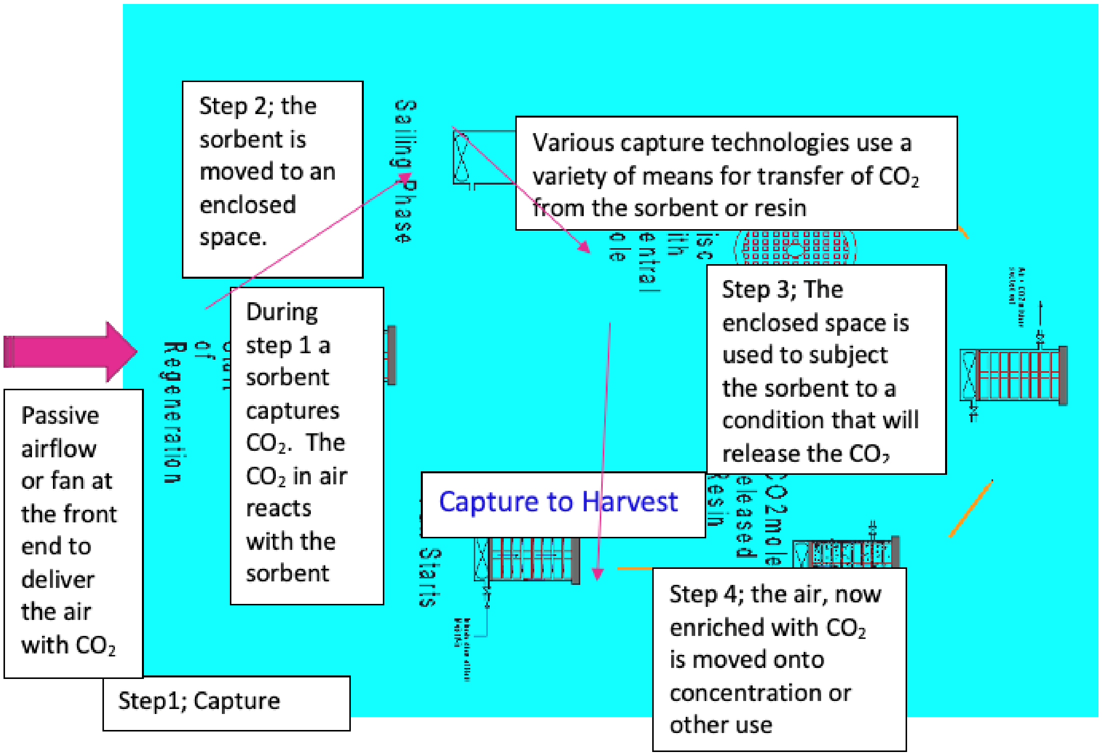

Figure 2. The cycling phases of the Direct Air Capture process. (ASU/CNCE SRP DAC Project).

DAC is in many ways like point source capture (PSC) in that it uses the same feed and capture mechanism along with the associated concentration. PSC is dependent on the air flow of concentrations of CO_2 greater than in nature, like those that can be found in the waste streams of fossil fuel power plants.

DAC comes in many forms and applications, and it is a technology that is adaptable to multiple environments and locations. DAC comes in a variety of sizes which are open to mass production and scaled growth.

DAC technologies

The DAC industry is growing rapidly and globally. However, it is still at demonstration scale. Entrepreneurs are now responding at an increasing pace to the opportunity and need that DAC has created a solution to.

There are currently roughly two dozen DAC plants operating worldwide, capturing more than 0.01 Mt CO_2/year (Mt = million metric tonnes), and a 1Mt CO_2/year capture plant is in advanced development in the U.S. The latest plant to come online, in September 2021, is capturing 4 kt

CO_2/year (kt = thousand metric tonnes) for storage in basalt formations in Iceland. In the International Energy Agency's Net Zero Emissions by 2050 Scenario, DAC is scaled up to capture more than 85 Mt CO_2/year by 2030 and ~980 Mt CO_2/year by 2050. This level of deployment will require several more large-scale demonstrations to refine the technology and reduce capture costs[10].

Today, two technology approaches are being used to capture CO_2 from the air - liquid and solid sorbent based (Table 1). Liquid sorbent systems pass air through or over chemical solutions, which remove the CO_2. After releasing the CO_2, the system recycles the chemicals back into the process by applying high-temperature heat or other options. The rest of the air returns to the environment. Solid DAC technology makes use of solid sorbent filters that chemically bind with CO_2. The sorbent is then heated or otherwise placed in a modified condition that promotes release of the concentrated CO_2, which is then concentrated for storage or product use (Figure 3).

Table 1. Technological approaches for DAC capture
Liquid and solid sorbents
Inorganic and organic
Passive and active air flow
Thermal swings
Moisture driven swings
Vacuum swings
Combination of different swings
Shaped after large industrial processes
Emulating the mass production paradigm

[10] IEA (2022). Net Zero by 2050. A Roadmap for the Global Energy Sector. Report, Paris, May 2021. Available at: https://www.iea.org/reports/net-zero-by-2050

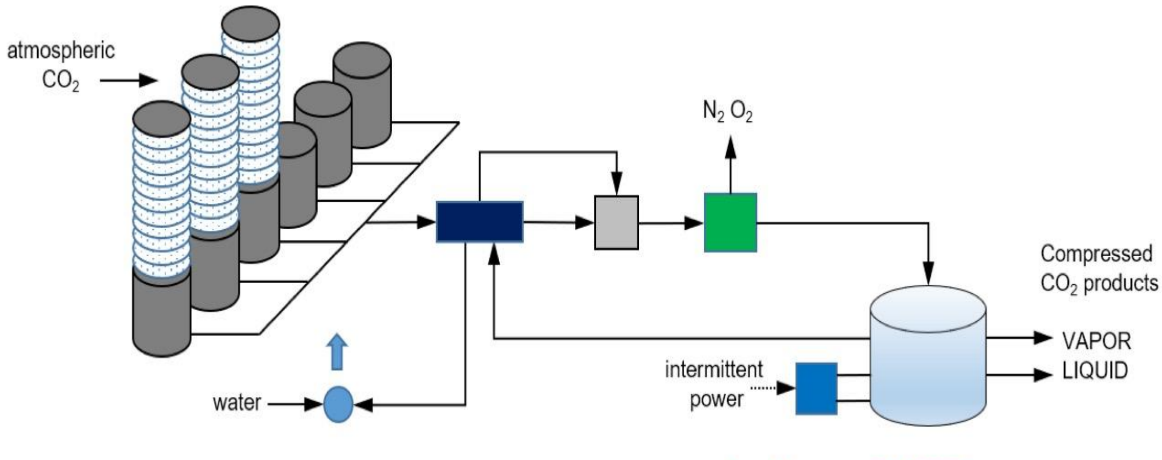

Figure 3. Illustrative example of flow from capture through compression. ASU/CNCE graphic 2018.

Capture is the first step in the process (Figure 3). Following capture, the CO_2 will most likely be concentrated (this step may not be necessary for feeding CO_2 into agricultural greenhouses). Concentration provides a CO_2 stream that can be fed into sequestration for permanent disposal or into product application. For some applications there may also be purification steps to remove “contaminants” within the CO_2 stream. Figure 4 provides an illustrative process flow through concentration and purification.

While there are multiple DAC technologies currently in development, none of the offerings can boast a capture cost that is likely to meet the projected pricing for capture of CO_2 in the hundred-dollar range; the current target. Some of the top players in the industry based on scale, investor backup, and publicly available articles, are listed below in Figure 4. This is not a comprehensive list as some capture technologies have not publicly revealed their approach and others are being introduced nearly every month. A few have completed pilot plants, while others are still at a “lab” stage.

Pilot (<5,000 tons/yr.)

Lab (1 ton/yr.)

Figure 4. Some of the companies with announced capture technology (ASU graphic).

Companies with announced capture technology

Climeworks

The technology used by Climeworks is advanced, particularly regarding demonstrating sequestration. The Climeworks technology is based on a cyclic adsorption and desorption process with a filter material. Climeworks is based in Switzerland and has a demonstration plant in Iceland.

Carbon Engineering

Carbon Engineering uses existing technology first used for paper mill processing. Carbon Engineering "proved" that CO_2 capture could work. The capture process is done by using an air contactor and a regeneration cycle for continuous capture of atmospheric CO_2. Air is drawn through plastic channels coated with potassium hydroxide to separate the CO_2 from their gases. The process requires turbines to increase the concentration and the entire process uses a significant amount of energy. This approach uses large fans to blow air over the sorbent material to trap more of the gas. It then uses heat to drive the subsequent reactions that release the CO_2. Carbon Engineering is based in Canada.

Global Thermostat

Global Thermostat has developed a proprietary technology that uses leftover process heat to collect carbon from power plants. The process uses large fans which draw air through slabs made of ceramic cubes. The cubes hold proprietary chemicals that absorb CO_2 at room temperature. The slabs rotate and the cubes are heated, releasing a stream of CO_2 into a steel pipe. Devices called monoliths maximize surface area. That area is covered with amines, the nitrogen-based chemical that absorbs CO_2 from the air. The CO_2 generated is directly proportional to the energy generated from the power plant.

Carbon Collect A relatively new entrant into commercializing DAC technology, Carbon Collect takes a different approach than the aforementioned companies with their passive MechanicalTree concept (Figure 1). The MechanicalTrees concept requires no energy for CO_2 capture. Instead, the wind delivers ambient air resulting in low capture costs.

CO_2 Solutions

CO_2 Solutions has developed proprietary enzyme-based technologies for CO_2 capture from various industrial flue gasses for reuse or sequestration. CO_2 Solutions claims to use a genetically engineered E. coli bacteria to produce enzymes that convert the CO_2 into a bicarbonate. CO_2 Solutions has developed technology in Canada, the U.S., and E.U.

Prometheus

Prometheus technology uses water and renewable energy to capture CO_2 from air to produce gasoline and jet fuel. The technology uses a modular approach for the production of micro-cell gasoline production based on excess renewable energy. The collected CO_2 is placed in an electrochemical stack. Using electricity, the carbon is combined with hydrogen molecules from water to create alcohols, while releasing oxygen. The alcohols are harvested using a type of nanotube membrane. In a catalytic step, the alcohols are reformed into fuel, and water is recovered. This final step can be customized to produce gasoline, diesel, or jet fuel.

Aircela

Aircela Inc. is developing small-scale, modular DAC-to-fuels systems. The modular approach means any user of hydrocarbons is a potential customer. The technology can be scaled at the household level (making ~1 gallon per day, capturing ~3 tons per year) or to the level of utility. The technology is intended to operate intermittently with off-grid renewables to allow remote communities with little grid access to deploy the systems.

The need for DAC

Climate change-related impacts costed the world $650 billion from 2016-2018[11], and climate change could cut world economy by $23 trillion in 2050[12]. The IPCC makes it clear that mechanical

[11] Morgan Stanley Research (2020). Five Sectors That Cannot Escape Climate Change. https://www.morganstanley.com/im/publication/insights/articles/articles_fivesectorsthatcannotescapeclimatechange_us.pdf

[12] SwissRe (2021). The economics of climate change. Available at: https://www.swissre.com/institute/research/topics-and-risk-dialogues/climate-and-natural-catastrophe-risk/expertise-publication-economics-of-climate-change.html

capture and sequestration are essential for temperature increases to remain below 1.5°C.[13]. Capture will also likely be necessary to stay below a temperature increase of 2°C[1], given the pace of current emissions.[14]. Current policies will drive a temperature increase of 2-3.6°C by 2100, and even the optimistic scenarios of new pledges bring the increase to 1.5-2.4°C[14].

We assume in this study that the world will need to return the CO_2 concentration in the atmosphere (or equivalently the amount of carbon in the mobile carbon pool) to a level that is lower than today's level (approximately 420 ppm.[15]). To get to 300 ppm, we need to remove 120 ppm that is already in the atmosphere plus emissions during the overshoot. The reduction of the CO_2 concentration by 1 ppm will require the removal of approximately 15 Gt CO_2, which includes carbon that will return to the atmosphere from the ocean and the biosphere. Whichever way this will be resolved needs to assure that there are capture methods in use and that sequestration is handled in a manner that is permanent and meets a certification standard.

We might start from the idea that all emissions need to be driven to zero. One view might be that if an entity produces CO_2, it will also need to guarantee an equal amount of carbon removal[6].

The second issue is the quality of the storage. For storage to be certified, the storage reservoir must be well defined, the addition to the storage site can be accurately measured, and the future monitoring of storage can assure that the carbon remains stored. This could be combined with the acceptance of liability of the storage operator that if the carbon is lost, this is considered an emission that needs to be matched by a new certificate of storage. If such well-defined constraints are in place, storage is not that difficult. If one operates a storage site that tends to lose carbon after a decade, we might include the cost of a future certificate into the cost of doing business and decide whether this process is economical after adding the additional costs. The storage operator might purchase an option on future storage or insurance in case there is a liability associated with "escape." The price for not doing that is that people can sell cheap certificates with unknown liabilities attached. We must ensure that storage is effective, long-term, and verified by an independent entity. As an example, if the biomass stored is going to rot away in a decade or two,

[13] IPCC, 2018. Summary for Policymakers, in: Global Warming of 1.5°C. https://doi.org/10.1016/j.oneear.2019.10.025
[14] Climate Action Tracker (2021). Glasgow's 2030 credibility gap: net zero's lip service to climate action. November 2021. Available at: https://climateactiontracker.org/documents/997/CAT_2021-11-09_Briefing_Global-Update_Glasgow2030CredibilityGap.pdf
[15] The Keeling Lab (2022). The Keeling Curve Hits 420 PPM. Available at: https://keelingcurve.ucsd.edu/2022/05/31/2114/

there must be a functional and measurable means to understand how it is going to be retrieved or covered by other storage.

The problem with some storage systems (for example in agricultural soils) is not that they cannot be made to work, but that by not delivering permanent storage and by avoiding measured accountability they will flood the market with cheap storage, which in the end turns out not to be storage (because of its short storage time) after all, but its low price point prevents real (long-term) storage from being implemented. An independently audit verifiable certification program that has international recognition and support could help solve accountability problems.

A model in which all produced CO_2 going forward must be put away by the emitter with a grace period of increasing capture and storage while the cost of capture/storage comes down is explored here. The grace period would not eliminate the obligation for capture and storage but would allow for some portion of one's emission to be resolved later (say ten years in the future). If we ramp up 5% per year, in 20 years we may reach a point of all emissions being neutralized. By requiring a percentage of CO_2 emissions to be removed (with an increase over time of that percentage) a market is created that will increase the options for carbon removal and drive down the capture price.

Roughly two-thirds of all energy generation emissions currently cannot be captured at point sources due to operational restrictions and the reduction in fossil power plant capacity (decreased capacity makes the capital cost of capture unacceptable). When fossil energy production declines, economic applications of point source will be reduced as well. Another consideration is that much of the CO_2 comes from distributed sources, and smokestack removal does not apply to the CO_2 distributed in the air due to indirect sources like transportation and past emissions.

Biological capture and storage could play an important role and be part of the early solution. Unfortunately, biological capture is limited by its transience and competition with food production. In spite of these limitations, biological capture may rise as high as capturing a third of the excess carbon in the atmosphere with a massive reforestation program[16]. The challenge for biological capture and sequestration is permanence, proof of capture, and land use.

[16] Conservation International (2022). Exponential roadmap for natural climate solutions. Available at: https://www.conservation.org/roadmap-pdf

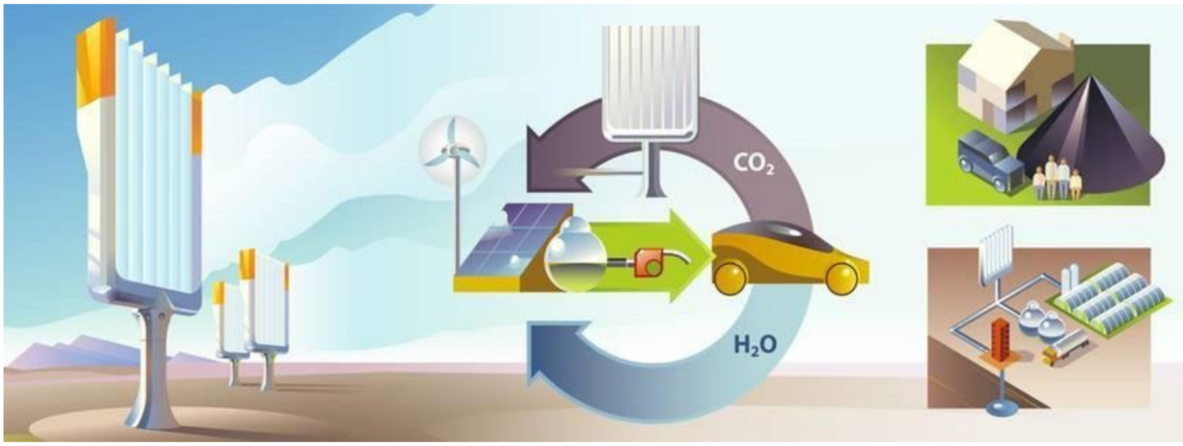

Figure 5. A model concept of the uses of CO_2 capture as fuels or sequestration. Captured CO_2 combined with renewable energy can be transformed into fuels and can be sequestered in various carbon reservoirs. Credit: Klaus Lackner, (April 2019 ASU) [17].

Therefore, we return to the question of how to remove CO_2 from the air by technical means; could DAC be feasible? If we consider a model in which windmills harvest kinetic energy while DAC scrubbers (artificial trees) remove CO_2, and one values kinetic energy at five cents per kilowatt-hour and considers a tipping fee of $30 for a ton of CO_2, then the CO_2 content of the atmosphere has a seventy times higher value than wind energy. Windmills are clearly feasible and economical.

DAC, as envisioned, offers important opportunities (Figure 5). First, it can, over decades, return the world to a pre-industrial CO_2 concentration if the captured carbon is sequestered and maintained in a sequestered state. Second, it can enable the transition to renewable energy as it may contribute to solving the intermittency problem of renewable energy by providing recycled liquid and gas fuel for those times when renewables are not producing; there will continue to be a need for liquid and gas fuels to support the economy and to provide backup generation for renewables. Also, the use of carbon for various products will not disappear, and this carbon could be provided from capture.

Like for most new technologies, the cost is a concern. Small field demonstration and lab models are not overly helpful in projecting large scale production cost. Today cost appears to be high, however modeling the possibilities for cost reduction in production and operation has led to encouraging conclusions. Although there are many steps between today and large-scale application there is hope for <$100/ton for capture, and even down to the $50 range.

[17] A Capture Graphic. Klaus Lackner. ASU (multiple dates)

For comparison, mass production has managed to drive down the cost of solar energy to the point that it competes with primary energy, not just grid electricity[18]. This required a hundredfold cost reduction. DAC will have a range of economic opportunities. Sequestration of CO_2 for the most part will be a cost of removing a waste, and sequestration can have positive economic gain such as with EOR. DAC will also have opportunities for the synthesis of products with economic value and thus a potential for profitability or at least an offset of costs of capture. For example, captured CO_2 might be a feedstock to be used to produce liquid fuels. By combining capture with solar energy, or other renewable energy sources, solar energy converted into liquid fuels might feed into the transport sector and provide energy in parts of the country where renewables are not available.

The same rational and forward thinking might apply to carbon related products that we wish to retain. Carbon capture might feed into carbon fiber, plastics, cosmetics, tires, and detergents.

DAC, when combined with sequestration, it is a long-term and permanent carbon removal technology that can address both emissions from sources that are not easily or cheaply decarbonized and collect the CO_2 that is already in the atmosphere. While the land area required for the technology to capture the carbon is non-trivial, it is much less than that required for forest management. Though DAC has infrastructure challenges such as connection to energy sources and water source requirements for some sites, it can be undertaken even in areas that are unsuitable for farming or forests.

DAC technology can be modular, and to date most DAC facilities have been relatively small, decreasing the barriers to entry, increasing the opportunities for learning-by-doing, and reducing the political salience of individual projects. The granularity of DAC technology may also allow it to be ramped-up relatively quickly. DAC application is flexible geographically and it is less dependent on transportation networks as DAC facilities can be co-located with geological storage, requiring only small-scale transportation systems. A key problem for all carbon capture technology is to create interest groups that will adopt. The flexibility of DAC to capture adjacent to storage, to use renewables to build recycled fuels, and to rapidly scale up may provide a bridge to support.

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[18] IPCC, 2022: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [P.R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, J. Malley, (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA. doi: 10.1017/9781009157926

Assuming wide use of DAC, and that the captured carbon is split between permanent storage (sequestration) and carbon for use as fuel, plastics, etc., the following product developments could be anticipated:

- Liquid fuel production – airplanes, ships, other transport, and specialty fuels such as race cars
- Gas fuel production for power plants, blast furnaces, and heating
- Production of base material for plastics, poly, and other carbon-based structural materials
- DAC device manufacturing, installation, and operation of DAC farms and concentrators
- CO_2 sequestration using geologic formations and mineralization

For this adaptable kind of program, DAC appears to be more appropriate for capture, sequestration, and carbon product development, based on current experience[19].

A story about DAC development and deployment

Thinking about a roadmap for DAC in the Intermountain West involves so many different elements and inputs that it is by nature too complicated for rational analytic prediction. So, at the start let us tell a story that can use an imaginary company that is attempting to commercialize a DAC device.

Our device for our imaginary company provides capture using large-scale commercial HVAC as the source of airflow and structure. This device is parasitic to the HVAC system and scavenges power from the HVAC to avoid the upfront energy costs for airflow. Energy use drives cost, so we need to minimize that and for our new DAC device we piggyback onto HVAC. Let's call our company "Capture America" or *CA* and our device the "Catcher's Mitt" or *CM*.

Our imaginary company and device are at the demonstration phase. How do we move from demonstration to sufficient capture of the CO_2 that is not either avoided or captured by all the other potential solutions? We ought to assume that DAC is the solution for all the CO_2 that isn't picked up by CO_2 reduction or the other capture methods such as point source capture and capture from biomass. That means DAC has a big job and CA needs to get moving.

CA is at demonstration, so they are learning how the CM needs to be re-engineered for the next round of fabrication at a small scale but large enough to add demonstration concentration and sequestration. Movement from demonstration to commercial scale is often the graveyard of new technologies. It will be important for physics to work in an enlarged environment, for the cost of

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[19] Post Combustion Capture or Direct Air Capture in Decarbonizing US Power? Environmental Science & Technology. D Azarabadi & K Lackner. April 2020

equipment to fall within our target, and for operations to be as smooth and productive as we assumed.

Following a small-scale demonstration with a commercial sized unit, we need to move to mid-stage, say installing the CM at a large commercial building complex. In addition to capture, this requires piping of CO_2 between the buildings and a CO_2 pipeline that takes the CO_2 to a sequestration site. Moving to a building complex will be costly but within the range of the funds that investors can handle.

At this point in the story CA is stuck. We are unlikely to be capable of raising funds to continue building out larger applications, because there is not a sufficient market with a determined future. The market for capture, hydrogen, and many other carbon neutral solutions currently does not include enough demand to move them ahead. There are volunteer applications of carbon credits for companies such as Microsoft and Stripe, but these are not sufficient to create a market for CA or any other capture venture.

Market examples do exist. Countries have made it clear that EVs (electric vehicles) will replace ICE (internal Combustion Engine) passenger vehicles in 2030 creating a firm market for EVs. Also, some countries are forcing the phase-out of fossil energy generation, creating a market for renewables and back-up power such as batteries and companies like Mainspring Energy. Therefore, part of the answer is being developed, but only part.

So, the main conundrum for the *Mitt* is where is the market? Unless a market with a future is created quickly, DAC is not going to make the rapid progress that is needed for carbon neutrality in the next 30 years.

Roadmap

Assumptions

DAC could be one of a suite of capture technologies employed to smooth the energy transition by gathering the excess CO_2 already in the atmosphere and removing the emissions created by those sectors of the economy which are extremely difficult to decarbonize or are decarbonizing but not completely converted.

I-WEST roadmap considerations

The Intermountain West is “home” to at least three demonstrated DAC technologies. As is true elsewhere in the U.S., demonstration efforts are underway but no large-scale deployment. The region has the advantage of favorable environmental conditions for DAC, open spaces for capture, and sufficient geological formations for sequestration.

A deployment scenario over a 5-, 10-, and 15-year period

5 years: DAC could reach a level of capture of several million tons per year in the region. The scale-up will take time as manufacturing gears up. New technologies need to create a supply chain, develop production facilities, create standards and processes, and build a workforce for everything from design to operations.

10 years: In a ten-year period, DAC in the Intermountain West, due the many favorable conditions in the region for DAC, might expand to a million tons per day of capture and sequestration. Once requirements for carbon reduction are in place both manufacturing and capture would likely expand rapidly. The environment and the workforce available in the region are favorable.

15 years: In a fifteen-year timeframe, DAC could be an established form of carbon reduction in the region. The geological- and business-friendly environment will be critical in developing a large DAC footprint. During this period the region should be adding a variety of production facilities to take advantage of carbon recycling through CO_2.

Consideration

Current State: DAC is at the demonstration stage for a few devices and at a conceptual design stage for many others. While it is tempting to believe some of the demonstration devices are going to be shortly manufactured at scale, it is too early to determine winners and losers. Most devices are focused on similar principles and use solid sorbents (although liquid sorbent technologies are moving ahead). It is hard to believe the field will end up being this limited, so one must assume there will be new ideas[20].

Impetus: Every new technology that succeeds has a period of discovery followed by a period of “push.” Sometimes the push is market demand, sometimes it is better cost, and sometimes it is the emergence of a need. DAC will fall into the need category. Currently the need is known but not

[20] Lackner, K. S., & Azarabadi, H. (2021). Buying down the cost of direct air capture. Industrial & Engineering Chemistry Research, 60(22), 8196-8208.

being pushed very hard. The next step for DAC could be DOE DAC hubs. By pulling a few devices forward some of the others will benefit from the directional thrust.

Demo to Field: Hub financing would allow 3-4 DAC technologies to produce sufficient machines to capture 1 ton of CO_2 in a 12-month period. The hubs are four years long, and we can assume that around the year 2027, we have a few “proven” DAC technologies that are capable of proceeding to larger production. If removal would be mandated by the year 2027 the devices could move into production and broad implementation.

Demand: The next step is demand. With the assumption of proven technologies around 2027, will the demand be there to bring about mass production? Will demand be there in the mid 2020s? This concept of capture will proceed or die depending on demand. Demand seems likely, unless there is another option to reduce the existing and future CO_2 in our atmosphere[21].

Infrastructure: If it proceeds, DAC will be a large industry and will require a large infrastructure to support it, that includes:

- Land – Land needs to be acquired.
- Supply chain – Difficult challenge for new industries.
- Fabrication – Could be focused in the Intermountain West and tied to capture farms in the area.
- Assembly – Site assembly creates new set of employment needing manpower.
- Ops Staff – Operating the DAC Farms is an opportunity for many well-paid jobs.
- Maintenance support – Many new support companies will be built to maintain the new farms.
- Concentration and Purification Process (CPU) – CPU of CO_2 is a new field that has proven. applications that work. The next step is to improve on quality, efficiency, and cost.
- Sequestration – Mineralization, geological and EOR (Enhanced Oil Recovery) permanent storage are available in the region. Early geologic survey work in the region indicates a number of viable locations for geologic and EOR storage. Mineralization should work as well in the region as elsewhere.
- Products – The use of carbon will not suddenly cease and one path to reducing extraction of fossil carbon is to use carbon recycled through capture. The region would benefit from capture.
- Codes and Standards – The rules for capture, sequestration, etc. need to be developed, implemented, and monitored.

[21] Carbon Futures and Certification of Sequestration. ASU/CNCE paper April 2022 (multiple authors)

- Certification - Sequestration should be based on rules drafted and administered by an independent body.

Mass production: The past indicates production can bring down cost. Factory production provides a path to cost reduction through higher production, and also increases quality and worker safety. Large scale, or mass production is key to cost reduction. Just as with photovoltaics the capture industry needs to design devices that can be factory produced. This requires a smaller scale and a sameness of production.

Cost curve: Time and large-scale fabrication along with replication of the same design will bring costs down. This assumes the devices are designed for ease of production, are readily shipped and can be field assembled with a rational amount of field labor and equipment. Bringing down cost is about volume and success in volume is about efficient and quality devices.

Product uses: There may be a need to use the captured CO_2 to fuel transportation and gas furnaces, support the growth of crops, and to provide chemical feedstocks for plastics and other applications. Figure 5 provides a graphic recycle concept for desalination, one of the potential uses for recycling of airborne carbon.

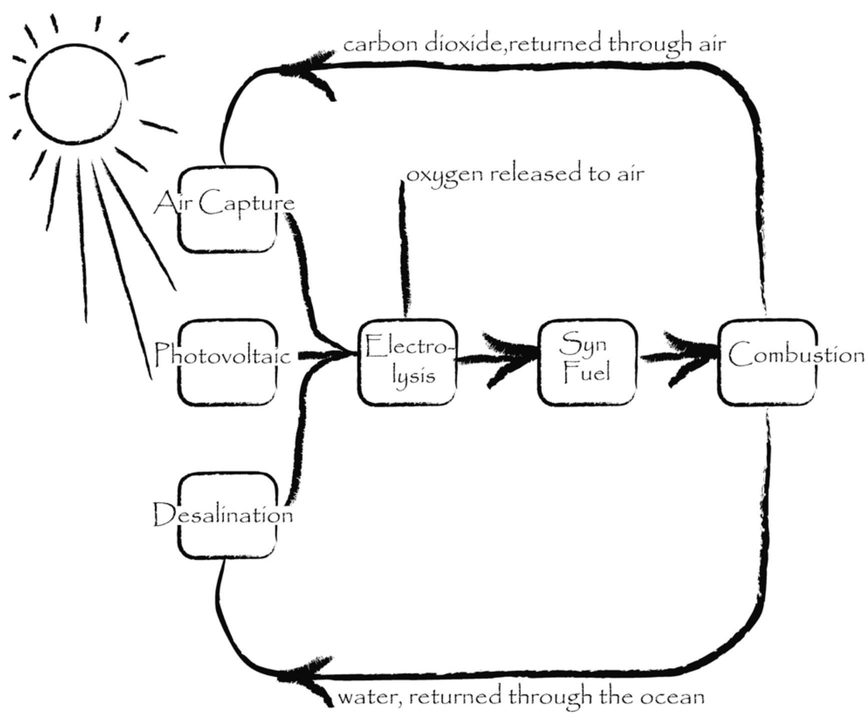


Figure 5. An illustrative look at capture. K. Lackner Feb 2020 to ASU Engineering Seminar.

I-WEST Roadmap

A roadmap is a journey from concept through full production capture. DAC is currently at the concept to early demonstration stage. The most advanced concept is Climeworks of Switzerland who have full demonstration from capture through sequestration in Iceland. After demonstration, which should occur in 2022 for four to six concepts detailed previously, the devices need to move to small scale production and field demonstration. Implementation of small-scale production should begin to happen in 2023 and 2025. If the DOE Hubs launch, the size of the production of devices will ramp up.

The DOE commitment of $3-4 billion for four devices and a demonstration capture of 1Mt/year in 2026 or 2027 would have an igniting effect on at least the selected technologies and likely influence the speed of development of some others. The opportunity provided by open investment and a hard goal is an encouraging step and should provide results.

Let's say as many as three make the end date and produce DAC technology capable of 1 million tons of capture. They will have done several important things: 1) learn what is wrong with their current concept and start iterating the design, 2) attract customers and investors, 3) grasp the enormity of the manufacturing process ahead of them, 4) need to consider a workable business model such as leasing or outright sales and 5) issues that are now hidden regarding certification and verification will become obvious.

Next, there will be a new design basis based on learnings, updated specifications, negotiations with fabrications facilities and supply chain, and a new timeline for design completion and new fabrication of units at an increased production rate, which should indicate how cost might be brought closer to the $100/ton CO_2 target.

Concentration, sequestration, and product ought to be getting more attention and initial resolution worked out. Sorbent advances and form factor for sorbent may require some alliterations in design, along with narrowing down of sites that will be viable. Engineering teams for design, crews to assemble, operators and maintenance will all become critical and likely slow progress as these professionals need to be trained and gain experience to efficiently operate the equipment.

Caveats

The hubs will develop the technology, but they will not create mass capture. For large-scale capture there needs to be market demand that is recognized as being sustainable over decades.

Customer demand and the ability to produce large numbers of units in a mass production setting will become critical for cost and availability. There must be some creation of a future market with a scale to drive growth of capture and the growth of technologies to reduce the reliance on carbon.

Requirements to get "passive" DAC into the marketplace

- For a committed market, first there needs to be demand.
- Technology must be licensed to encourage growth.
- Prototypes must be produced quickly and fit a mass production scenario.
- Energy costs for capture need to be low.
- Communication and marketing promotion and branding.

Keys to success

- Public understanding and acceptance must grow.
- A market will be created by regulation or tax.
- The market will be paid for by the polluting entities.
- Market timing will be staged to allow growth of capture production.
- Renewables will grow to meet the energy demand of capture and sequestration.

Summary execution plan: a sample idea for the Intermountain West

The DAC devices and the accompanying Concentration and Purification Process (CPU) needs to complete development, go through prototype testing and begin production by 2028 based on the DOE Hub schedule. It is our assumption that the market will enter a stage of increased vigor around 2027/2028 and DAC needs to be ready to participate in that market. To achieve readiness, all aspects of development need to be pushed forward quickly. Early-on during DAC device development a few critical decisions need to be made:

- Confirm design and size
- Select sorbent and absorbent alternatives
- Develop a material for the sorbent to reside within that is strong and flexible
- Design and fabricate "low cost" machines out of "low cost" materials
- Prepare for mass production and large farm operation
- Require removal of new CO_2 creation and the removal of some existing CO_2
- Determine tactical approach to markets based on the type of customer and location
- Develop price mechanisms and marketing strategies
- Build the trained staff for fabrication, assembly, operations, maintenance, and support

– Determine who handles the scope of services – fabrication, assembly, operations, maintenance?
– Will regional companies develop to fill these roles?
– Develop an on-going R&D to revise and improve

The execution will be determined by early planning and a waterfall schedule focused on the next five years. A ten-year plan and schedule will focus on growth to profitability. DAC companies will need to recognize and acknowledge that planning will be subject to the whims of the marketplace. This is an entirely new market, served by an entirely new industry that may develop vastly differently than we currently assume, and thus there will be adjustment to the realities on the ground.

DAC and the Intermountain West

What is the starting point in terms of DAC for the region?

Technology overview

Three DAC technologies are tied to the region, and one is currently being demonstrated. As DAC is relatively adaptable to different climates and environments, most of the technologies are likely to fit into application in this region. Having technology tested in the region is beneficial.

Aspects of siting

Sequestration: DAC sites used primarily for sequestration will most likely be located near sequestration opportunities. Potential geologic and well sequestration sites are abundant in the region.

Energy: DAC sites may be located where renewable power is plentiful and less costly to benefit from non-carbon power. The Intermountain West has large areas that could be used for wind and solar generation.

Land: DAC requires land. Ideally the DAC device ASU is testing would be able to capture 80 kg CO^2 per day and >1.1 million tons per year per km^2. While the ideal may not be reached, the amount of land is not prohibitive, and the region has open land that would be better suited for capture farms than areas of the country that are more congested.

Policy and funding

Policy: Congress has moved forward with funding for four Hubs to support DAC devices. While this is an indication of interest, there is not a firm U.S. policy or policy by any of the Intermountain West states supporting DAC.

Funding: As indicated above, the legislation funding the Hubs is substantial, and there are other funding opportunities for DAC coming out of the DOE.

What is the potential for DAC in the Intermountain West region?

Conceptually how might DAC best be funded and supported?

Capture in general and DAC, in particular, needs a future. If there is a sizable market identified that has volume and timing, capture investment will occur.

What is the best-case scenario when everything aligns, and all resources are available?

- **Technology:** The DAC technologies that are being demonstrated are indicative of a successful future for DAC. The current ideas are diverse and show signs of potential. Best case these and off-shoots from these, plus other new ideas, will reduce their energy and capital costs allowing for the beginning of a new industry.
- **Build-out:** While funding is the current impediment to growth, once devices begin down a commercial development road there will be supply chain, manufacturing, assembly, and operations challenges. All of the challenges are manageable, the reason for concern would be the ability to ramp up in a timely fashion.
- **Cost of capture:** Once a ramp-up in manufacturing begins, the benefits of mass production kick in and should begin driving down the cost curve. Ideally, the cost ought to drop below $100/t, potentially close to $50/t.
- **Price:** Cost may not be the only driver of price; future public demands may drive up the price until production can catch up to demand.
- **Timing:** Many factors impact timing, including how quickly manufacturing can begin, what drives demand, what the cost is, and what other options might be available. An ideal scenario might look like this:
    - Funding allows several devices to emerge – 2 years
    - Market established by tax or regulation – 2 years
    - Commercialization of a dozen or more devices funded for growth – 2 years
    - Engineering moves to mass manufacturing – 3 years

    - Sales, assembly, and operations (multiple business models) – in parallel
- **What does that pathway look like?**
    - As noted above, the pathway may take a decade
    - The true start date will be when there is a known demand going forward
    - After the start and within a decade there will be commercial machines; after that, ramp up of production and building a knowledgeable workforce will determine application volume

What are the assumptions that we are making?

Constraints:

- **Interconnections with other technologies:** DAC needs an ability to sequester, and potentially synthesize products with carbon and hydrogen.
- **Competition:** Competition with other DAC devices is good. Competition with other solutions is also favorable.
- **Supply chain:** Supply chain for new products is often a very difficult challenge.
- **Policy:** There is currently no push in the U.S. to move DAC capture forward.
- **Raw materials:** DAC does not have need for materials that are in general hard to obtain, except for water.
- **Financing:** First there needs to be a known market with a timeframe before private financing emerges, and without private financing there isn't commercialization.
- **Demand:** This is the critical constraint. The need for gigatons of capture exists, but demand is needed.

What would create a pathway that is more plausible?

- Funding to build out some of the potential devices to scale to determine what works
- Demand

How would a plausible pathway for the Intermountain West differ from other regions?

- Demonstrations in the region
- Leverage the existing environment
- Sequestration geologic investigation on a broad scale across the region
- Prepare areas that are economically distressed to play a role in new types of employment

– Train a workforce for this new industry from fabrication through certification. A portion of the potential workforce already exists due to fossil generation in the region

Gap analysis

Plans to be effective should consider what is missing and where the pitfalls might be. Capture and DAC are so new that many of the gaps are not yet apparent. However, let's review some of the more obvious ones:

- Definition of what parameters are acceptable as a part of capture needs to be worked out. Today this does not appear to be difficult, but once there are many devices, standards will be needed. Standards boards are typical in industrial applications, and it is time for capture to form one.
- There needs to be a market created by demand.
- Capture devices including biological capture need to improve design and application quickly. Designs are slow and mass manufacturing is nonexistent. While market demand will speed this up, there needs to be far greater investment.
- Fabrication, supply chain, and delivery mechanisms do not exist. Capture fabrication is going to compete with existing fabrication for space and with existing supply chains for equipment and material. Early development is going to be costly as it seeks to edge in and disrupt current production.
- The trained technicians to fabricate, assemble, and operate the capture farms are not in place. Teams need to be trained, procedures need to be written, and operating practices developed. The same is true for the engineers who should be drafting the drawings to build and install. Training can be developed but the experience that builds good teams takes time.
- Educational and research facilities working on capture are few and scattered. There needs to be platforms for sharing and cross-fertilization of ideas.

- Higher education of the engineers, scientists, lawyers, accountants, and teachers for this field is almost entirely absent.
- Storage needs to be permanent and few of the intended storage solutions have been tested and verified.
- Product transition of using recycled carbon for fuel, plastics, and other transition products has been explored in the lab but not at scale.
- Certification is not in place to control claims and false applications. Many credits only store for a brief period of time (often only a few decades) and some carbon credits are being exposed as fraudulent. Permanent long-term sequestration will need vigorous rules that include audits and monitoring.

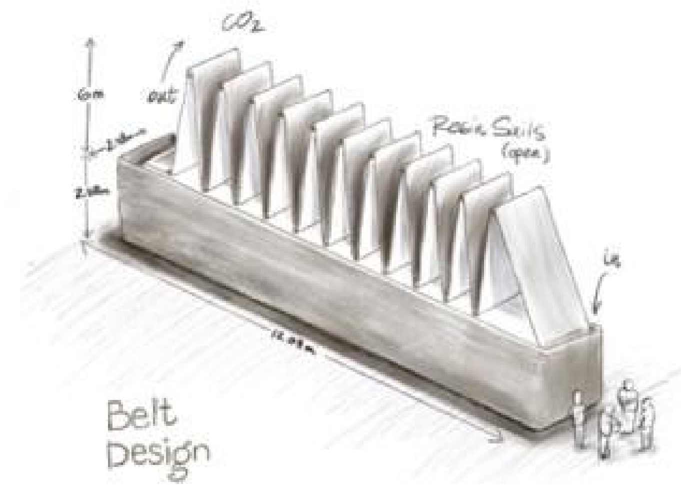


Figure 6. Conceptual drawing of a DAC device. Image credit: ASU/CNCE patented design for DAC CO_2 capture.

Gaps include new ideas; there are multiple design options for DAC devices. This drawing (Figure 6) is a concept focused on continuous flow of air enriched with CO_2. Today's designs are a starting point, with more ideas to come.

Gap analysis of options other than DAC

Point Source Capture (PSC) is very similar to DAC. One might consider PSC as the first line of CO_2 capture, by capturing at the smokestack. PSC has several drawbacks that may over time favor DAC. First, PSC must be located by the smokestack. Not being located close to the sequestration site often adds to the cost and hassle of piping CO_2 to a sequestration site. Second, PSC only captures when the plant is operating. Thus, when the plant is not operating the capital cost of the capture equipment is idle, and not returning on the investment. This second item is a particular problem with fossil power plants; if they gradually reduce the amount of operating time, the result is a reduction in the time initial investment and the cost of operations crew can be recovered. Third, PSC is not easily adapted to mass production as PSC units will need to be customized to the configuration and flows of each plant.

Industrial scavenged capture is a newer conception and has less demonstrable applications to judge. The idea of piggybacking on existing equipment that already provides an airflow is intriguing and may be successful in the future. The downside is that each application is unique to the industrial equipment that one is merging into. There may be industries with a large amount of similar equipment that will make this a rational form of capture, and, in a sense, this is DAC in a new context. Tying to already-in-place equipment has the same disadvantage of needing to remove and deliver the CO_2 to a sequestration or product conversion location.

Photosynthetic methods

Forests could become a component of the early capture and storage method; they are available now and can be expanded. Forests have several drawbacks including the need for constant maintenance to keep the forest alive and to hold the designated amount of CO_2 for thousands of years. Forests have difficulty expanding as they compete with food production. Forestation will have an early application but likely fade as we expand the amount of capture and sequestration. Forests are also less easy to accurately measure regarding the amount of capture and sequestration. Gross measurement averages will probably be applied but will face questions and future policy risk.

Crops and fallow land will be used although the amounts sequestered will be small with a slow pickup. Measurement and land use will be issues that still need to be worked out. This may be helpful financially to agricultural interests but will not be much of a competition to DAC.

Algae may play a role once an application is determined that can be demonstrated at scale over an extended period. Algae also have a problem with the issue of long-term sequestration. Algae in general has suffered from die off and species transfer.

Alkalizations of oceans by adding magnesium hydroxide to ocean water to get to magnesium bicarbonate would capture and store CO_2. Projects ought to carefully assess impacts on biodiversity and ocean processes. Issues with certification and verification will need to be worked out, as does some clarity on how much the oceans can sustain this and other capture concepts.

Building materials could be enhanced to capture and hold CO_2. Currently there are test demonstrations using building materials for capture and long-term storage. Building materials will pick up CO_2 slowly in small volumes but considering the number of buildings in the world this is an intriguing addition to capture. Measurement will be hard to quantify and will probably be estimated based on lab demonstrations. Certification and verification will be challenging, although probably doable.

Cost factors and risk

All DAC devices are in the conceptual design phase or early demonstration. From there, a lot of steps have to be made, as briefly noted below. If there is funding and a future market, these steps can go fairly rapidly, if there aren't too many unfortunate occurrences. New technologies do have unfortunate events as they evolve. Required steps:

- Prototype design and engineering upgrades from the demonstrations.
- Demonstration testing and building the supporting infrastructure.
- Revised design will be required based on testing and innovations.
- Sorbents that can handle different environments will be critical to the future.
- Sorbent improvement will go on for many years.
- The form factor of sorbent is proving difficult although some recent exciting breakthroughs.
- CPUs to support DAC have been designed; however, the current designs are costly to build and operate. Engineering and testing of revised CPUs needs to occur.
- Fabrication process using a mass production approach will be the appropriate goal. As this hasn't begun, the learning curve will need to be steep.
- Mass manufacturing is viable only for devices that are produced with the same basic configuration tens of thousands of times.
- Assembly cost in the field will be determined by location and experience. A priority to reduce field costs is to place as much equipment as possible on the skids during fabrication.
- Need to build trained teams for multiple site installs. Well-trained and experienced assembly teams might be a large cost benefit.
- Operations and maintenance processes being uniform may also reduce overall costs. Again, repetition is critical.
- Operations teams should be multi-disciplined and trained against the same training program and manuals.
- Common parts over multiple units will decrease supply chain and warehouse costs.
- Sequestration design and build-out for multiple applications and different types of applications need to be developed and the detailed engineering accomplished.
- Education and training need to be expanded exponentially to accommodate the variety of new jobs.

Mass production

There are many excellent treatises on the values of mass production related to cost, quality, safety, and other advantages. Fabrication at an adaptable scale allows exploitation of the learning curve and reduced cost during field assembly. Below is a sample set of equations that build on this concept applied to carbon capture devices (Eq. 1, Table 2). The values are theoretical and allow for the progression of the quantification. Assuming mass production for the device one may also calculate the advantage of growth in numbers in the field (Table 3). The lessons and advantages of mass production are multiple[22]. Replication reduces cost. Work is repetitively done in stages. Machinery to support labor can be applied and adapted to each production step. Factory work is better controlled and results in higher quality equipment. Factory work has a lower incidence of worker loss time accidents. Factory production has less wastage than field assembly. Factory work is more energy efficient.

Mass manufacturing scaling law: $c(n) + r = c_1\, n^{\varepsilon} + r.$ Eq. (1)

[22] Parsons Brinckerhoff Power Division; London Presentation of the US Power Labor Study and PM Process.

Table 2. Analysis of scaling impacts on the reduction of cost

Parameter	Value	Comment
α	2/3	Power coefficient relating size to cost. Typical value for rules of scaling up. Seen in both scale-up by numbers or scale up by unit size.
$\varepsilon = 2^{\alpha-1}$	0.79	Learning cost reduction. Estimate for PV has been between 0.76 and 0.8. Note that the assumption of a residual price lowers the effective learning rate we use.
c_1	\$470/t	The initial cost of a ton of CO_2, which we assume is \$500/t minus the irreducible cost. The current cost is based on public statements of current prices.
r	\$30/t	Estimate of the irreducible cost. This is based on estimates of raw material and energy inputs into the manufacture and operation of DAC systems, which for the ASU system are less than r.
t	\$100/t	Starting point for a self-sufficient industry based on industrial cost of CO_2 and current trajectories of CO_2 prices
Y	5 yr	Lifetime of an early farm unit
M	1000 t/yr	Starting size of a unit farm. The size of the total established system based at the initial scale of CO_2 capture. It defines the scale at which c_1 is measured.

Table 3. Value equations on increasing the number of devices and impact on price

Threshold Values	Value	Comment
$n_t = \left(\frac{c_1}{t-r}\right)^{1/(1-\alpha)}$	300	The number of unit farms required to drive the cost down to the target price.
$E = \frac{1-\alpha}{\alpha}\left(\left(\frac{c_1}{t-r}\right)^{\frac{\alpha}{1-\alpha}} - 1\right) YMc_1$	\$50 million	Total cost above the threshold price
$T = MYn_t = MY\left(\frac{c_1}{t-r}\right)^{\frac{1}{1-\alpha}}$	1.5 million tons	Total amount of CO_2 captured at breakeven
$K_{\text{threshold}} = YMc_1\left(\frac{c_1}{t-r}\right)^{\frac{\alpha}{1-\alpha}}\left(\frac{1-\alpha}{\alpha} + \frac{t}{t-r}\right)$	\$200 million	Total cost of CO_2 produced by break-even

Large-scale application

Developing devices and DAC farms that are identical and replicable will be critical to keeping down costs. From fabrication to operation, similarity is a natural cost reducer. Fabrication will work best in reducing cost by manufacturing many multiples of the same device. Over 100 years ago, the U.S. demonstrated the advantage of mass manufacturing, using the same design, form, and parts to drive down cost[23]. DAC needs to follow the same pattern.

Operations similarly benefit from sameness. If multiple devices and farms are similar, or only vary in a few particulars, this will result in lower operating costs as operators and maintenance technicians can learn and perfect their craft. There are a host of opportunities from savings in "sameness" including parts, tools, training, and safety.

During the ASU/CNCE Salt River Project (SRP) program students calculated capital cost reduction due to growth. The resulting learning curves were adapted to a host of assumptions and the team applied variables to different models. The resulting "Best, Worst, and Likely" curves provided illustrative examples of growth resulting in cost reduction, within the assumptions. Below is a demonstrative curve from the most likely scenario of DAC cost reduction as more and more units are built and put into production (Figures 7 and 8). The assumptions used in the study for SRP are feasible for actual DAC unit production and operation: 1) Develop devices that can be fabricated and assembled in a controlled production setting; 2) Make many thousands of the same device with modest variations (such as different sorbents) that can be shipped over common rail or truck applications and the manufacturing costs will come down; 3) Combine that with ease of assembly at the capture site, including such features as skid mounting of the devices, and again apply that to many units at a site and there are additional savings due to learning and ease of handling. One gets additional quality, safety, and supply chain advantages.

[23] Srinivasan, B. (2017). Americana: A 400-year history of American capitalism. Penguin.

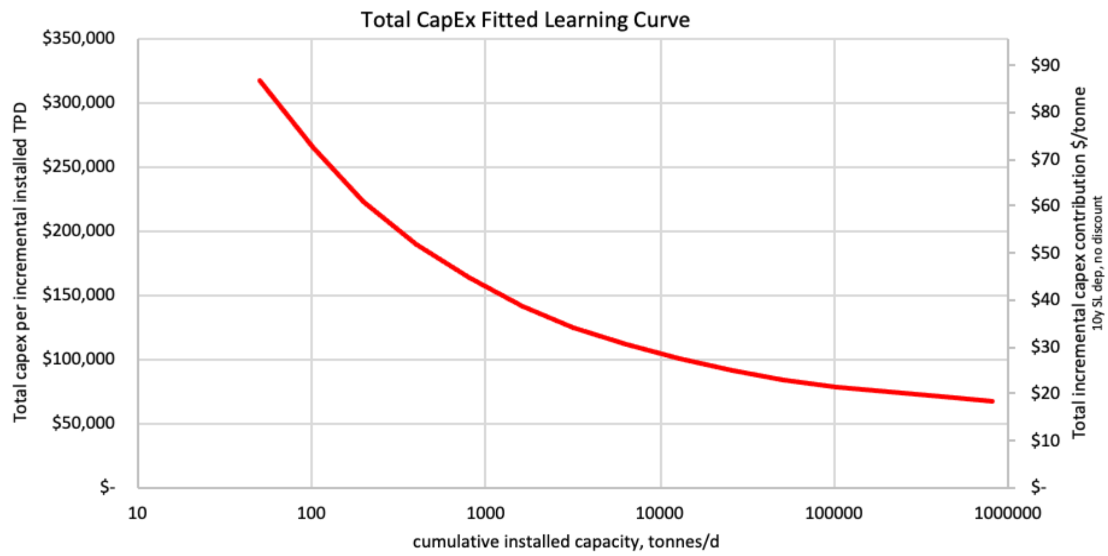


Figure 7. Total CapEx fitted learning curve for DAC. ASU/CNCE exercise in 2020 for SRP program.

Once the devices are at a site there are further cost and efficiency gains to be made by operating large numbers of similar units. As above, the chart below (Figure 8) was the result of an extensive student project on learning curve gains related to operation of DAC devices. The device chosen was one developed by the university and may not directly reflect on any actual device. The operating assumptions were matched to real world experience from several gas fired combined cycle power plants. Briefly the advantages of replication and learning curves for DAC operation are:

- Operator learning is critical for efficient and safe operations. As operations (and maintenance teams) learn the behavior of the equipment they continually get more efficient, modify preventive maintenance to better anticipate failure, and adjust mechanical settings for optimum production.
- Optimizing parts on site for routine and other maintenance requires time and experience. As learning progresses, the site will warehouse fewer of the less needed items and more of the items that are more frequently required. This increases operating time and reduces cost.
- Safety is first and foremost about sending everyone home at the end of every shift as fit as when they started the shift. There is also a cost factor tied to safety. Using factory made skids means a safer working environment, as does more time and experience operating the facility.

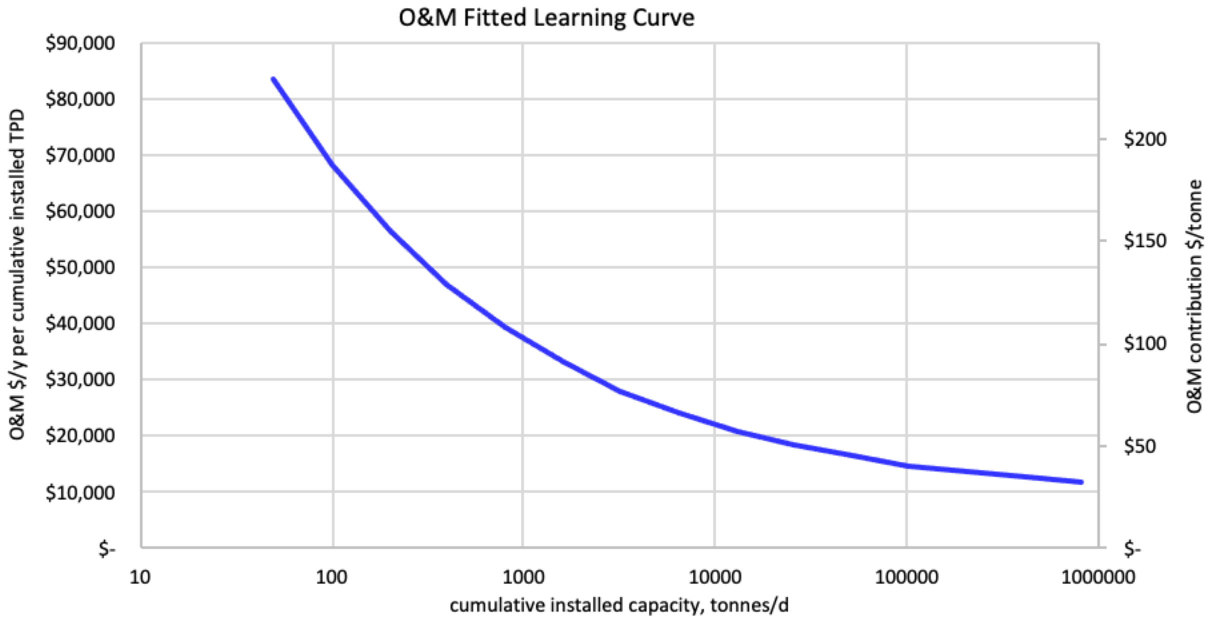


Figure 8. O&M fitted learning curve for DAC. ASU/CNCE SRP DAC project 2020.

Barriers to entry

The capture market is a new, emergent market, where every player is new. Therefore, barriers to entry such as economies of scale, brand loyalty, patents, switching costs etc. all need to be worked out by the new players. One barrier to entry we do see is high set-up costs for a fabrication facility. A large-scale facility manufacturing business is highly capital intensive, which deters inadequately funded startups from entering the market. A summary of barriers include:

- Technology – is the idea good enough to compete?
- Recognition – newer entrants will need to find a means of being recognized outside of the ones already in the market.
- Capital – new fabrication facilitates new supply chain, new site assembly, new standards to meet, and new operations which will require extensive capital infusion.
- Product delivery chain - any entrants to this field must develop a valid idea, fabricate the device, get it into the field, and develop an operating process; this is a long chain that will require extensive expertise to accomplish.
- Personnel – the acquiring and training of staff will take time and good planning. Staff will need to be trained for many new functions, and training takes experience that is missing.
- Cost – the cost for all entrants is from development to end-use product. Leasing and other options may lower the cost or spread the initial cost.

- Time – once there is a commitment to DAC, it will take time to build the infrastructure of equipment, parts, fabrication, trained personnel, building codes, siting and a host of other challenges.

Risk assessment

Many potential pitfalls exist for new technologies, particularly when the introduced technology is reliant on a shift in behavior and cultural patterns. The following summarize the most recognized risks, and indications of how they may be overcome.

Market development

- Risk: New advancements in renewables can lead to a wider spread adaptation of those technologies. This leads to lower emissions thus reducing the need for carbon capture technologies.
- Mitigation: Even at the best scenarios for renewables, the need for carbon capture technology will exist and grow. This is due to the past CO_2 emissions and the need for continued large-scale energy production to enable economic growth. Renewables only reduce future emissions and have no impact on already produced CO_2. Some carbon uses do not currently have non-carbon solutions.

State-sponsored requirements

- Risk: The profitability of the business model is heavily reliant on future government push.
- Mitigation: Various coalitions and working groups are working towards educating both the public and private sectors to acknowledge the need to adapt carbon removal technologies.

Design deficiencies

- Risk: The designs are new and untried.
- Mitigation: The building of commercial-scale prototypes through programs such as the DAC Hubs and investor financing such as Climeworks will begin to sort out what works and what needs to be upgraded. Upgrades and improvements will continue for many years.

Cost of the device

- Risk: The final production and operational cost might be higher than expected, which will impact our competitiveness in the market.

– Mitigation: We have reviewed many ways that DAC can reduce costs. In the final say there will be competition between capture methods and devices, and there will also be competition between means of reaching neutrality.

Advances in technology

– Risk: Technology may advance to stifle all of the current capture methods, or one or more of them will evolve to dominate.
– Mitigation: Research and advancement of design through operation as well as being well run and conscious of the advancement in other areas may serve to mitigate.

Business model

Let's assume there is a requirement for the reduction of CO_2 production and release into the environment. Assume that each ton of CO_2 released is required to be captured, which would spur reduction and capture. With that demand for the end of the release of CO_2 the market becomes real, and an industry of capture and sequestration (plus carbon products) will develop. Worldwide one might assume DAC capturing and sequestering 40 to 50 gigatons per year for most of the century, once fully implemented. To meet international limits, emissions must fall by about 13% a year. Emissions grew about 6% in 2021 after dropping in 2020 during the pandemic[24]. The Intermountain West could be the center of capture for the U.S. The region has the environment, the sunshine, and the space to be the leader in capture. How might the new businesses in this new industry be organized?

Manufacturing business

– DAC would begin with fabrication, assuming the acceptance of one or many designs. Fabrication of devices and the associated building of the CO_2 concentration, sequestration, and product creation could all be new regional industries. Fabrication will likely be located close to capture farms favoring short-distance delivery; therefore, if farms located in the Intermountain West could also be accompanied by a fabrication industry.
– Manufacturing will likely be based on an assembly line approach with components mounted on skids. Assembly line production remains the most efficient and highest quality approach to

[24] IEA (2022), Global Energy Review: CO2 Emissions in 2021, IEA, Paris https://www.iea.org/reports/global-energy-review-co2-emissions-in-2021-2

manufacturing, at least at present. Skid mounting facilitates fabrication at a central location which increases productivity, enhances quality, upgrades worker safety, and is most efficient.

- R&D and design of sorbents also provide an economic future for the Intermountain West. Sorbents will likely be mass-produced and the focus of large chemical companies, but that doesn't remove the manufacture of sorbents from the region. If large-scale DAC is present, the work on sorbent improvement may also be focused in the region.

Operations for capture and sequestration:

The DAC industry and its supply chain will create a suite of new products and services. The main ones include a new mechanical service industry and products from the captured CO_2. A range of customers are anticipated. As with any new industry there will be opportunities and pitfalls, including the opportunities to build new businesses that directly or indirectly relate to the new industry. For the Intermountain West, it is important to early-on consider the opportunities that may be presented through DAC and to create avenues for the region to take advantage of the growth. While the potential is too broad to exhaustively cover here, it is important to point out a few of the regional businesses that might be developed, and to highlight the potential for local or smaller scale business. Carbon capture, utilization and sequestration will create a new fabrication and services infrastructure. Workers will be hired for operations, assembly, and maintenance. New maintenance support companies will emerge to service the new industry. A new set of occupations will be developed with new skill sets and training. Many opportunities for large and small businesses will emerge. Figure 9 offers a graphic example of some of the business models that may emerge. A partial list of work that will be needed is noted below:

- **Research:** A new world of how to capture and sequester needs to be researched and developed.
- **Engineering:** Design and engineering firms (both large and small) will have many opportunities in this new industry.
- **Fabrication:** The facilities to mass produce will probably be large but may intentionally be located near potential farms.
- **Siting:** This is going to be a new field adopting some of the practices from other industrial siting practices but also creating new techniques and approaches. This is a brand-new business.
- **Assembly:** Site assembly will need contractors who build familiarity with this work and have the equipment to do it efficiently.

– **Performance testing and initial startup:** This is a specialty field often handled by small, highly qualified teams. The extensive start up experience resident in the region for oil well, mining, power generation, and large-scale building may serve as a good launch for this business.
– **Operator and maintenance training:** Training is a specialty area that is suited for small companies.
– **Operation:** Turn-key operations and maintenance are as likely as operations owned by the initial DAC developer. This provides another opportunity.

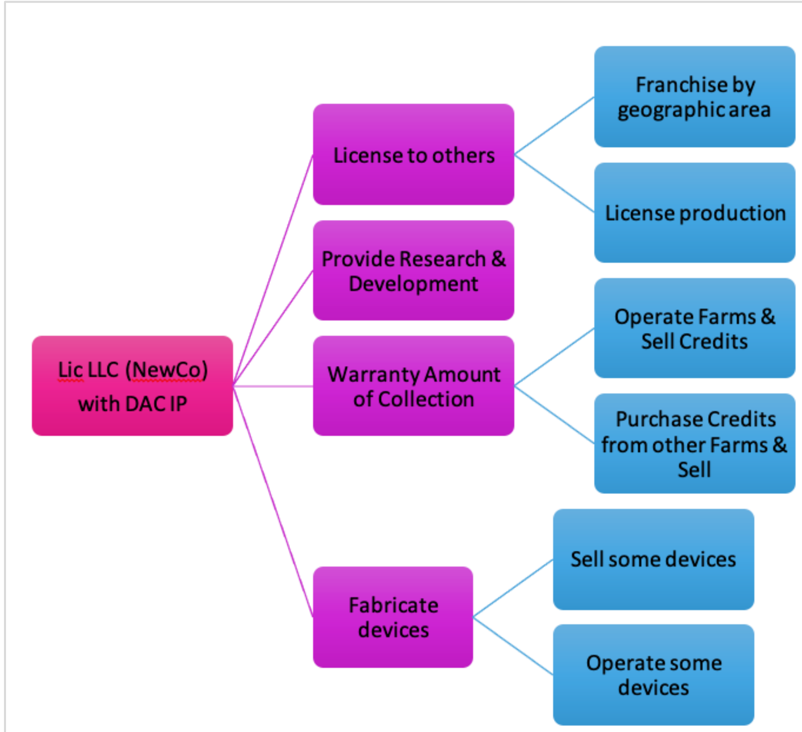


Figure 9. Sample of options for business model.

– **Maintenance:** Site on-going maintenance will probably be a part of the work accomplished by the Farm owner/operator. However, there are generally opportunities to develop local business to support no-routine maintenance and outages.
– **Upgrades:** DAC will be similar to other industrial applications that will learn and modify as it learns. Operators and design teams will seek and find means to improve. Work will be generated by the need for improvement and small local firms will have opportunities to participate.
– **Supply:** Supply chain will create many opportunities for large and small contributions.
– **Sequestration** operations and monitoring along with the supporting geologist and geologic studies and analysis.
– **Geologic analysis:** Sequestration, plant siting, and pipeline routing will all require extensive geological and other forms of environmental investigations and planned mitigation.
– **Product:** This will be a big area of opportunity. There are many products that may be developed using the carbon from capture. Each of these offers an avenue for business development that may remain in the region, and in many cases be developed by rural and tribal communities.

- **Small scale capture:** Another “local” opportunity for small business would be to do capture on a smaller scale. Applications such as Aircela are designed for this type of applications and there are other devices that would fit the small entrepreneur model.
- **Monitoring, auditing, certification, and testing:** Capture and storage will engender a new industry that tests and certifies the capture and the storage.
- **Education:** This new technology will need to be learned.

The options for the creation and formation of new businesses and types of businesses are as large as the business community’s imagination. The need for capture and tying capture to the production of CO_2 is coming. Opportunity will draw imagination and investment. States and regions will need to be prepared to allow for some interesting new applications and enterprises.

Sample product uses **(Figures 9 and 10)**

- **Storage:** Envisioning the future is always fraught with challenges and none of us get it right. However, one might postulate that CO_2 will be captured, and probably in the early years the CO_2 will be sequestered. CO_2 storage opportunities remain under development with high potential for the Intermountain West. Multiple possible options exist including sequestration in rock formations or pumped and sealed in deep caverns. The DAC designs ought to fit most, if not all, storage applications.
- **Fuel:** At some point, enterprising companies will begin to convert some portion of the captured carbon into fuel and other products. Currently one might be able to value concentrated captured CO_2 at $200/ton based on the California rules for capture if the carbon is redirected into a fuel. There are many parts of a fuel conversion process that are currently not in place. However, a fuel recycling industry based on capture is technically feasible and some new technological advances indicate it may come soon.
- **Cement production:** According to the IEA, cement production all around the globe produces more CO_2 than any other manufacturing process. A ton of CO_2 is emitted for every ton of cement produced. The plants produce as much as 7% of global CO_2 emissions[25]. Research is currently underway to feed DAC CO_2 into cement as a permanent sequestration, and New York will shortly begin requiring cement producers to feed DAC CO_2 into cement production. Other

[25] Gutenberg, J. (2021). Less risk, less costs: Portable spectroscopy devices could soon become real. Science Daily. Nov. 9, 2021. Available at: https://www.sciencedaily.com/releases/2022/09/220901135754.htm

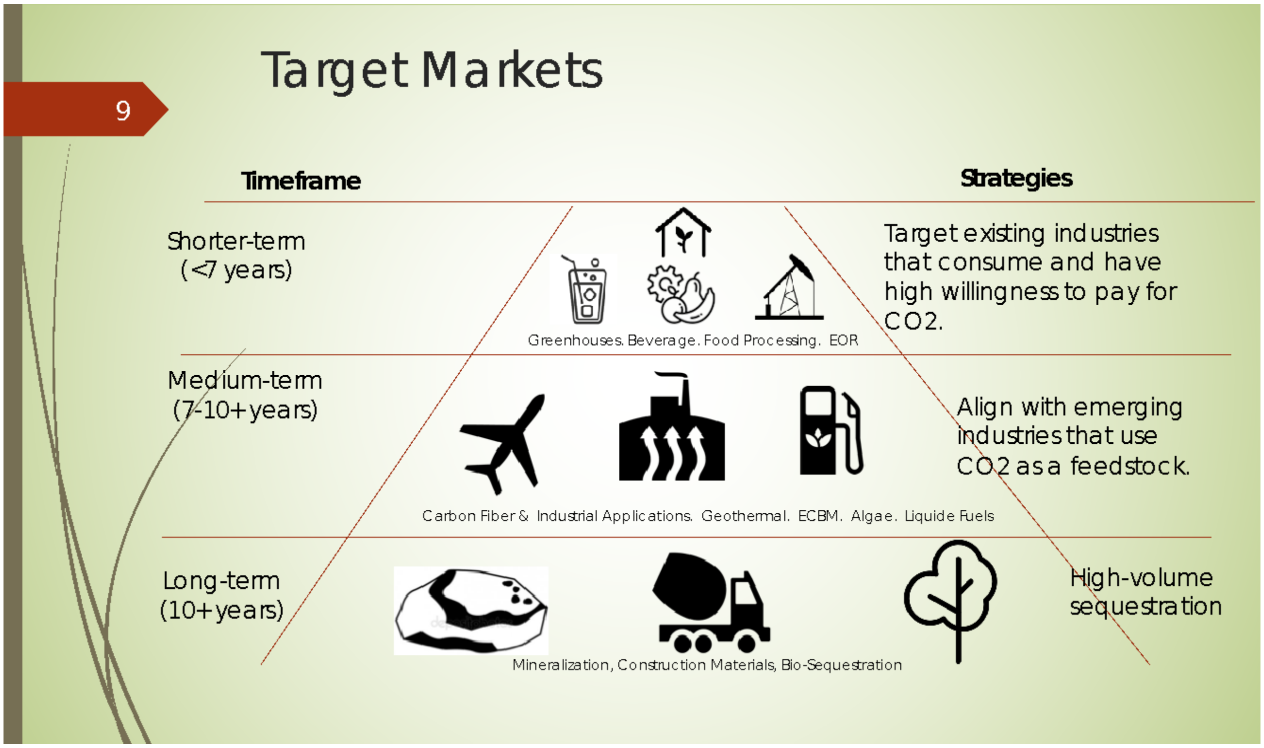


Figure 10. ASU/CNCE student project 2018.

steps are underway to deal with emissions emerging from the cement plants. For example, a private company based in New Jersey claims to have come up with a solution to reduce emissions by 70% by using an alternate chemical formula and procedures to manufacture cement. Instead of curing the concrete using water and steam, the new method involves CO_2 which in turn decreases the usage of water as well.

– **Closed agriculture for greenhouses, algae production, and tube-based crops:** CO_2 is an essential component of photosynthesis. The difference between the rate of photosynthesis and the rate of respiration is the basis for dry-matter accumulation (growth) in the plant. In agricultural production, all growers aim to increase dry-matter content and economically optimize crop yield. CO_2 increases productivity through improved plant growth and vigor. For most greenhouse crops, a CO_2 level increase from 410 to 1,000 ppm is advantageous and will increase photosynthesis by about 50% over ambient CO_2 levels. The recent increase in interest in greenhouse agricultural applications and the growth of algae production may open a meaningful market for CO_2 capture and product delivery.
– **Electronics fabrication:** Electronic fabrication creates a considerable amount of CO_2 during the fabrication process. Semiconductor industries use CO_2 for precision cleaning and machining applications. While less than 1% of greenhouse gas emissions are caused due to these

industries the source of the CO_2 might come from DAC and be part of a greater recycling process.

- **Plastic production:** According to an article published by the Stanford magazine, approximately one ounce of CO_2 is emitted for each ounce of polyethylene (PET) produced[26]. The Environmental Protection Agency's (EPA) indicates that between 100 million tons to 500 million tons of CO_2 are emitted during plastic related production, this represents 4.5% of global greenhouse gas emissions[27].
- **Volunteers:** There is an intriguing market for CO_2 capture using volunteers. It is not unusual for Earth-based challenges to be first addressed by citizen volunteer action; such as 4-Oceans (4-Ocean is a global movement actively removing trash from the ocean and coastlines while inspiring individuals to work together for cleaner oceans). One might envision a major gasoline distributor, car manufacturer, or utility, formulating a program to accept some level of voluntary contribution toward cleaning up a car or a home's carbon footprint.

DAC can be a means to remove emitted CO_2. The big picture for DAC is to remove CO_2 that is being produced and has been produced. CO_2 delivery to the atmosphere will continue because it is going to take many years to make the transition to renewables, more efficient energy use, and overall reduction in fossil fuels. It will continue in order to sustain the economic viability that is needed to make the carbon neutrality transition possible.

Capture will open up many new opportunities for large and small corporations and communities in the Intermountain West. With some foresight and direction, the region and its communities will have immense opportunities within this new emerging industry. Opportunity needs foresight if it is to be grasped, and the efforts of states like Wyoming, New York, Texas, and California will hopefully be a guide for the region to adopt policies that favor taking advantage of the coming change.

[26] Chui, G. (2019). Scientists finally find superconductivity in exactly the place they've been looking for decades. Stanford Earth Matters Magazine; September 2019. Available at: https://earth.stanford.edu/news/scientists-finally-find-superconductivity-exactly-place-theyve-been-looking-decades#gs.du43k7

[27] World Economic Forum article Dec, 2021; E H Zurich

CO_2 Markets

Merchant CO_2 - Markets are small and distributed

Chemical commodities – May include plastic feedstock and carbon fiber

Biomass production – Greenhouse agriculture, algae reactors may operate with CO_2 enriched air limiting water consumption in the produce foods

Enhanced oil/gas recovery - Air capture aims at small fields, exploratory work in the absence of pipelines; providing fuel and sequestration

Synthetic renewable fuels - Input is excess, intermittent renewable power, often distributed, energy rather than CO_2 drives cost

Sequestration – DAC is amenable to remote locations therefore adaptable to the be geologic formations for permanent storage

Air capture has a competitive advantage in satisfying small, distributed or remote demands

Figure 11. A sample of carbon uses. K. Lackner, CMTC Presentation 2015.

Review of the Intermountain West's advantages in establishing a DAC industry

- **Workforce, education and training:** The Intermountain West has the available workforce but needs training programs. Please refer to the Workforce chapters of the I-WEST Phase One Final Report.
- **Space:** The capture application will require space to deploy. Ideally DAC would be deployed near sequestration locations. The region is ideal for this type of combination.
- **Access to renewable energy:** Renewables would be preferred to help play a role in progress toward carbon neutrality, particularly in the Intermountain West where solar could be the energy source and provide over 300 days a year of power.
- **Community support:** DAC has workforce and other opportunities that communities might be pleased with. However, industrial applications in or near a community have downsides. DAC companies will need to be adroit at landing community support. This is particularly significant based on the need for rapid deployment to meet the 2050 target.
- **Supply chain and manufacturing:** The needs of fabrication and supply chain is critical to the timing and rate of growth for DAC. Breaking into existing supply chains with needs for a new industry requires effort and perseverance.
- **Sequestration location:** Ideally, sequestration would be preferably close to the capture sites, and the regional geologic features seem to fit this need.

- **Fuel as a product:** The future of DAC-to-fuel is intriguing but today only a potential product. The region could become a net producer of renewable fuels. With renewables to power DAC, captured carbon could be converted to liquid and gas fuels.
- **Other products:** Carbon may be used for plastics, chemicals, and other product uses. When products lose fossil carbon feedstock DAC may offer a replacement.
- **DAC inventions:** The Intermountain West is the birthplace of at least three viable DAC entrants for large scale capture, and regional universities are working on several more. Access to the research teams that created the devices will play a role in the locations of future capture farms.
- **Education:** Regional colleges and universities have taken the lead in several significant fields vital to the future success of capture. Additional growth in this area would position the Intermountain West as a place that would support physical growth of this new industry.
- The I-WEST initiative has demonstrated the **interest and viability** of the region becoming a centerpiece for future carbon neutrality programs and industry, DAC among them.

Impacts on social and economic justice

I-WEST is assessing is the ability to implement massive DAC in the Intermountain West. The capture, sequestration, and product development could be a huge industry for the region, providing high-quality jobs for thousands. As a benefit to rural communities, these jobs will often be outside of urban areas, as the capture takes space and needs to be co-located with a sequestration site.

With a large number of sunny days, open land, and good sequestration geology, the Intermountain West could be an industrial center for DAC from fabrication to deployment focused on rural locations upgrading the economic opportunities of those areas.

Conclusion

There are currently a couple of dozen small-scale DAC plants operating worldwide[28]. The technology has been proven in the same way as photovoltaic energy was proven before Germany decided to stimulate demand for the technology through liberal feed in tariffs. Back then, photovoltaic power was proven but was too expensive to be considered a serious player in the world's energy infrastructure. The promise of renewable energy appeared to be worth the risk.

[28] IEA (2022), Direct Air Capture, IEA, Paris https://www.iea.org/reports/direct-air-capture

DAC has been demonstrated in the laboratory, in small commercial applications, and it has been shown to work at a cost that is roughly ten times higher than what markets could support in the long run. The challenge for DAC is easier than it was for photovoltaic energy as it starts from a much smaller base. The financial gap between today's implementations and commercial viability is also much smaller because the size of the required operation is much smaller. The risk of trying out this novel technology seems well worth the potential benefit if it succeeds.

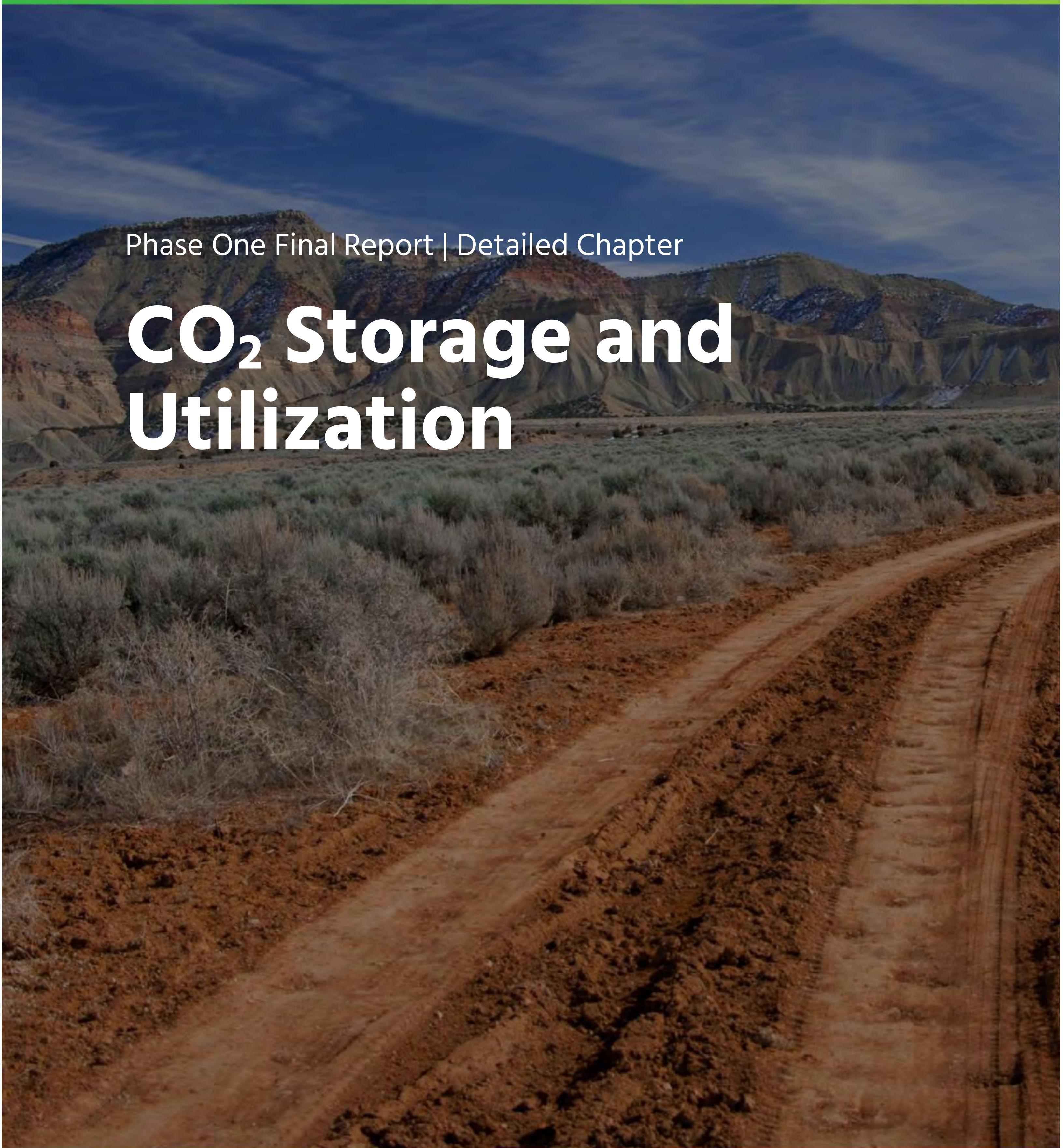
DAC is the "overflow" capture technology that will need to gather the CO_2 that other solutions cannot handle. Today it is unclear how large this role for DAC will be. It will depend on the future cost of DAC, and the future cost of all the other alternatives. However, even if DAC plays a very minor role in balancing the world's carbon budget, this role is still very large and will include the removal of billions of tons of CO_2. As the one part of the solution that must adapt to the need not yet handled by other means, DAC will be critical in our removal of excess CO_2. A successful implementation will provide a backup to other technologies.

When it comes to sequestration, DAC offers another important service. It makes it possible to quantify the cost of the loss of CO_2 from storage. If sequestered carbon escapes, recapture and restorage via DAC is always an option, and it therefore sets the cost of losses. Since costs can be specified upfront it is possible to demand assurances in the form of bonding or insurance that losses are taken care of. By quantifying the damages, it becomes possible to integrate them in the cost analysis from the start. This makes the existence and viability of DAC important, even if it is only used for a small fraction of all CO_2 emissions.

"We have been called on to solve a challenge. It is a big challenge, but one with solutions. It is time that we step up and solve the problem." Klaus Lackner, April 10, 2022

Phase One Final Report | Detailed Chapter

CO_2 Storage and Utilization



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About this chapter

The Intermountain West Energy Sustainability & Transitions (I-WEST) initiative is funded by the U.S. Department of Energy to develop a regional technology roadmap to transition six U.S. states to a carbon-neutral energy economy. I-WEST encompasses Arizona, Colorado, Montana, New Mexico, Utah, and Wyoming. Each state is represented in this initiative by a local college, university, or national laboratory. Additional partners from beyond the region were selected for their expertise in applicable fields. In the first phase of I-WEST, the team built the foundation for a regional roadmap that models various energy transition scenarios, including the intersections between technologies, climate, energy policy, economics, and energy, environmental, and social justice. This chapter presents work led by an I-WEST partner on one or more of these focus areas. A summary of the entire I-WEST phase one effort is published online at www.iwest.org.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACRONYMS AND ABBREVIATIONS

AGI	Acid gas injection
ASI	Ambient seismic imaging
BBA	Bipartisan Budget Act
bbl	Barrel
BECCS	Bioenergy with carbon capture and storage
CarbonSAFE	Carbon Storage Assurance Facility Enterprise Initiative
CCS	Carbon capture and storage
CCUS	Carbon capture, utilization, and storage
CFR	Code of Federal Regulations
CH_4	Methane
CO_2	Carbon dioxide
CO2_S_COM	FECM/NETL CO_2 Saline Storage Cost Model
CO2_T_COM	FECM/NETL CO_2 Transport Cost Model
DAC	Direct air capture
DOE	Department of Energy
E&J	Environmental and justice
EGS	Enhanced geothermal systems
EIA	Energy Information Administration
EOR	Enhanced oil recovery
EPA	Environmental Protection Agency
FECM	Office of Fossil Energy and Carbon Management
ft	Foot
GCS	Geologic carbon storage
GHG	Greenhouse gas
H&C	Hub-and-cluster
I-WEST	Intermountain West Energy Sustainability & Transitions
IEA	International Energy Agency
IRA	Inflation Reduction Act
LANL	Los Alamos National Laboratory
m	Meter
M	Thousand
mD	Millidarcy
mi^2	Square mile
MRV	Monitoring, Reporting, and Verification
MW, MWe	Megawatt electric
NETL	National Energy Technology Laboratory
O_2	Oxygen
PISC	Post-injection site care
ppm	Parts per million
R&D	Research and development
ROW	Right-of-way
SDWA	Safe Drinking Water Act
SMR	Steam methane reforming
STB	Stock tank barrels
SWOT	Strengths, weaknesses, opportunities, and threats
TDS	Total dissolved solids
tonne	Metric ton (1,000 kg)
U.S.	United States
UIC	Underground Injection Control
USD	U.S. dollar
USDW	Underground source of drinking water
UTM	Universal Transverse Mercator
WAG	Water-after-gas
WGS	World Geodetic System
°C	Degrees Celsius
°F	Degrees Fahrenheit

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1 PATHWAYS TO CO_2 UTILIZATION AND STORAGE IN THE INTERMOUNTAIN WEST

Funded by the United States (U.S.) Department of Energy (DOE) and headed by Los Alamos National Laboratory (LANL), the Intermountain West Energy Sustainability & Transitions (I-WEST) Initiative goal is to develop a regional, stakeholder-informed technology "roadmap" for transitioning the Intermountain West to a carbon neutral and economically sustainable energy system. By building regional coalitions, it plans to implement and deploy this roadmap by 2035 [1]. Composed of Montana, Wyoming, Utah, Colorado, Arizona, and New Mexico, the region is a unique landscape strained by increasing water scarcity, pervasive wildfires, and persistent drought. Historically, the region has been a fossil-based economy, but a transition to carbon-based economy has the potential to not only mitigate the ill effects of climate change but bring new, good-paying clean-energy jobs to the region [2].

As part of this initiative, various carbon mitigation strategies and low-carbon energy technologies (e.g., renewables, hydropower, hydrogen, and biofuels) were analyzed and modeled in the context of the region. To achieve the end goal of carbon neutrality, a conglomerate of strategies and synergistic approaches will be necessary. The I-WEST Roadmap report, which summarizes all technology pathways and considers a holistic and equitable approach to leveraging them toward an energy transition with net-zero emissions, is available for download at https://iwest.org/. One component of the roadmap expected to play a critical role in an energy transition, is carbon capture, utilization, and storage (CCUS). This report, an expansion of the I-WEST Roadmap's storage and utilization chapter, is an in-depth review of this proven and mature technology and its potential applications and contributions to the I-WEST initiative's goals. It seeks to support CCUS development in the region by

- Offering documentation for use by a multitude of stakeholders to better understand both the opportunities and roadblocks associated to CCUS given regionally relevant considerations
- Supporting broader CCUS adoption by providing technical and non-technical insight that can help mitigate the perceived technical and/or business case risks associated with CCUS by regional industries, investors, regulators, policy makers, and residents
- Showing how projects that blend advanced technology with policy-level support can generate positive regional economic benefits in terms of decarbonization
- Establishing the opportunity case for CCUS in the region as well as emphasizing viable next steps that may help facilitate further CCUS deployment. This includes identifying research gaps and needs, supporting the formation of regional coalitions, and supporting the alignment of CCUS with new, emerging economies related to hydrogen production and utilization, bioenergy, and direct air capture (DAC)

This report aims to provide a concise, yet comprehensive overview of the variety of storage and utilization approaches available, relevant governing regulations, and technical and non-technical grand challenges faced by each. Particularly, this report intends to provide an understanding of the technical aspects of CCUS and how they interface with economic, social, and policy aspects of decarbonization applicable to the Intermountain West geographic region. The content within leverages shared experiences, lessons learned, and best practices from project leaders that have conducted or are planning to conduct CCUS operations within the region. Much of this information was deliberated in a workshop with roundtable discussions specifically targeted to discuss CCUS in the region from practitioners' perspectives [3]. More specifically, the takeaways of this report will help the reader to

- Understand that captured carbon dioxide (CO_2) can be managed by several approaches spanning geologic storage, enhanced oil recovery (EOR), or other utilization methods, all of which are essential components of the portfolio of strategies that support regional carbon management. These methods can be safely and effectively implemented when necessary due diligence is put into practice, including storage site screening and characterization efforts and performance monitoring
- Identify technological and non-technological factors that must be considered in helping facilitate a substantive realization of CCUS deployment—one that will enable both deep regional decarbonization and present considerable economic opportunities; these factors relate to sustained research and development [R&D] needs, infrastructure, policy landscape, and societal readiness
- Understand the potential economic opportunities provided by CCUS in terms of supporting the region's energy transition by offering low-carbon versions of existing and future commodities (from both power and industrially facilities) through CCUS
- Explore a high deployment scale scenario for subsurface CO_2 storage applications based on regionally relevant point source types and geologic formations to estimate the needed storage resource capacity, pipeline infrastructure, cost implications, storage project volume, and workforce volume needed to achieve large-scale CO_2 emission reduction using CCUS in the region
- Facilitate networking across CO_2 storage and geologic utilization projects, identify opportunities for collaboration and public discourse, and discuss pathways to build new CO_2-based economies

Scope of the Report

This report provides an evaluation of the opportunity space for CCUS to deploy at significant scale within the Intermountain West region. The analysis couples knowledge gained from place-based data gathering exercises with insight from using several well-established CCUS analytical tools developed by the NETL and LANL that incorporates region-specific geologic, topographic, and demographic data. CCUS approaches described within include the following:

- CO_2 storage in saline formations
- CO_2-EOR
- CO_2 use as a geothermal working fluid
- CO_2 feedstock utilization
- CO_2 mineralization

2 SUMMARY OF THE TECHNOLOGY

CCUS includes a suite of technologies aimed to reduce the level of CO_2 emitted to the atmosphere or to remove CO_2 from the air directly. CCUS involves a sequence of integrated components, which collectively defines the CCUS value chain. Essential components include 1) separating and capturing CO_2 from industrial and fossil-fuel power generation sources or directly from the air, purifying the CO_2 stream as needed, and compressing it for transport; 2) transporting the CO_2 to a geologic storage or utilization site, which can occur onshore via pipeline, truck, or rail, or possibly via ship in offshore storage settings; and 3) injecting the delivered CO_2 (or potentially beneficially reusing or utilizing the CO_2 as a feedstock and converting it into useable products) into a suitable onshore or offshore geologic storage formation where the CO_2 can be isolated from the atmosphere [4, 5]. The ability to effectively integrate these value chain components is critically important for CCUS to be deployed widely at commercial-scale—however, integrating these components effectively is non-trivial task given the disparity in the notable business models involved and technical and non-technical challenges applicable to each component.

The Intermountain West has an enormous opportunity to enable rapid, large-scale CO_2 emission reduction to the atmosphere as well as removal of legacy carbon from the atmosphere via the injection and long-term disposal (i.e., storage) of captured CO_2 into engineered subsurface systems. Approaches to achieve this include point-source CO_2 capture from power generation facilities, heavy industrial sectors (i.e., cement, steel, and chemical facilities), or blue hydrogen generation facilities with associated storage, DAC with subsurface storage, bioenergy with carbon capture and storage (BECCS), and utilization of captured CO_2 in enhanced geothermal systems (EGS). These approaches encompass a portfolio of long-term subsurface storage and utilization options that offer the potential for large-scale CO_2 reduction given that the necessary critical geologic resources needed are widely distributed across the region, contain enormous storage resource capacity (described later in Section 3.1.1), and are largely co-located with many stationary sources of CO_2 within the Intermountain West footprint [6, 7, 8]. Many of the technologies that exist across the CCUS value chain (i.e., capture, transportation, and storage/utilization) are believed to be at or near commercial readiness, while others require more support that include both technical innovation and non-technical policy or regulatory support mechanisms [9].

The need for CCUS to be deployed at significant scale to meet long-term climate targets consistently is demonstrated in studies such as those by the Intergovernmental Panel on Climate Change and the International Energy Agency (IEA) [10, 11]. The IEA Sustainable Development Scenario, which is consistent with meeting the global goals of the Paris Agreement, suggests the CO_2 emissions abatement impact of CCUS will reach 2.8 billion tonnes (gigatonnes) per year by 2050. This would require *a one-hundred-fold increase* in the current number of such facilities in operation around the world today. IEA forecasts growth in world CO_2 capture by 2050 that would facilitate 25–60 percent of reductions associated with heavy industries [12]. CCUS for coal, natural gas, industrial processes, biomass, and DAC make the biggest strides between 2030 and 2050 [13]. These outlook studies stress that excluding CCUS from the suite of technologies used to meet emission reduction targets will lead to increased costs, especially for hard-to-abate sectors. Further, the versatility of CCUS and its ability to reduce both the supply volume and flow of CO_2 makes it an imperative strategic risk management tool for climate mitigation [14].

Given this need, CCUS has yet to fully live up to its promise. Annual CCUS investment has consistently accounted for less than one-half of 1 percent of global investment in clean energy and efficiency technologies for several reasons [15]:

- Many planned projects have not progressed due to commercial considerations and a lack of consistent policy support. In the absence of incentives or emissions penalties, CCUS may not make commercial sense, especially where the CO_2 has no significant value as an industrial input.
- Investment has been impeded by the high cost of geotechnical screening and characterization of storage site candidates, high cost of installing long-lived infrastructure assets like capture facilities and pipelines, and risks associated with installing or scaling up CCUS facilities.
- Difficulties exist in integrating the different interdependent elements of the CO_2 supply/value chain.
- Difficulties exist in allocating commercial risk among project partners. CCUS lacks familiar business models, structures, and practices common to other mature and analogous industries that act to reduce the perceived investment risks [16].
- A perception issue is exemplified by public resistance to CCUS, based on concerns about potential impacts to human and environmental safety, an aversion to living in proximity to CCUS operations [17], cost-inefficient CO_2 abatement for certain CCUS technologies, and competition between CCUS and renewable energy for public and private investment [18].

Though these challenges are evident, the I-WEST Initiative provides an alliance of champions capable of supporting and implementing CCUS among other energy and low-carbon transition elements. The region and CCUS technology, fortunately, have many characteristics and features to allow CCUS to assume a pivotal role and grow at scale. However, both perception and technical barriers must be overcome, with the former being the more difficult. The I-WEST Roadmap will be a living document and this report seeks to advance the narrative, providing recommendations on how CCUS can be advanced and moved into the mainstream given the geologic resource opportunities and other attributes common to the region.

Experts recognize that meeting the challenges for implementing scaled CCUS as a carbon mitigation strategy will pivot on critical factors involving its role in fighting climate change and its value to society, particularly the effectiveness of relaying that message to the public. Further, CCUS activity will be driven by three important factors [19]: 1) supportive action from state and federal government, 2) technological (including sustained R&D efforts) and non-technological advancements (including policy and financing) to accelerate the deployment of CCUS, and 3) business solutions to scale up CCUS. These elements are key to enable projects, build trust among relevant stakeholders (from citizens to fossil energy producers and consumers), and allow CCUS projects to materialize. Stakeholders that span both governmental and public sectors must work together to overcome the perception barriers and build trust to progress forward.

2.1 Technology and Mechanisms to Enable CCUS

In the energy transition, a CCUS future for the Intermountain West is within reach if the region focuses on investing in and accelerating place-based technologies and supporting policies that complement its skills, experience, existing infrastructure, and natural resources. The states that make up the region have an excellent combination of CO_2 sourcing, subsurface geologic resources (which include the injection and storage intervals as well as their confining strata), and an existing CO_2 pipeline infrastructure. The region can also boast its successful record of accomplishment of deploying CCUS thanks to several projects currently in operation. Needed are scalable supply chains and low-cost, zero-emission electricity to underpin industrial-scale operations. These will be driven by technology and mechanisms such as policy changes that can support the CCUS sector.

Figure 1 provides an overview of the CCUS technology value chain and the opportunities that exist across it. The chain comprises a suite of technologies that source CO_2 primarily in a limited number of ways: point-source capture and DAC. Point-source capture extracts emissions from energy assets and energy-intensive industries with hard-to-abate emissions, and could provide a platform for blue hydrogen production. DAC removes carbon straight from the atmosphere, and therefore, can be located nearly anywhere and address emissions from any source type. As a result, DAC facilities could be placed directly proximal to subsurface utilization or storage options to minimize or eliminate CO_2 transportation.

Point-source capture technology involves methods of collecting CO_2 from power plants (e.g., coal, natural gas, biomass) and other industrial sources (e.g., ethanol, steel, cement) to lower emissions. The region has several coal power plants where three main types of capture methods could be used based on the existing process and current infrastructure: 1) pre-combustion, 2) post-combustion, and 3) oxyfuel combustion. For instance, in New Mexico, Enchant Energy is exploring an opportunity for post-combustion retrofit of the San Juan Generating Station in San Juan County, New Mexico, which could capture upwards of 6–7 million tonnes (metric tons) per year of CO_2 for local storage within the San Juan Basin. The project is currently in its characterization phase, with an upcoming stratigraphic test well; a U.S. Environmental Protection Agency (EPA) Underground Injection Control (UIC) Class VI permit application is being developed in parallel to the geologic carbon storage (GCS) characterization [20, 21]. As another regional example, the Wyoming CarbonSAFE continues evaluating the prospect of secure, permanent, geologic storage of CO_2 from coal-based electricity generation facilities near Dry Fork Station near Gillette, Wyoming [22].

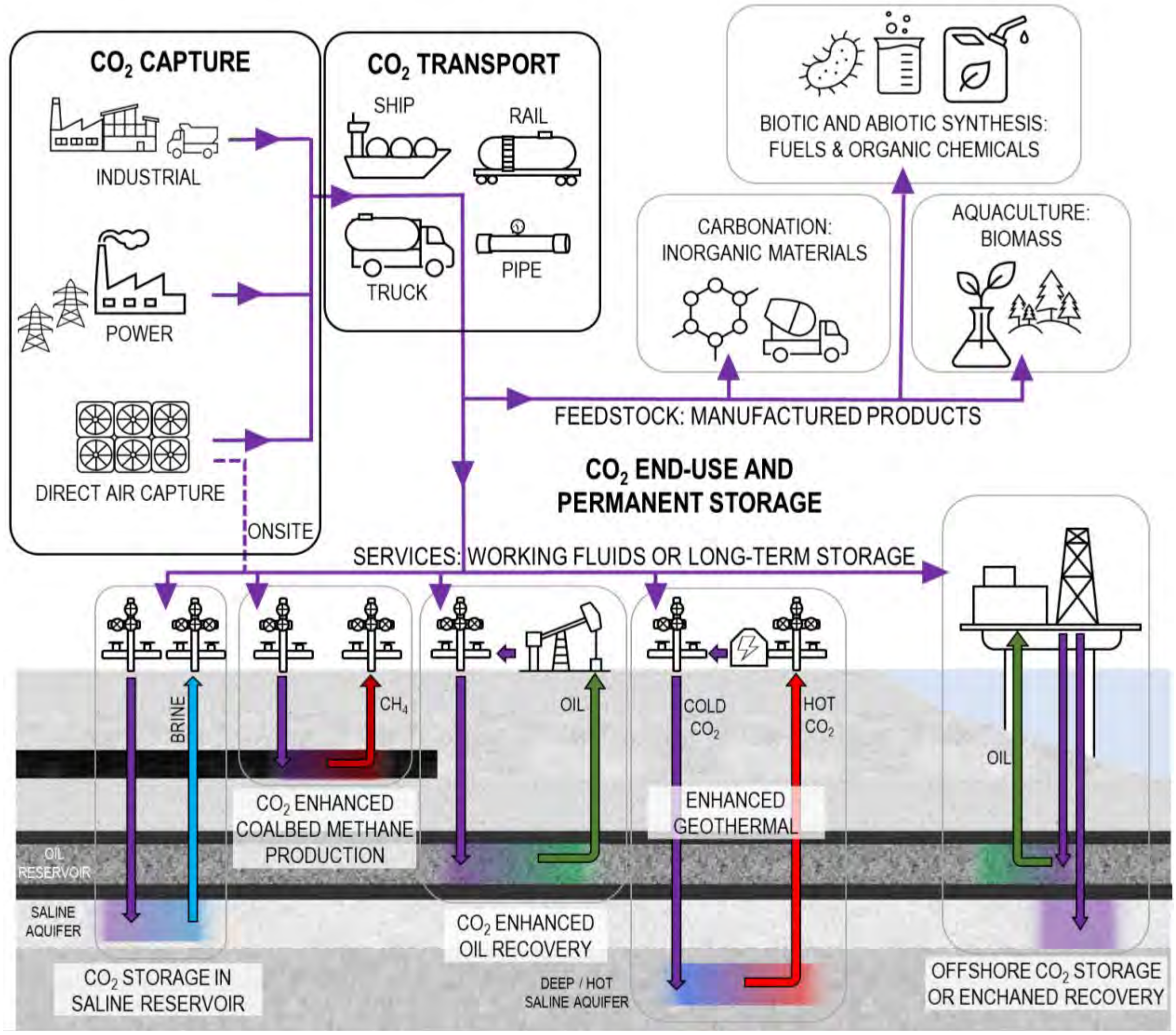


Figure 1. Schematic diagram of the portfolio of technologies spanning the CCUS value chain with an emphasis on transportation and subsurface utilization options

For energy-intensive industries, electrification is not a viable option to mitigate CO_2 emissions associated with their core processes or is not practical for the high heat (above 400 degrees Celsius [°C]) that many of those industries requires [19]. CCUS will be crucial to decarbonizing steel, cement, blue hydrogen, and waste-to-energy production. For instance, LafargeHolcim, together with partners Total, Svante, and Oxy Low Carbon Ventures, has completed a joint feasibility study of a commercial-scale carbon capture facility at the Holcim Portland Cement Plant in Florence, Colorado, which would involve permanently storing captured CO_2 underground [23]. Additionally, BECCS, where biomass (which extracted CO_2 from the atmosphere as it grew) is intentionally grown and then burned to generate negative-emissions energy, is one of the few technologies that can deliver negative CO_2 emissions at scale.

Hydrogen is believed to be key for the energy transition. Blue hydrogen production is hydrogen produced from fossil fuels with CCUS applied to manage CO_2 emissions. Globally, approximately

98 percent of current hydrogen production is from the reformation of methane or the gasification of coal or similar materials of fossil-fuel origin (e.g., petcoke or asphaltene); of that, only about 1 percent includes CCUS [24]. IEA estimates that less than about one-half percent of hydrogen is green hydrogen, which is produced by the electrolysis of water powered by renewable electricity. Current hydrogen production is emissions intense, emitting around 830 million tonnes per year of CO_2 globally [25]. Potentially, a CCUS plant could be configured with hydrogen production and carbon-capture capacity that exceeds the boiler/turbine and generating capacity, significantly reducing its carbon footprint. There may be economies in combining hydrogen generation and power generation in one facility that can capture the carbon emissions from both processes [26]. A noteworthy project, the coal-fired Intermountain Generating Station in Delta, Utah, is slated for replacement in 2025 by an 840 megawatt (MW) natural gas plant, designed to also burn hydrogen [27]. A further development in the hydrogen sector is exhibited by the states of Colorado, New Mexico, Utah, and Wyoming signing a memorandum of understanding to coordinate and develop a regional clean hydrogen hub [28].

DAC, as mentioned, is a process of pulling CO_2 directly out of ambient air. To do this, a DAC facility employs large fans that pull atmospheric air through its system. The air is scrubbed to bind the CO_2 molecules and separate them. The rest of the air is released back into the environment while the CO_2 is processed and compressed for storage. DAC has advantages and disadvantages. A strong advantage for DAC is that it does not need to be located near an emissions source since the concentration of CO_2 in ambient air is relatively constant. This allows DAC plants to be constructed very close to storage sites, reducing, or eliminating CO_2 transportation/pipeline infrastructure needs. However, DAC is highly energy intensive and can operate with a low-carbon footprint when powered with electricity generated using CCUS or via excess renewable power. An example of a DAC facility is the one being built by Carbon Engineering and Occidental in Texas to capture 1 million tonnes per year of CO_2, due to be operational in 2024. The system uses a closed-loop process that recycles chemical reactants [29].

As shown in Figure 1, transport of CO_2 from where it is produced to where it is stored or utilized is an important component of the technology chain. If not being used onsite, the captured CO_2 is compressed and transported by pipeline, ship (in offshore settings), rail, or truck. New pipelines must be constructed along rights-of-way (ROWs) or approved corridors, often requiring significant legal and regulatory negotiations and due diligence.

As shown in Figure 1, several subsurface geologic resource opportunities exist where CO_2 can be injected and utilized as a working fluid as well as directly stored. The formation types that are widely considered applicable candidates for long-term storage options include saline-bearing formations and even basalt; whereas those in which CO_2 can serve as a working fluid while simultaneously storing injected CO_2 include depleted oil and gas reservoirs, unmineable coal seams, organic-rich shales, and EGS [8, 30, 31]. In certain cases, saline formations, oil and gas reservoirs, and basalts are found in offshore settings in addition to those onshore. Many of these geologic resources can be found throughout the region (see Figure 5) and have the resource potential to hold CO_2 emissions from large point sources into the distant future, with the largest potential storage capacity of these formations found in saline-bearing formations [6]. A brief overview of each GCS formation type is provided below:

- **Saline-bearing formations:** These formations have the largest potential to store anthropogenic CO_2 given their large pore volume, high storage capacity potential, vast spatial distribution, and geologic history (where in specific occasions, CO_2 has been stored for tens of millions of years or more). These formations occur in both onshore and offshore sedimentary basins. Saline formations comprise of layers of sedimentary porous and permeable rocks and are saturated with salty water called brine. EPA determined that a saline formation used for CO_2 storage must have at least 10,000 parts per million (ppm) of total dissolved solids (TDS)—a measure of the amount of salt in water. Most drinking water supply wells contain a few hundred ppm or less of TDS. In certain cases, knowledge may exist pertaining to the geologic attributes for certain saline formations from proximal exploration and production of oil and gas. However, saline formations are typically not as well characterized and include a greater amount of uncertainty relative to oil and gas plays given that they have historically lacked an economic incentive for development.
- **Depleted oil and gas reservoirs:** Porous rock formations (usually sandstones or carbonates) can contain hydrocarbons (crude oil and/or natural gas) that have been physically trapped. These reservoir types are favorable geologic storage sites because they have proved capable of trapping buoyant hydrocarbons in place typically for thousands to millions of years. Furthermore, their architecture and geologic properties can be well understood as a result of exploration and production efforts. Also, infrastructure assets characteristically exist in proximity (wells, roads, pipelines, etc.) to support CO_2 transportation and storage efforts. Depending on the remaining hydrocarbon volumes in place, these reservoir types can support multiple injection and storage strategies. Substantially depleted reservoirs could be used for dedicated CO_2 storage. Reservoirs with significant volumes of remaining hydrocarbon reserves (22–55 percent pore volume) and that have undergone successful secondary (i.e., waterflood) production strategies could be targets for CO_2-EOR [32, 33]. CO_2 has been proved to be helpful in moving crude oil in the subsurface to production wells when injected into oil and gas reservoirs. The process has shown to increase production of crude oil by 10–30 percent [34, 35, 36]. Given its commercial motivation, CO_2-EOR can be an efficient and feasible way to store CO_2 while producing “greener” oil that can displace other conventional or unconventional production [37]. In a recent development, Occidental indicated that it delivered the world’s first carbon-neutral oil, which was produced in Texas [38]. A challenge posed to CCUS in mature oil fields is the likely abundance of pre-existing wells and well bores that can act as high-permeability leakage pathways from the storage/oil producing formation to underground sources of drinking water (USDWs) or the atmosphere.
- **Unmineable coal seams:** Coal that is considered unmineable because it may be excessively deep, too thin, or lacks the internal continuity to be economically mined may have potential for CO_2 storage. Coal preferentially adsorbs CO_2 relative to the methane naturally occurring in coal seams. This adsorption-trapping effect provides the basis for CO_2 storage. CO_2 (typically injected into coal in a gaseous state) flows through the coal’s cleat systems (natural, orthogonal fractures), diffuses into the coal matrix, and is adsorbed onto the coal surface, freeing up methane, which has a lower affinity to coal. The methane can then be recovered from production wells. The process of injecting and

storing CO_2 in unmineable coal seams to enhance methane recovery is called enhanced coalbed methane recovery. Injected CO_2 does not need to be in the supercritical (dense phase) state for it to be adsorbed by coal, so operations can take place at shallower depths relative to other geologic storage options (typically requiring at least 2,624 feet [ft] [800-meter (m) depth]) [31]. Geologic storage using the enhanced coalbed methane faces certain technical challenges associated with swelling of the solid coal matrix during the adsorption process, which can reduce cleat aperture and overall permeability, thereby limiting injectivity [6].

- **Basalt/mineralization:** CO_2 can be rendered inert by binding it in mineral form, making for a highly stable storage pathway. Basalt includes igneous rock formations with unique geochemical characteristics that could potentially enable conversion of injected CO_2 to a solid carbonate mineral, which offers permanent storage [39]. Research efforts related to the storage of CO_2 in basalts are ongoing and focused to better understand the carbonate mineralization process and its effects on formation porosity and permeability—two factors that influence the storage capacity and injectivity for candidate sites. The enormous volumes of reactive minerals at the earth's surface and near its subsurface make the volume potential for carbon mineralization effectively limitless, although there are practical limits that are a function of mineral kinetics, reactive surface area, and the quality of the mineral resource [40]. Basalt formations are geographically limited in the United States and not prominent in the region. However, the nearby states of Idaho, Oregon, and Washington are noted as containing sizeable basalt formations [8].
- **Enhanced geothermal systems:** EGS aim to extract geothermal energy from the subsurface by 1) exploiting or creating permeability by opening existing fractures or creating new ones through induced hydraulic stimulation or fracturing and 2) establishing fluid circulation through the fracture network by using a combination of injection and production wells. The thermal energy brought to the land surface via fluid extraction can then be used for heating or potentially electricity generation [41]. These systems can potentially enable the use of CO_2 as a working fluid for coupled carbon storage and geothermal extraction [42]. CO_2 is believed to provide better heat transfer from hot fractured rock relative to water due in part to its greater compressibility and expansivity compared to water and higher buoyancy relative to water—the latter of which reduces the system's parasitic power consumption for fluid circulation [43]. While the thermal and hydraulic aspects of a CO_2-EGS system appear promising, uncertainties exist regarding associated chemical interactions that may occur between fluids and rocks [44]. The Utah FORGE project located near Milford, Utah, [45] and led by the University of Utah is developing a geothermal field laboratory in order to evaluate and advance EGS opportunities by researching and characterizing subsurface temperatures, rock types, seismicity, and associated groundwater systems. Additionally, regional-scale assessment of geothermal reservoirs of Nevada for CO_2 storage is being investigated [21]. The overall CO_2 volume expected to operate EGS is considered negligible relative to the storage capacity available in other geologic storage options, like saline-bearing formations and depleted oil and gas fields.

UIC Primacy Authority Status in the I-WEST Region

Under the SDWA, EPA can delegate oversight authority to implement and enforce its UIC Program to states or tribes upon an approved application. Primary enforcement authority, often called primacy, refers to state, territory, or tribal responsibilities associated with implementing EPA-approved UIC programs. A state, territory, or tribe with UIC primacy oversees the UIC Program in that state, territory, or tribe [98]. While primacy application is not a mandate to conduct CCUS operations, states and tribes that maintain primacy over UIC wells tend to be able to issue permits much more rapidly [157].

States, tribes, or territories seeking UIC Program primacy must demonstrate to EPA that their entity has 1) jurisdiction over underground injection, 2) can put regulations in place that meet or exceed the federal SDWA requirements, and 3) possess necessary administrative, civil, and criminal enforcement penalty resolutions. The UIC primary status for I-WEST states and tribal nations is shown in Figure 2. Most states and tribal nations have some form of primacy for many of the UIC well types. Wyoming is the only entity with primacy for a Class VI well. Arizona is in the pre-application process for applying for primary for wells I through VI.

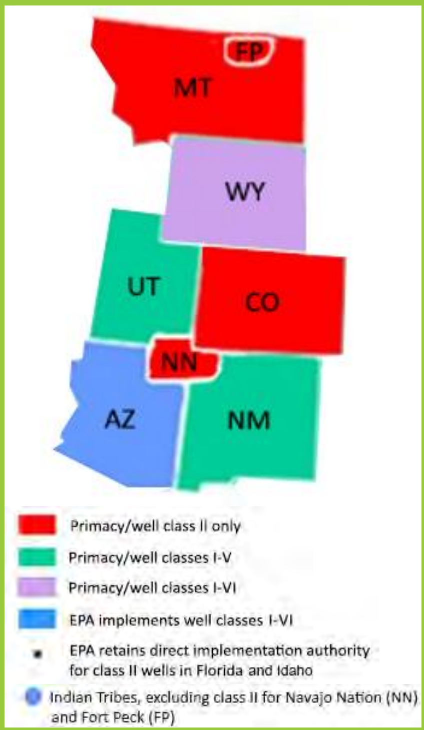


Figure 2. Map featuring UIC primacy status for states, territories, and tribes in the Intermountain West

Injection operations for the purpose of long-term geologic storage and utilization of CO_2 or CO_2-EOR are subject to EPA's UIC regulations. The Safe Drinking Water Act (SDWA) of 1974 establishes requirements and provisions for the UIC Program to protect public health by preventing injection wells from contaminating USDWs via infiltration of brine or any injected fluid. Different UIC well classes and associated regulations apply depending on the injection operations—Class II for CO_2-EOR or enhanced coalbed methane projects, Class V for geothermal (typically), and Class VI for CO_2 storage. Specific regulations (based on Code of Federal Regulations [CFR] 40 CFR 144, 146, and 148) vary from well class to well class to accommodate the injection type and expected fluid characteristics in order to ensure protection of USDWs [46] and safeguard the environment, public health, and public safety as CCUS projects move forward; however, there are substantial similarities and overlap for many of the requirements across all well types. For instance, in all cases, project sites must meet certain regulatory standards pertaining to site design, geologic system suitability, well construction, operations, maintenance, demonstration of well integrity, monitoring, threat/hazard identification and risk assessment, site closure, post-injection site care (PISC), and emergency response and preparedness to ensure safe and effective operations [47]. Operators that pursue injecting CO_2 must acquire a UIC permit relevant to the intended operations prior to commencing injection operations. The process for obtaining a permit for a CCUS project is not unlike that for any industrial activity but can mandate extensive investment in site characterization and appraisal efforts to determine site(s) suitability.

Operators that pursue geological storage of CO_2 under 45Q are additionally subject to EPA's Greenhouse Gas Reporting Program requirements under 40 CFR Part 98 - Subpart RR, which mandates CO_2 accounting, reporting, and site-specific monitoring for potential leakage should it occur. A Monitoring, Reporting, and Verification (MRV) Plan must be developed for each site and approved by EPA. These MRV plans support the 45Q secure geologic storage requirement.

If not stored in the Earth's crust, captured CO_2 can be used as feedstock to produce valuable products such as synthetic fuels, chemicals, building materials (cement and aggregate) and a variety of products such as carbon fiber/tubes, plastics, and composites. CO_2 can also be used in processes such as biosynthesis (e.g., algae and production of synthetic fuels) where CO_2 is mixed with hydrogen to achieve hydrogenation synthesis via a catalytic reactor. CO_2-to-fuels conversion include carbon monoxide, syngas (a hydrogen and carbon monoxide mixture), methanol, and eventually long-chain hydrocarbons—which are more challenging but also of greater value and can be used as alternative drop-in fuels [48].

In the CCUS value chain, carbon capture generally is the costliest component and is inversely related to the partial pressure of CO_2 in the gas stream, all else being equal. Transportation and GCS are relatively more dependent on the specifics of the project being developed.

The costs for the various CCUS processes are shown in Figure 3. The costs for CO_2 capture technologies range from less than $25/tonne for high CO_2 purity sources like natural gas processing and biofuel generation to well over $100/tonne for DAC (Figure 3) [49]. These costs for capture generally correlate with effluent CO_2 concentrations [50]. CO_2 transportation costs (prices) are dependent on the flow rate through a pipeline and the distance of transport (Figure 3)[a] and range from a $1/tonne or less for short distances to over $100/tonne for lower flow rates through longer pipelines (hundreds of miles [mi]). The costs associated with implementing subsurface CO_2 injection and storage operations is highly variable on several conditions, including the type and scale of storage/utilization operation, the prevailing geologic conditions, and the intensity of the necessary due diligence (i.e., site characterization, monitoring, or corrective action). A typical storage/utilization project involves the time and cost-intensive steps of site screening, site selection and characterization, permitting and construction, operations, PISC, and site closure [51]. Reservoir depth, thickness, permeability, and porosity affect injectivity, storage capacity, and formation pressures, which, along with structural setting, impact the aerial extent of the CO_2 plume, one of the primary cost drivers of storage costs [52, 53]. A smaller plume footprint, particularly when physically constrained by dome or anticlinal structures, lowers cost by reducing the number of wells needed for monitoring or injection, permit requirements, and the need for surface access [54]. In general, the lowest storage costs are associated with formations that have the highest storage capacity that enable economies-of-scale benefits, even if those subsurface resources are further away from a CO_2-generating source [55, 56, 57]. Typically, these are relatively thick, shallow (but still at a depth where CO_2

[a] CO_2 transportation costs were estimated using a DOE Office of Fossil Energy and Carbon Management (FECM) NETL-developed model, the FECM/NETL CO_2 Transport Cost Model (CO2_T_COM) [158]. Modeling assumptions used to generate the CO_2 transportation data in Figure 3 can be found in supplementary material developed by Morgan et al. [134].

remains in a supercritical state) and highly permeable formations [58]. A screening-level assessment of CO_2 storage and utilization costs to relevant saline-bearing formations and fields in which CO_2-EOR could be applied and located within the region is presented in Section 4.

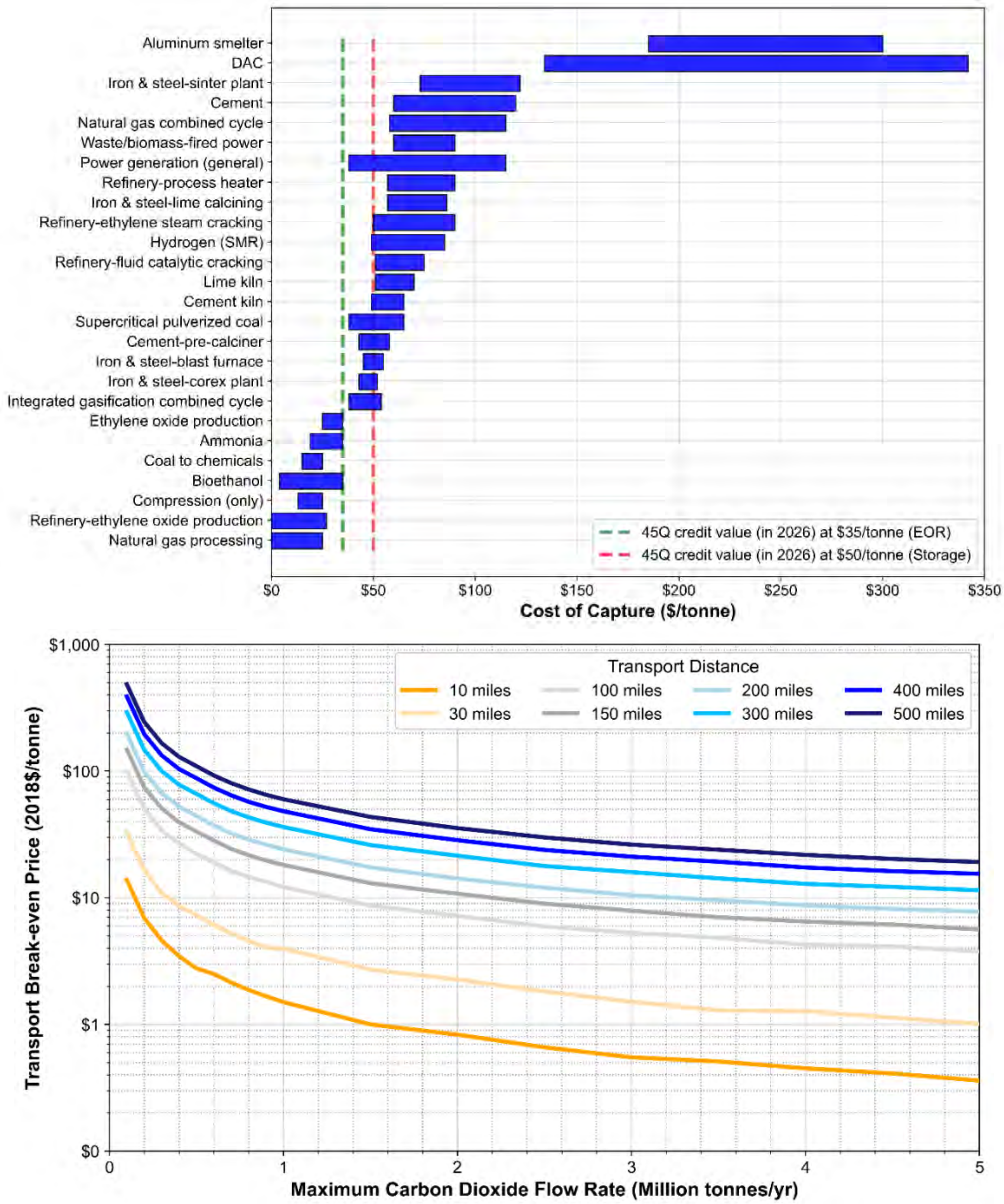


Figure 3. Levelized cost of CO_2 capture by sector (top) and CO_2 transport by flowrate and transportation distance (bottom)

2.1.1 Business Mechanisms for CCUS Implementation

The vision for the I-WEST is to take advantage of the region's unique characteristics and features, to allow CCUS to assume a pivotal role. This can entail decarbonized coal, oil and gas, net-zero energy-intensive industries, production of blue hydrogen production at scale, long-lived capital stock infrastructure re-use, deferral of decommissioning, negative emissions, job creation, and support for economic growth. CCUS can function to meet the growing need for system flexibility as the share of renewable energy generated and the need for dispatchable capacity increases. Similarly, CCUS can complement nuclear power generation for decarbonization. Finally, CCUS can facilitate a just energy transition by alleviating geographic and timing discordance. For the Intermountain West, CCUS can emerge as a sustainable technology that ensures economic prosperity and energy exports and offers first-mover advantages for a technology that can be expected to be around for decades.

To date, the high cost of carbon capture and lack of market "pull" has hindered the deployment of CCUS projects, resulting in a scarcity of viable business models for deployment at scale, but the landscape is evolving. Such models are essential to deal with external factors, particularly for projects with a long industry chain and complex relationships among stakeholders, traits common to CCUS projects in the United States, especially those using the 45Q tax credit. Broadly, there are a limited number of business models for CCUS in general use [59, 60, 61]. These models (Figure 4) are not mutually exclusive and should be thought of as a spectrum as opposed to discrete models; their advancement depends on funding sources, capital and ownership structure, and risk management allocation:

- **Disaggregated source-to-sink(s):** These typically are joint ventures or business arrangements, with the project comprising a single source to a sink(s). Examples include the Quest CCUS project (Shell, Chevron, and Marathon) in Canada, the Snøhvit CO_2 storage project in Norway, the Petrobras Lula oil field in Brazil, and the Occidental/Carbon Engineering project in the Permian Basin of Texas. Variants to this model include the following:
    - CCUS operator case, where, for example, the Coffeyville Gasification plant in Kansas, where Chaparral Energy owns the compression and dehydration facilities at an ammonia nitrogen fertilizer plant owned by Coffeyville Resources Nitrogen Fertilizers.
    - CO_2 transporter case, where, for example, the Val Verde Natural Gas Plant project in Texas, where Sand Ridge and Occidental Petroleum provide the carbon capture, Kinder Morgan and Petro Source provide transport, and Kinder Morgan, Occidental Petroleum, and Chevron provide the storage in EOR. Exxon's Shute Creek project in Wyoming provides another example [62]. Elsewhere in the midcontinent, two companies, Summit Carbon Solutions and Navigator CO_2 Ventures, want to build pipelines that will be used to move CO_2 captured from ethanol, fertilizer, and other agricultural industrial plants to storage sites. Summit Carbon plans to store carbon in North Dakota; Navigator CO_2 in Illinois [63].

- **Vertical integrated source-to-sink:** In this model, a point-source company controls capture sources, transportation systems, and the storage/EOR site. This model is more typically the domain of state-owned companies. Examples include the Uthmaniyah site in Saudi Arabia and Yanchang Integrated CCUS project in China.
- **Hubs-and-clusters (H&Cs):** This model represents a progression where new business models and deployment approaches facilitate rapid CCUS scale-up by separating the components of the CCUS value chain and developing multi-user transport and storage networks that industrial facilities can access. Areas where there is both a high concentration of CO_2-emitting industries and a nearby capacity for storage will be prime sites for H&C developments that can share CO_2 transport and storage infrastructure within CO_2 market systems. H&C networks as part of CO_2 market systems offer several distinct advantages for participants compared with "point-to-point" projects, including economies of scale, reduced unit costs and risks, participation by small volume industrial facilities, and optionality for emitters. Efforts to develop CCUS hubs have commenced in at least 12 locations around the world. In the United States, Exxon is proposing a $100 billion regional storage hub on the Gulf Coast that would be the world's biggest carbon capture and storage (CCS) project. The company, along with a multitude of private and public partners, would build a facility to collect emissions from refineries, petrochemical plants, and other industrial facilities along the Houston Ship Channel. Early projections show that the project could store 50 million tonnes per year beneath the Gulf of Mexico by 2030, more than all CCUS projects currently operating globally. Exxon has said that figure could double by 2040 [64].

The main risks for H&Cs are commercial, not technical, and, currently, the most successful H&Cs are those based on the use of CO_2 for EOR. For the development of H&Cs in the early years, a major obstacle will be the presence of a core organization, a project champion, that is able to carry a CCUS cluster project forward given complexities [65]. Of note, the initial oversizing of infrastructure increases the capital cost of the project, thus making it more challenging to raise financing, but it can reduce unit transport and storage costs substantially in the long-term.

In the Intermountain West, it remains to been seen how the business models play out should CCUS be deployed at large scale, but factors such as geographic proximity of suitable sources and quality sinks, costs of capture and transport (see Figure 5 for perspective on the region), mineral access to pore space, right-of-way for CO_2 transport, societal readiness and acceptance, and regional market developments will be important. It may be that a disaggregated transport and storage business model allows businesses to focus on their core competencies and avoid the risk and cost that comes from overextension.

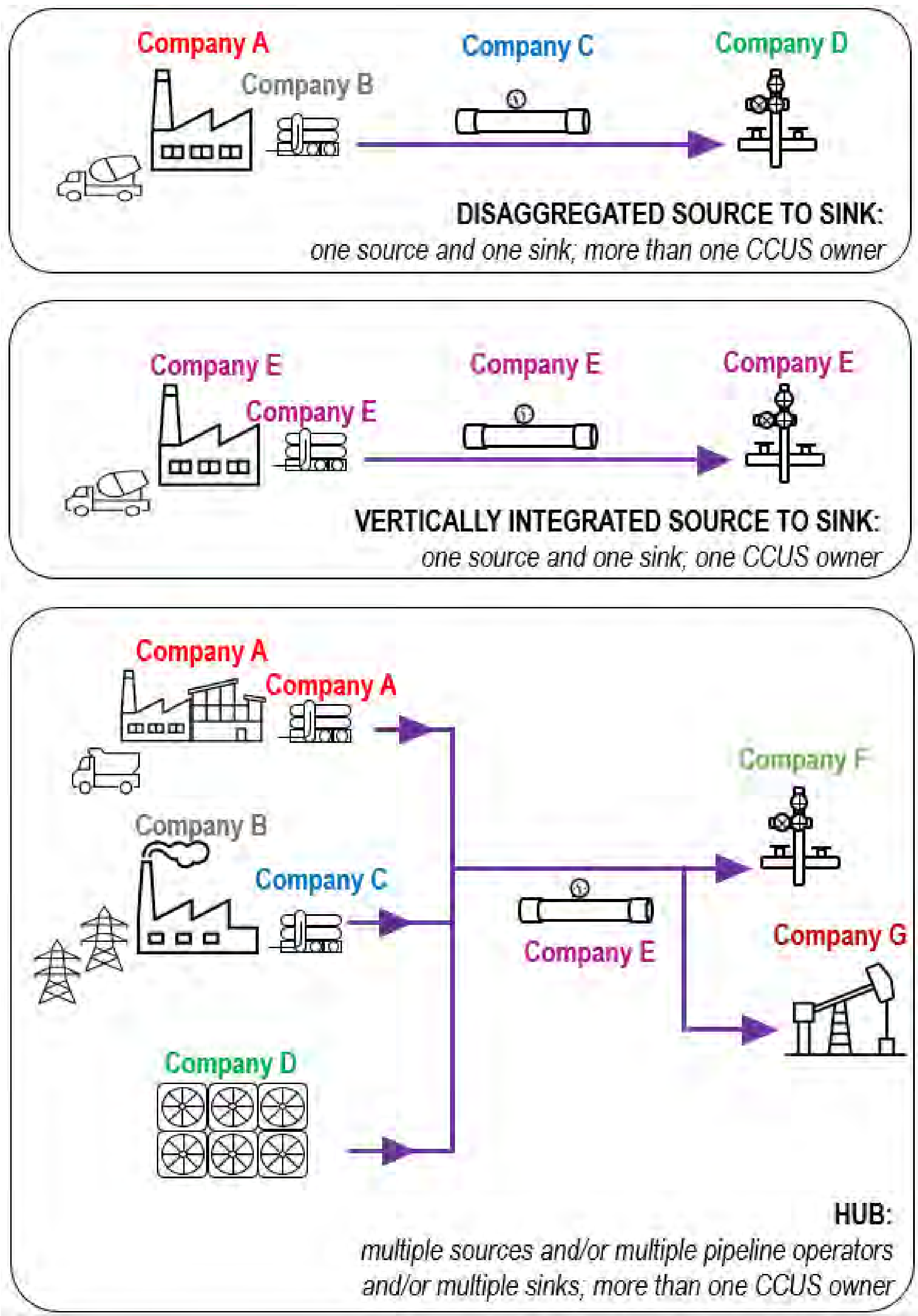


Figure 4. Schematic examples of CCUS business models

For the land-locked Intermountain West, a typical storage hub could include multiple CO_2 emission sources, CO_2 pipelines and spur lines to transport CO_2, more than three injection wells, more than five monitoring wells, a separator and CO_2 compressor, and a monitoring facility. A hub itself can be modest in size, requiring about 30 surface acres [29]. The region itself would have its advantages and pose its own challenges to bring such a project to fruition. On the one hand, the population density is low and the area in which to build hubs is large. On the other hand, the mountainous terrain affects feasible pipeline routes, and a mix of private, state, and federal lands complicates pipeline ROWs, as well as surface and pore space rights required for storage operations. A hub, compared to just a one-off CCUS project, requires more of all of this, further exacerbating these issues.

However, these obstacles can be overcome, and Tallgrass Energy plans to prove just that with their Eastern Wyoming Sequestration Hub project in the northern reaches of the Denver-Julesburg Basin. The hub aims to provide a cost-effective means of capturing, transporting, and storing CO_2 across multiple states, benefiting the Rocky Mountain and Midwest regions. With its recently awarded Wyoming Energy Authority grant, Tallgrass will fund development activities and the drilling of a characterization well for its impending UIC Class VI permit filing [66]. This project, if successful, can provide a blueprint for further H&C development throughout the region.

Revenue models for CCUS that can be applied in the region are largely incentivized by the 45Q tax credit and the California Low Carbon Fuel Standard. These have both been recently expanded—the low carbon fuel standard was modified in 2019 to include DAC [61]. August of 2022, saw the passage of the Inflation Reduction Act, which brought to fruition many of the 45Q enhancements CCUS advocates had long sought. Credit amounts were augmented to $60–180 all-in total credit value depending on capture technology leveraged and if the CO_2 is geologically stored or used [67]. The 2021 Federal Infrastructure Bill includes multiple provisions supporting CCUS, such as grants for DAC hubs and CO_2 utilization. Notably, on a per-tonne basis, the CO_2 capture incentive is less for a gas plant than a coal plant because an unabated gas plant inherently produces far less CO_2 per megawatt hour than an unabated coal plant.

Additional drivers for CCUS are increasing and include environmental standards and regulations, environmental, social, and (corporate) governance, and shareholder and consumer pressures. In response to this, the U.S. Securities and Exchange Commission plans to propose climate change disclosure rules [68], which, if materialized, will act as an added driver for CCUS.

3 Relevance of CCUS for the Intermountain West

During the I-WEST CO_2 Storage and Utilization Technical Workshop, stakeholders in region indicated [3] the critical importance and value of CO_2 capture technologies coupled with utilization and/or storage as components of the portfolio of strategies needed to achieve regional carbon neutrality. Additionally, CCUS offers important economic opportunities as well—ones that can support the region's transition by offering low-carbon versions of existing and future commodities (both power and industrially derived). A significant ramp-up of CCUS deployment will be required in the next 15 years to put the region on track toward a lower carbon, net-zero future. The region's attributes pertaining to its geologic resources, their co-location with point sources, and variety of existing, active CCUS physical infrastructure makes the region highly amenable to the application of CCUS.

3.1.1 Opportunity Case for CCUS in the Intermountain West

The development of CCUS projects depends on a multitude of aspects; spanning both technical and non-technical that must, to some degree, co-exist in order to provide the technology with the greatest opportunity case [69]. A strengths, weaknesses, opportunities, and threats (SWOT) analysis was used in the I-WEST Roadmap to highlight the status of CCUS development and its opportunity potential in the context of the region in this regard. This type of analysis is an effective planning tool commonly employed for the comprehensive evaluation of an organization or project to inform investment and strategic direction. The fundamental premise of SWOT is to gain a detailed and holistic understanding of the internal (strengths and weaknesses) and external (opportunities and threats) environment in which invested effort would take place as well as recognize potential pathways for growth and their associated challenges. For CCUS development in the region, the knowledge gained can orient strategic decisions and be used to avoid unnecessary and undesirable circumstances. The SWOT summary is shown in Table 1. The content within was derived from a variety of sources, including publicly available material in recent technical literature, regionally significant news releases and websites, the vast collection of region-specific information that was generated from the I-WEST CO_2 Storage and Utilization Technical Workshop [3], and via discussions with stakeholders in Intermountain West states.

Table 1. CCUS SWOT analysis in context of the Intermountain West region

Strengths

• High TRL technology suite that includes dedicated storage in saline reservoirs and CO_2-EOR, each with enormous near-term potential to decarbonize the region from point-source emitters and DAC CO_2 removal
• Ample geologic storage potential and pipeline infrastructure exists in and proximal to the region that is geographically distributed and proximal to CO_2 generating sources [8]
  ○ Substantial geologic data exists to leverage in region for detailed evaluation of potential storage sites
  ○ Several CO_2 pipeline networks exist and are operating in the region; largely dedicated for CO_2-EOR but also amenable to GCS
• CO_2-EOR is a scaled, proven technology in operation at commercial-scale since the 1970s that improves oil field economics with additional recovery; can reuse existing oil field assets (production wells, gathering system, any separation)

- CCUS requires significantly less land and water (100 times or more) than nature-based carbon removal solutions such as afforestation
- Advantages for job creation
  - Preserves jobs at facilities that retrofit with CCUS
  - Creates a new-sector job demand that makes valuable use of transferable skills from the energy sector
- CCUS seen as a less volatile income generator compared to oil and gas
- Headway on CCUS favorable policies exist or are in development in the region [70]:
  - Many regional states have committed to GHG emission reduction goals
  - Wyoming: Has UIC Class VI primacy, CO_2 pipeline corridor mapping, and long-term liability transfer
  - Utah: Established pore space ownership with respect to the surface estate and potential jurisdiction for UIC Class VI injection well primacy
  - Montana: Transfer of liability for GCS sites operators to the state 30 years after CO_2 injection ends. Property tax incentives for facilities installing CCUS equipment

Weaknesses

- The UIC Class VI permitting process is slow, requiring a 2–6-year permitting duration before authorization to inject is issued, particularly for states without Class VI primacy [71, 72]
- Economically challenging technology requiring large capital investments—even when coupled with existing subsidies and tax credits
  - Currently, projects developed under 45Q can involve significant financial planning and allow for limited project duration (12 years 45Q eligibility) that can prove to be a barrier
- Requirements for PISC and site closure can prove difficult and cost intensive
- Injecting CO_2 can pose the potential for induced seismicity or leakage to aquifers or atmosphere—particularly if conducted at a site(s) lacking the needed geologic criteria for safe injection or if unsafe injection operations are performed
- CO_2-EOR creates additional fossil fuels that would be consumed and, therefore, generate additional CO_2 emissions
- CO_2-EOR is contingent on a steady supply of CO_2 and disruptions to supply can affect project economic viability
- Landowner safety concerns can exist near storage sites; these can be more suppressed for CO_2-EOR given greater familiarity with oil and gas operation
- Uncertainty in the needed supporting policy landscape across some regional states, most notably, ambiguity related to pore space rights and long-term CO_2 storage site liability ownership
- Arizona's geologic setting may not be amenable to deploying CCUS locally; captured CO_2 would likely need to be transported to reservoirs in other states

Opportunities

- The opportunity set for GCS exists in efforts to define the quantity of suitable sites and the volume of actionable storage reserve capacity
- CCUS technologies continue to improve in cost and efficiency
- CO_2-EOR offers material ability to store CO_2 while providing a revenue stream from hydrocarbon production
- Evolving policy landscape for CCUS broadens opportunities
  - Recently expanded 45Q in the form of direct pay, increased credit values for industrial, power, and DAC facilities, a ten-year construction commencement, transferability of credits to third party, and greatly reduced capture thresholds
  - Additional tax credits are applicable, most notably the California Low Carbon Fuel Standard
  - Increased number of states with primacy for UIC Class VI oversight could materially expedite permitting
  - Storing CO_2 and Lowering Emissions Act offers potential for 1) loans and grants for up-scaling common carrier CO_2 pipeline networks, 2) Class VI well funding at U.S. EPA for states to gain primacy, 3) funding for front-end engineering design studies, and 4) cost-share programs for commercialization of CO_2 storage [73]
- Up-scaling operations affords logistical and cost advantages
  - Trunklines can be used to improve source-to-sink transportation economics

- Storage hubs can improve economies of scale and permitting logistics; high-grading sites developed under federally subsidized projects can serve as first-movers [74]
- The Bipartisan Infrastructure Law includes provisions for establishing large-scale CCUS projects and infrastructure development efforts, including DAC hubs, CO_2 transportation infrastructure financing, and power and industrial capture facilities [75]
- Natural gas separation/acid gas injection using UIC Class II wells coupled with 45Q and MRV plans offers a unique, regional business case; many of the rgion's CO_2 emissions are derived from these gas processing sources
- Synergies exist with other economies and capture facilities, like bioenergy, hydrogen, and DAC facilities
- Treatment and utilization of produce brine extracted from CO_2 storage sites undergoing pressure management
- Emerging approaches involving CO_2 utilization, CO_2 mineralization, and CO_2 as a working fluid in geothermal systems offer potential complementarity to saline storage and CO_2-EOR
- Elevation of the full suite of CCUS technologies up the TRL [12] scale through R&D, investment, and early-mover projects
- Outreach campaigns that increase the awareness of climate change at all social levels and offer insight to suggested solutions, including CCUS; these must highlight the advantages of a lower-carbon transition, the risks that may exist and their associated mitigation strategies, and the near and longer-term benefits

Threats

- Pushback via lack of social public acceptance of CCUS rooted in notions of "not in my backyard/not under my backyard" Deficiency in public understanding of both the technology and the advantages that it offers may prohibit broader deployment in the region [76]
- CCUS not considered as "green" as other decarbonization options resulting in environmental counterclaims concerning prolonging fossil fuel usage
- Possibility of quicker expansion of renewable energy and energy storage than expected
- Fossil-based power plants shuttered at an accelerated rate moving forward
- Slower CO_2-EOR payback compared to unconventional oil projects; also, it is a mature technology with less likelihood for breakthroughs
- Pushback exists elsewhere in country (e.g., Midwest) to proposed CO_2 pipeline expansion efforts
- Presence of split estate circumstances can add ambiguity between surface, pore, and mineral ownership and complicate project logistics
- Federal and state-based leasing restrictions may prohibit deployment options in the region by making certain lands inaccessible at times of the year or at all
- Water usage restrictions can limit CCUS implementation, particularly given that CO_2 capture can be water-intensive [77]
- Geologic formation pressurization becomes an issue when not well managed

The SWOT analysis for the region is useful to highlight the technological and non-technological considerations that could facilitate a full realization of the opportunity case for CCUS. Further, it provides context for the technology maturity, policy and societal readiness, and the business cases for CCUS in the region. The energy and low-carbon transition will be a vector force and will cause disruption. Described below are several salient themes that provide dimensionality to SWOT analysis of the CCUS development opportunity in the region.

Favorable geologic resources exist across the region: The Intermountain West contains numerous geologic basins that hold a significant carbon storage resource endowment. Within these basins, multiple strata can act as "sinks" for GCS to be used for CO_2 injection into deep formations (including saline formations, depleted oil and gas reservoirs, or unmineable coal seams) that can store CO_2 for permanent storage. As Figure 5 shows, these storage sinks are co-located with or proximal to a large portion of the CO_2 point source fleet.

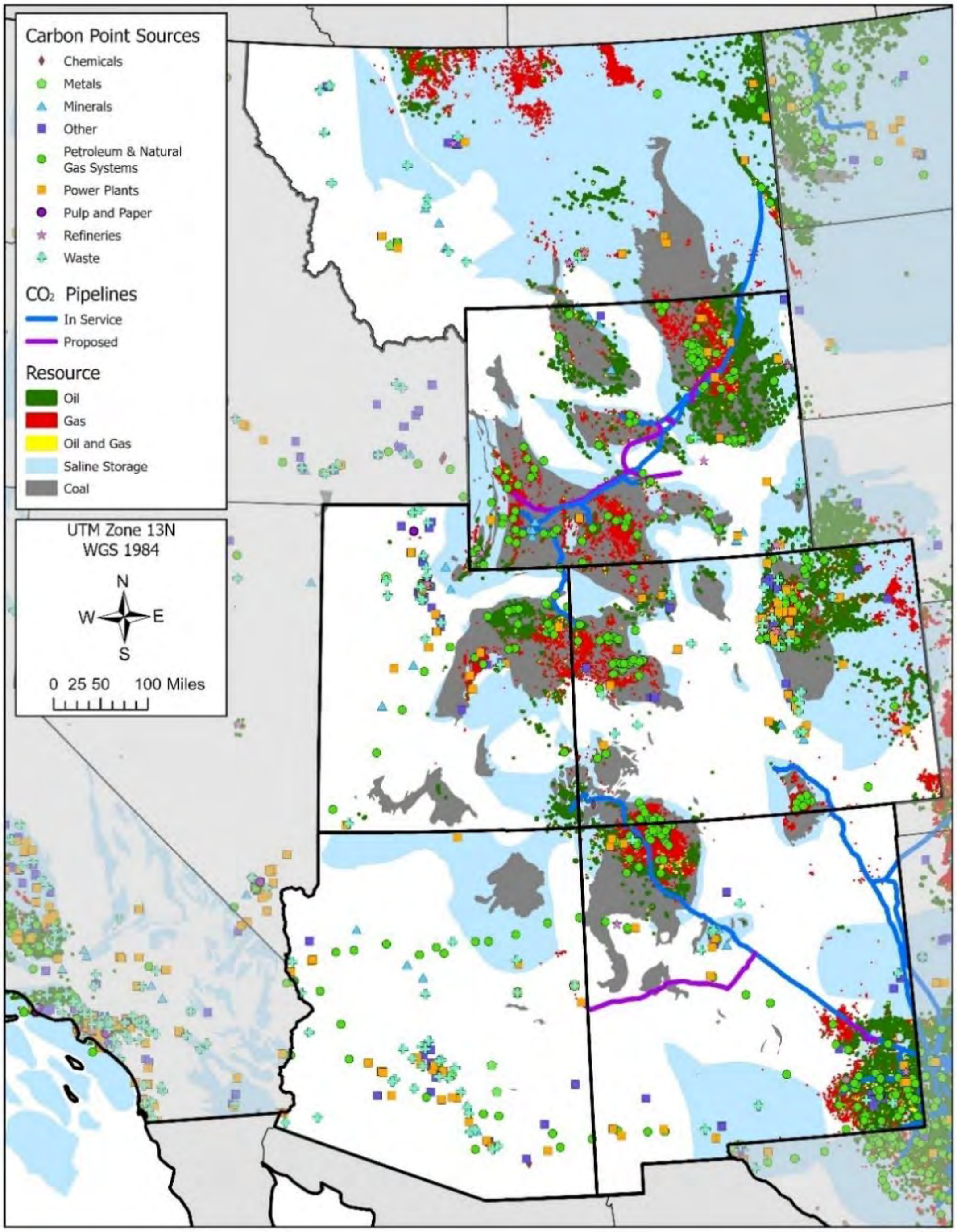


Figure 5. CO_2 sources, GCS areas, and CO_2 pipeline infrastructure

The carbon storage potential in the region is large, estimated at 354–3,365 gigatonnes (Table 2). That volume of storage capacity is sufficient to store all the yearly CO_2 emissions from existing I-WEST point sources eligible for 45Q for approximately 1,550–15,000 years.

Table 2. Estimations of CO_2 storage capacity within the region [8]

State	Saline Formations (Gigatonnes)			Oil and Natural Gas Reservoirs (Gigatonnes)			Unmineable Coal Seams (Gigatonnes)		
	Low	Medium	High	Low	Medium	High	Low	Medium	High
Colorado	34	131	354	1.31	2.35	2.66	0.49	0.65	0.86
Montana	98	336	857	0.15	0.38	0.90	0.33	0.33	0.33
New Mexico	33	129	349	9.71	9.71	9.71	0.08	0.16	0.3
Utah	23	89	239	1.31	2.39	2.66	0.03	0.07	0.12
Wyoming	146	571	1,540	0.23	0.59	1.41	6.55	6.64	6.78
Total (Gigatonnes)	**334**	**1,256**	**3,339**	**12.71**	**15.42**	**17.34**	**7.48**	**7.85**	**8.39**

Nevertheless, the timely development of these regional geologic storage opportunities will require extensive place-based geologic assessment and analysis. As highlighted in the SWOT analysis, the I-WEST initiative recognizes that place-based economic, infrastructure, policy, and community considerations will be critical for the timely deployment of commercial GCS. More complete place-based GCS assessment can support industry investment, policy solutions, and community buy-in to commercial storage projects.

The current regional CO_2 pipeline network, which is currently used for EOR, but could also be readily leveraged for CCUS, is depicted in Figure 5. Notably, the states of New Mexico, Wyoming, and Montana have well-developed existing infrastructure networks with further development anticipated—the states of Wyoming and Montana recently signed the CO_2 transport infrastructure memorandum of understanding to establish a collaborative mechanism to develop and implement an action plan for the buildout of regional CO_2 transport infrastructure to enable large-scale carbon management [78].

The Colorado School of Mines, New Mexico Institute of Mining and Technology, University of Utah, and University of Wyoming have developed comprehensive assessments of GCS resources within their respective states. These assessments are appended to the I-WEST roadmap and address a variety of attributes beyond capacity that are critical for assessing the technical and commercial viability of GCS opportunities. Additionally, they afford a more refined, state level complement to capacity estimates provided by DOE's 2015 Carbon Storage Atlas shown in Table 2.

Early-mover CCUS opportunities exist in the region: Within the Intermountain West, early mover projects are unfolding. The region contains attributes that are presenting early-mover opportunities for CCUS. These opportunities relate largely to CO_2-EOR expansion as well as CO_2 separation and storage associated with oil and gas operations. One such project is Denbury's CO_2-EOR expansion efforts in Wyoming and Montana, where, in late 2021, the company completed a Cedar Creek Anticline CO_2 Pipeline extension in southeastern Montana. The pipeline is large and has a capacity of about 7 million tonnes of CO_2 per year and is enabling CO_2-EOR operations in oil fields within the Cedar Creek Anticline. In another example, Lucid Energy's (Targa Resources Corporation) carbon storage project Red Hills Gas Processing Plant is being developed in association with an acid gas injection (AGI) facility in New Mexico. Aside from power generation, oil and natural gas processing facilities like Lucid Energy's Red Hills Gas Processing Plant are the second largest set of CO_2 point-source emitters in the region. Achieving a major milestone, this project recently had its MRV plan approved. Lucid is also operating injection with UIC Class II wells (versus the typically more rigorously regulated Class VI wells) given that operations are associated with oil and gas.

Overview of the 45Q Carbon Oxide Tax Credit

The 45Q tax credit (Section 45Q of the Internal Revenue Code) originated in 2008 through the Energy Improvement and Extension Act. Specifically, Section 45Q provides a performance-based tax credit that can be claimed by a carbon capture project when the CO_2 is either securely stored in geologic formations, like oil and gas or saline reservoirs, or through beneficial use as a feedstock to produce products like chemicals, concrete, or fuels.

In 2018, U.S. Congress passed the Bipartisan Budget Act (BBA), which prompted a revision of the CCUS tax credit accessible under Section 45Q. Tax credits increased for CO_2 captured from new facilities, following a steady ramp up to \$35/tonne CO_2 in 2026\$ stored by EOR and up to \$50/tonne CO_2 in 2026\$ for storage in saline reservoirs (Table 3).

The Inflation Reduction Act, signed into law in August 2022, further enhanced CCUS tax credits. Beginning in 2022, industrial-captured CO_2 garners a flat \$85/tonne CO_2 for storage in saline reservoirs and \$60 for use or EOR; CO_2 captured via DAC sees further benefit at \$180/tonne CO_2 and \$130/tonne CO_2, respectively (Table 3). Additional improvements include the option for direct pay, the ability to transfer credits to a third party, and substantially reduced capture volume thresholds for qualification.

Table 3. Schedule of 45Q tax credit by year

Storage Type	Capture Type/BBA	Tax Credit by Operational Year (\$/tonne CO_2)									
		2018	2019	2020	2021	2022	2023	2024	2025	2026	2027+
Dedicated Geologic Storage	Industrial capture	26	29	32	35	85	85	85	85	85	85
	DAC	26	29	32	35	180	180	180	180	180	180
	BBA	26	29	32	35	38	41	44	47	50	Indexed to inflation
CO_2-EOR & Use	Industrial capture	15	18	20	23	60	60	60	60	60	60
	DAC	15	18	20	23	130	130	130	130	130	130
	BBA	15	18	20	23	25	28	30	33	35	Indexed to inflation

Now, power plants must capture 18,750 tonnes per year and at least 75 percent of baseline emission, whereas DAC is now 1,000 tonnes per year and all other facilities must capture at least 12,500 tonnes per year. Currently, construction of the CCUS project's carbon capture equipment must begin before January 1, 2033. The passage of this bill should be monumental for spurring CCUS development [67].

For early-mover CCUS opportunities to take shape, one or several enabling factors often exist that make CCUS advantageous to an entity's business case. In the absence of any carbon tax of emissions penalty in place, these enablers may include the opportunity to generate revenue via hydrocarbon production through CO_2-EOR, if low-cost CO_2 capture and separation opportunities exist or are already prominent as part of prevailing business practices, and if CCUS-related incentives can be readily leveraged. CCUS-related incentives, particularly the 45Q tax credit, are at the core for supporting the business case for the Denbury and Lucid project examples, and with the recently Passed Inflation reduction Act's (IRA) increased incentives and reduced capture thresholds, 45Q will make future CCUS projects more economically viable and allow the technology to be implemented at scale.

Reservoir pressure management strategies offer the potential for expanding the region's water resources: Most Intermountain West are highly arid and have been facing prolonged and severe drought. Given the interdependencies between water and energy systems, water management is a critical component of any regional energy and low-carbon transition plan. Additionally, any water usage restrictions in place due to severe or prolonged drought can potentially limit the deployment of emerging low-carbon technologies like CCUS.

As CCUS deployment scales up, it is expected that reservoir pressures will increase due to injection operations. Regulatory guidance that mandates operational due diligence from EPA's UIC Program is in place to protect USDWs (across all well classes) during and after injection operations—this is no different for CO_2 injection. Nonetheless, the extraction of storage formation brines as part of CO_2 injection operations has been heavily researched as a promising strategy to mitigate pressure increases in the subsurface—helping to maintain safe operating conditions and retain effective storage capacity.

A common practice for managing produced water in the oil and gas sector (an aspect of hydrocarbon production and not a direct reservoir management strategy) is via reinjection into the subsurface through UIC Class II disposal well [79]. Disposal of produced waters via underground injection tends to be low cost and perceived as a safe, proven, and widely used method for disposal [80]; however, induced seismic events have occurred in certain instances that are believed to be a result of disposal operations [81]. In the Intermountain West, an opportunity exists for potentially treating produced waters from both oil and gas operations and pressure management strategies for CO_2 injection and storage operations to augment regional water resources. The process of treating produced water from saline storage reservoirs generally involves a pretreatment process, desalination of the brine water, and the production of a low-TDS product stream and a waste stream consisting of highly concentrated brine water. Produced water requires a tailored pretreatment process to specifically remove the unwanted minerals, large particulate matter, and other organic or inorganic compounds followed by desalination to remove TDS. Many types of desalination processes exist, but their application and associated cost of treatment depends heavily on the TDS concentration of the water influent and targeted TDS removal level [82, 83, 84]. EPA's UIC Program defines USDWs as having less than 10,000 ppm TDS; saline is on the order of 35,000–to 50,000 ppm TDS; brine is defined as 50,000–>150,000 ppm TDS [85]. The range of TDS in groundwater and deep aquifers is known to vary significantly (Figure 6) [7].

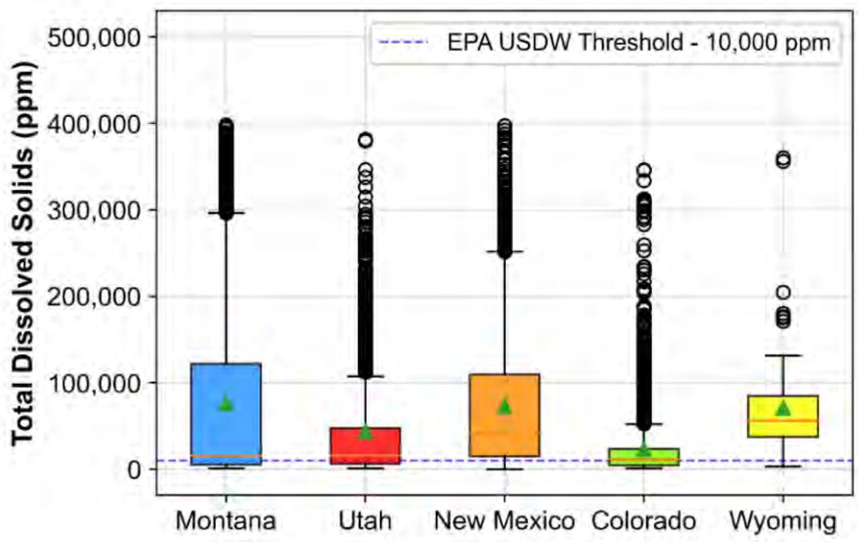


Figure 6. Box and whisker plot depicting TDS ranges in aquifers in the Intermountain West states

To provide perspective of scale, a single CO_2 project that injects 1 million tonnes per year of CO_2 and would produce an equivalent volume of water to the volume of CO_2 injected (a single tonne of brine occupies roughly three-fourths the pore space than that of supercritical CO_2 under reservoir conditions of approximately 3,500 ft deep and 97 Fahrenheit (°F) [36 Celsius (°C)]) would produce upwards of 8.6 million barrels (bbl) of water per year that could be treated for reuse or would require some form of disposal. In the context of water usage by the states (Table 4), approximately 100 CO_2 storage projects deployed at this scale that produce and treat formation waters at a comparable 1:1 injection/production volumetric rate would 1) abate roughly one-half of the region current point-source-derived annual CO_2 emissions and 2) generate new water sources on the scale of 55 percent of current regional livestock water usage volumes, 41 percent of industrial water usage volumes in the region, or upwards of 28 percent of power generation water usage. [86] Critical to these assumptions is the available deployment of water production, surface handling, and treatment technologies at equally sufficient scale.

Table 4. Total water withdrawals for states by use category circa 2015

Water Use Category	Arizona	Colorado	Montana	New Mexico	Utah	Wyoming	Regional Total
	Yearly Water Usage by State and Use Category (Circa 2015) (million bbl)						
Public	10,429	7,335	1,330	2,277	5,449	878	**27,697**
Domestic	209	308	206	214	90	78	**1,104**
Irrigation	39,368	78,214	82,125	20,596	26,332	67,699	**314,335**
Livestock	338	289	367	278	138	141	**1,551**
Aquiculture	300	2,260	149	209	722	250	**3,890**
Industrial	53	731	84	30	1,158	70	**2,125**
Mining	594	277	329	1,271	2,272	1,228	**5,970**
Thermoelectric Power	726	323	658	291	604	450	**3,052**
Total (million bbl)	**52,015**	**89,737**	**85,246**	**25,166**	**36,765**	**70,793**	**359,723**

CCUS value chain components are technologically mature: Is the CCUS technology chain "ready for prime time"? The core technology is mature, industrial-scale CO_2 capture that has operated successfully since 1938, and, downstream, GCS of CO_2 has been performed since 1972 [87]. These central technologies are fully matured with high Technology Readiness Levels (TRLs). Appendix A: CCUS Technology Readiness Level Matrix shows a comprehensive listing of TRLs by CCUS value chain component. Table 5 shows the TRL progression from a technology's basic idea (TRL 1) to its stable commercial growth (TRL 11) [9]. Figure 7 shows the TRLs for component mid- and down-stream CCUS technologies.

Although CCUS technology can be improved with focused R&D, there are no fundamental technical barriers to its scale-up. The costs have been noted as potentially inhibiting factors. However, they are within conventional boundaries of energy investments. The next ten years will prove decisive—to meet climate goals, policies must enter into force and public trust must be gained. Governments will have a role to play to solve the apparent contradiction between urgent investments and remote future impacts on climate change.

Table 5. Technology Readiness Level ranges for the variety of CCUS technologies

TRL	Description
1	Initial Idea - Basic principles have been defined
2	Application Formulated - Concept and application of solution have been formulated
3	Concept Needs Validation - Solution needs to be prototypes and applied
4	Early Prototype - Prototype proved in test conditions
5	Large Prototype - Components proved in conditions to be deployed
6	Full Prototype at Scale - Prototype proved at scale in conditions to be deployed
7	Pre-Commercial Demonstration - Solution working in expected conditions
8	First-of-a-Kind Commercial - Commercial demonstration, full-scale deployment in final form
9	Commercial Operation in Relevant Environment - Solution is commercially available, needs evolutionary improvement to stay competitive
10	Integration Needed at Scale - Solution is commercial and competitive but needs further integration efforts
11	Proof of Stability Reached - Predictable growth

Carbon capture has already been applied globally either directly or as retrofit to steel, power, hydrogen, and other large facilities [88] and the technology works on existing stock and new facilities; existing technology has TRLs of 9 or higher. Additionally, CO_2-EOR has a TRL of 11 [4] and a half-century of successful operational history attributed to CO_2-EOR operations in West Texas and in the Rocky Mountain region of the United States [89, 90, 35]. Moreover, the CO_2-EOR industry has utilized both naturally sourced CO_2 as well as CO_2 captured and separated from anthropogenic point sources. Storage of CO_2 in saline formations and in depleted oil and gas fields also has a TRL of 11. While the TRLs vary, by and large, the value chain is technologically robust enough currently to allow it to scale given proper market drivers. Cost improvements can be enhanced through R&D, which low TRL components will require in order to become commercial-ready options [91]. These could yield an even wider range of applications and low-carbon products that are feasible in the near-term. Further, CCUS technologies are evolving, and examples that are currently advancing include the following:

- **Carbon capture at industrial sites –** Production of cement, steel, and aluminum releases substantial amounts of carbon. Several private companies have been at the forefront of viable carbon capture solutions. British Columbia-based Svante developed carbon capture technology for both existing infrastructure and future plant development that uses nano-solid adsorbents with high storage capacity for CO_2, with a cycle time of less than 60 seconds [92].
- **Reservoir characterization and monitoring –** A novel approach to GCS applies ambient seismic imaging (ASI), which effectively "listens" to rock formations by detecting fluid- and gas-filled fractures. Providing near real-time detection, more precise reservoir mapping and monitoring along with the ability to record temporal changes, the ASI technology shows promise for risk mitigation at carbon storage projects and long-term cost efficiencies [93].
- **Remote sensing –** Use of satellite imagery has become a powerful, robust technology with dozens of multi-scale applications across numerous industries. Capable of covering large areas with high resolution and advanced precision at the millimetric level, InSAR—radar satellite data—is employed in CCUS to detect and analyze ground behavior and anomalies while minimizing the need for fieldwork [94]. Satellite data continues to become more widely available, decreasing costs and allowing timely and more thorough analysis of ground cover at multiple scales.
- **Process-based attribution monitoring via geochemistry at GCS sites shows promise –** Environmental monitoring of CO_2 storage sites using baseline methods often results in false positives of leakage, putting project development at risk despite the due diligence of the developer. Baselines do not consider atmospheric anomalies and variations from environmental changes. Using a geochemical relationship (percentage volume of oxygen [O_2] relative to that of CO_2) rather than concentration comparisons to identify the key processes that are occurring, process-based attribution monitoring can identify anomalous CO_2 to determine whether there is a risk at the project site. The technique requires only a one-time characterization to collect accurate and immediate data, versus years of baseline studies that are subject to variations and atmospheric changes [95].
- **Rock volatiles stratigraphy –** This technique presents a faster methodology to assess risk at potential and existing sites by extracting and identifying volatile chemistries in rocks and analyzing site cuttings for historical evidence of pressure loss or CO_2 migration. Rock volatiles stratigraphy is cost effective, typically accounting for about 1 percent of well drilling costs and is effective for application for Class VI wells [96].

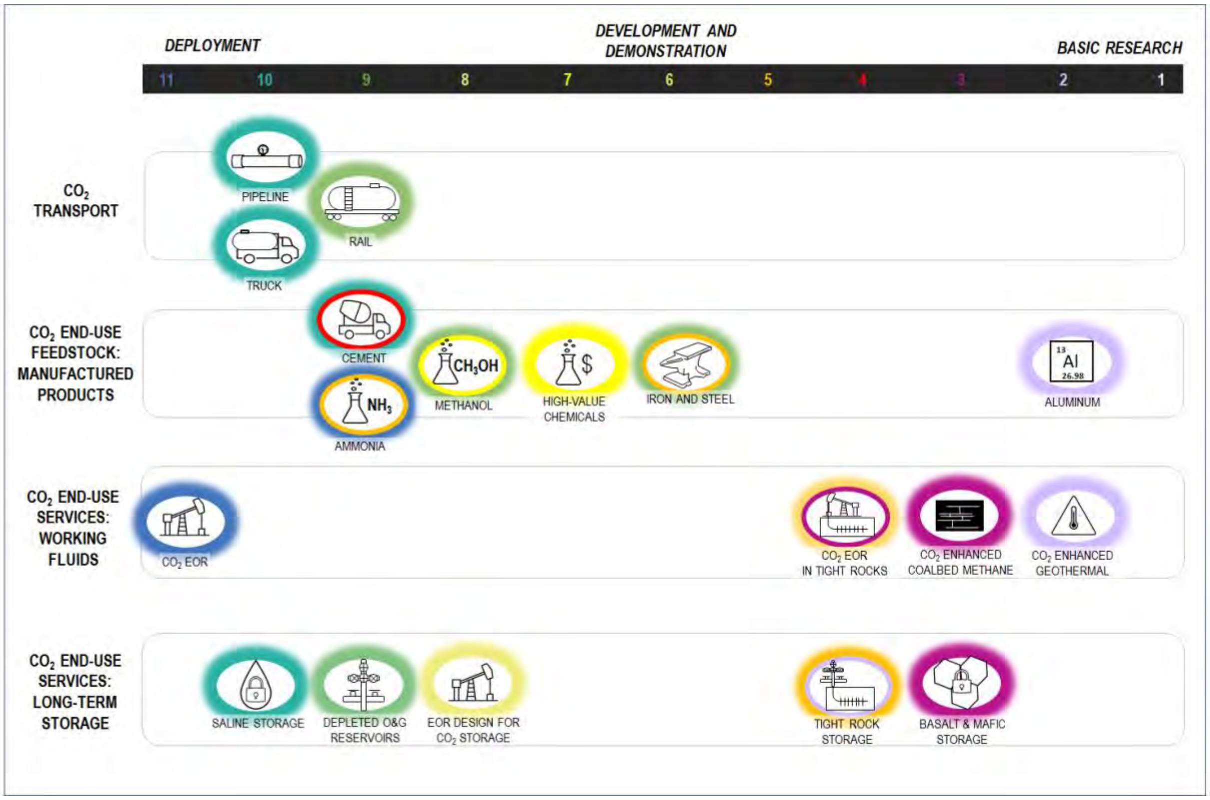


Figure 7. Current and emerging portfolio of technologies spanning the CCUS value chain

Policy and societal readiness are critical enabling mechanisms needed for CCUS to move forward : Given the UIC Class VI well's relatively nascent nature (established by EPA in 2010) the policy surrounding it remains mutable [97]. Through the past decade of project R&D, invaluable learnings have been accumulated to better inform CCUS policy and regulation. From this, it has become apparent that in order to reduce business risk and entice future investment, two things are imperative. First, a cleaner and more solid regulatory framework is necessary so prospective investors and operators are assured they can secure the right to inject in a timely fashion, comply with all regulatory requirements, and fully understand their potential liability. Second, these projects rely heavily on tax credits to become net-present-value positive and get off the ground, and additional aid is necessary [15]. To these ends, much progress has been made at a state and federal level in the region:

- **UIC Class VI Primacy –** One often-discussed impediment to CCUS development historically has been the lengthy, (i.e., 2–6 year) federal UIC Class VI permitting process. In an effort to streamline and expedite the process, some states are contemplating or have acquired Class VI primacy allowing them to control the permitting process at a state level. In the region, Wyoming has already established primacy, Arizona is in the pre-application phase, and Utah has recently passed a CCUS-related bill laying the groundwork to move toward primacy application in the near future [98, 99]. These efforts seem like the most logical and effective method for improving permit approval speeds. Additionally, it affords the appropriate state-based entity with intimate knowledge of the local geologic setting, state-level laws and policies, and awareness to current and historic development activities of relevance oversite authority.

- **Pore Space Rights –** Another hindrance to CCUS development is ambiguity surrounding pore space rights, with some states yet to determine who owns pore space for CO_2 injection and a lack of clarity on federal lands. Utah, Wyoming, and New Mexico have resolved this uncertainty by clearly identifying the surface owner as the rightful owner of the pore space [99]. Additionally, the requisite aerial extent of pore space needed for a CCUS project permit necessitates further definition. Neighboring North Dakota determines this by the area of the modeled CO_2 plume projected to the ground surface. However, states like Montana and Wyoming have yet to tackle this issue. Further clarity around pore space rights and requirements in the region is paramount [3].
- **Long-Term Liability –** Current federal policy dictates that the PISC period concludes once the operator has shown substantial evidence that their project no longer poses a risk to USDWs, and the operator's non-endangerment demonstration is approved by the UIC Director [100]. At this point, the operator is still liable for any incident that occurs at the injection site in perpetuity. This is an investment risk that many project suitors are just not willing to take. To mitigate this risk, some states have enacted legislation to transfer long-term liability to themselves once certain non-endangerment criteria are met. Wyoming, for instance, will take on long-term liability once 20 years (at minimum) have passed since last injection, all pending claims pertaining to the injection and storage have been addressed, CO_2 is no longer expected to migrate, and it poses no risk to human health or safety or to USDWs or the environment, among other things [101]. Utah and Montana follow a similar protocol, with variations in their post-injection eligibility timeframe at 10 and 30 years, respectively [99, 102]. In the case of Montana, the 30-year timeframe consists of two key intervals: 1) 15 years after injection of CO_2 ends, the Montana Board of Oil and Gas Conservation Commission can issue a certificate of completion to the operator given full compliance of all specified rules; and 2) an additional 15 years after the certificate of completion is issued, the operator must continue adequate monitoring of the wells and reservoir and continue to accept all liability until non-endangerment is achieved. Given the perceived risk without these safety nets in place, it seems likely that other states intent on promoting CCUS in the region may follow these states' leads.
- **Tax Incentives –** Lastly, tax incentives are and will continue to be critical to the widespread implementation of CCUS in the region. With no carbon tax currently imposed in the United States, investors need financial incentive to pursue CCUS and that has largely come in the form of the 45Q tax credit. Since the passage of the IRA, geologic storage is eligible for \$85/tonne CO_2 in credit for industrial capture or \$180/tonne CO_2 for DAC. CO_2-EOR or use is \$60/tonne CO_2 or \$130/tonne CO_2 for industrial capture or DAC, respectively. These enhancements alone greatly improve project economics. However, the legislation also addresses many previously identified limitations by now allowing for direct pay, substantially lower capture thresholds requirements, and transfer of the credit to a third party for cash, and it pushes the construction commencement date out to January 1, 2026 [67]. One hurdle it does not address is the credit's 12-year eligibility window. In order to

maximize project returns and cumulative emissions reductions, many projects intend to operate for upwards of 30 years (e.g., Carbon Storage Assurance Facility Enterprise Initiative [CarbonSAFE] Wyoming, Lucid Energy Red Hills Acid Gas Injection) [103, 22]. Expanding the eligibility window would improve these project's economics and stimulate further CCUS interest. Aside from 45Q, some states have recognized the need for supplementary incentives to push these projects over the economic threshold. Most notably, California's Low Carbon Fuel Standard is a market-driven credit, either earned or purchased depending upon the carbon intensity of the fuel being sold in California [104]. Montana, on the other hand, has implemented a reduced market value property tax rate for facilities installing carbon capture equipment [105]. These incentives and, in particular, the recent passage of IRA will be invaluable to the proliferation of this burgeoning industry. However, it will be paramount to continually review and revise these incentives as the industry inevitably evolves.

Is there the will to make CCUS grow to scale? Gaining public support for CCUS as a low carbon solution is critical. In a recent survey performed in Wyoming, most of the respondents supported carbon-neutral technologies related to CCUS, wind, nuclear and solar energy. Although a slight majority of respondents were likely to support carbon neutrality (52 percent), most of the respondents believed the country is transitioning from carbon-emitting energy to carbon-neutral energy industries (73 percent) and that it is a long-term transition (67 percent). Respondents also believe overwhelmingly that it is important for Wyoming to continue supplying energy to the region in the next 20–50 years (94 percent). These results are promising for implementation of CCUS given Wyoming's reputation for independent thinking and its role as an energy producer and exporter, but support of carbon neutrality likely will need to increase for CCUS to grow to the scale necessary to achieve carbon neutrality.

Shovel-ready storage and utilization sites are needed to accelerate deployment: Deploying CCUS requires the integration of CO_2 capture with transportation to viable geologic storage and/or utilization options. However, there remains a lack of certainty regarding the effects of CO_2 injection on the subsurface when conducted at commercial scale, as well as identifying potential geologic opportunities within the region that are prime for injection. These circumstances can inhibit CCUS investment decisions and slow overall project development efforts. During the I-WEST Point Source Capture Workshop, regional stakeholders shared a sense of confidence in carbon capture technology readiness and performance but expressed concern regarding the uncertainty of CO_2 storage site performance [106]. As a result, needs exist for early identification and effective characterization and appraisal of suitable candidate subsurface storage sites in the region. Understanding site performance regarding CO_2 movement and pressure evolution as a result of injection operations is an essential step in any CCUS endeavor. Site characterization efforts are crucial for gaining insight on how the candidate site may perform when CO_2 injection is applied. Site performance will dictate monitoring strategies, surface and pore space access considerations, risk mitigation approaches, and infrastructure requirements. Similarly, site performance is critical to the permitting process for demonstrating safe operations.

Candidate storage sites should, at a minimum, contain certain geologic conditions that have been shown to provide for safe and effective injection and storage operations [107] (Table 6)

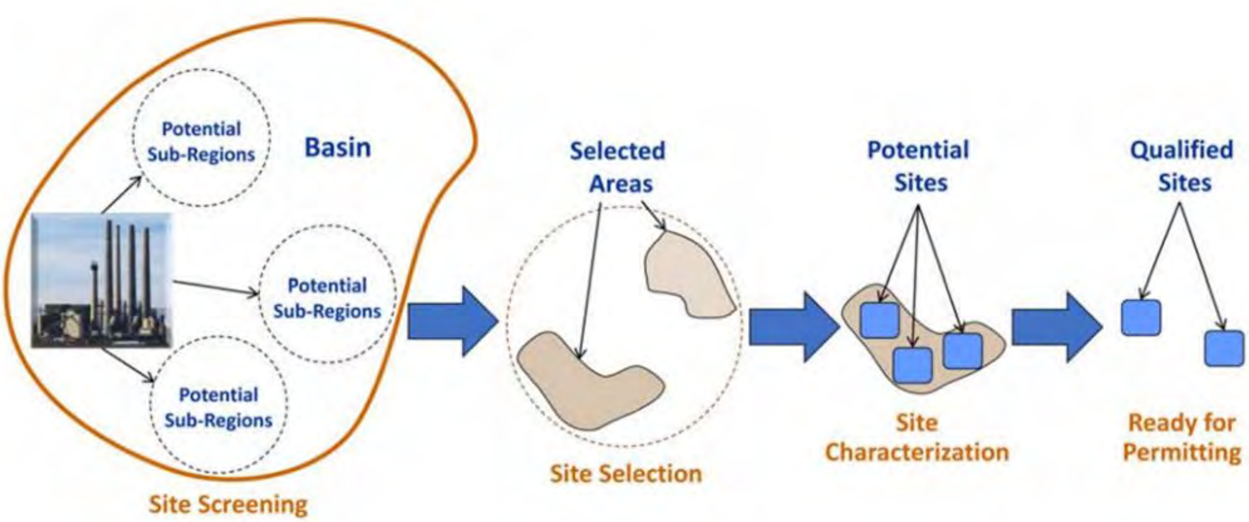
[76]. Selection of a viable GCS site must address capacity, injectivity, containment, and salinity characteristics. A qualified project site, therefore, is one that meets all required technical and non-technical criteria for CO_2 storage and is ready to seek permit to inject. Several stages of site development are typically organized around decision points related to narrowing the scale of investigation from very large regional assessments down to specific qualified sites that might be developed for commercial storage (Figure 8). Qualified sites must be operated, monitored, and closed in a manner that avoids or manages risks. EPA UIC rules for Class II, V, and VI wells under 40 CFR § 146 contain a series of requirements that relate to the specific objectives of each project stage and associated well class. The UIC requirements are intended to ensure that candidate storage sites can receive and store the volumes of CO_2 specified by operators, while protecting USDW, throughout each project stage. These regulations tend to specify minimum siting, monitoring, operational, and testing requirements for several specific functions; these include injection and confining zone siting criteria, injection pressures, rates, and volumes, analysis of the CO_2 stream, and well mechanical integrity. However, regulations are more indistinct for other functions, like tracking the extent of the CO_2 plume and pressure increase in the subsurface. Those strategies are to be proposed by operators and approved by regulatory authorities prior to issuance of permits. Given that modest issuance of actual Class VI permits across the U.S. (and even a smaller number of projects have conducted CO_2 injections under those permits to confirm the utility of proposed monitoring), case study examples are limited.

Table 6. Summary of geologic controlling factors related to injectivity, storage capacity, and containment for potential geologic CO_2 storage sites

Characteristic	Favorable Geologic Controlling Factors	Inhibitors
Injectivity	• Thick reservoirs • High reservoir permeability • Homogeneity in reservoir permeability distribution	• Effective permeability constraints arising from geochemical effects (e.g., mineral dissolution/precipitation phenomena, salt precipitation) • Reservoir over-pressurization from injection and/or proximity to other injection wells • Near-well formation damage and effective permeability loss • Transport constraints associated with CO_2 and rock interactions
Storage Capacity	• Large reservoir areal extent • Large reservoir thickness • High reservoir porosity • Stacked reservoirs • Open boundary system	• Thin reservoirs with low net storage thickness • Limited effective pore volume due to high heterogeneity • Formations with limited areal extent and closed or semi-closed boundary conditions
Containment	• Multiple and/or thick confining zones that are laterally extensive • Low confining zone permeability absent of faulting or fractures	• High permeability zones causing extensive vertical or lateral CO_2 and/or brine migration • Poor integrity of wellbores penetrating confining layers • Thinning or intermittent presence of caprock

Characteristic	Favorable Geologic Controlling Factors	Inhibitors
	• High confining zone capillary entry pressure • Absence of leakage conduits • Closed boundary system	• Dissolution of confining zone material due to reactions with CO_2/brine mixture • Natural or induced seismic activity, which may activate flow pathways in confining units
Salinity	• Formation waters contain TDS that are > 10,000 ppm	• Formation waters contain TDS that are < 10,000 ppm • Formations that serve as a source of drinking water or supply a public water system in any way

Note: Attributes described are specific to CO_2 storage capacity and containment criteria; they do not emphasize site screening criteria for favorable oil or gas production during CO_2-EOR or geothermal heat recovery

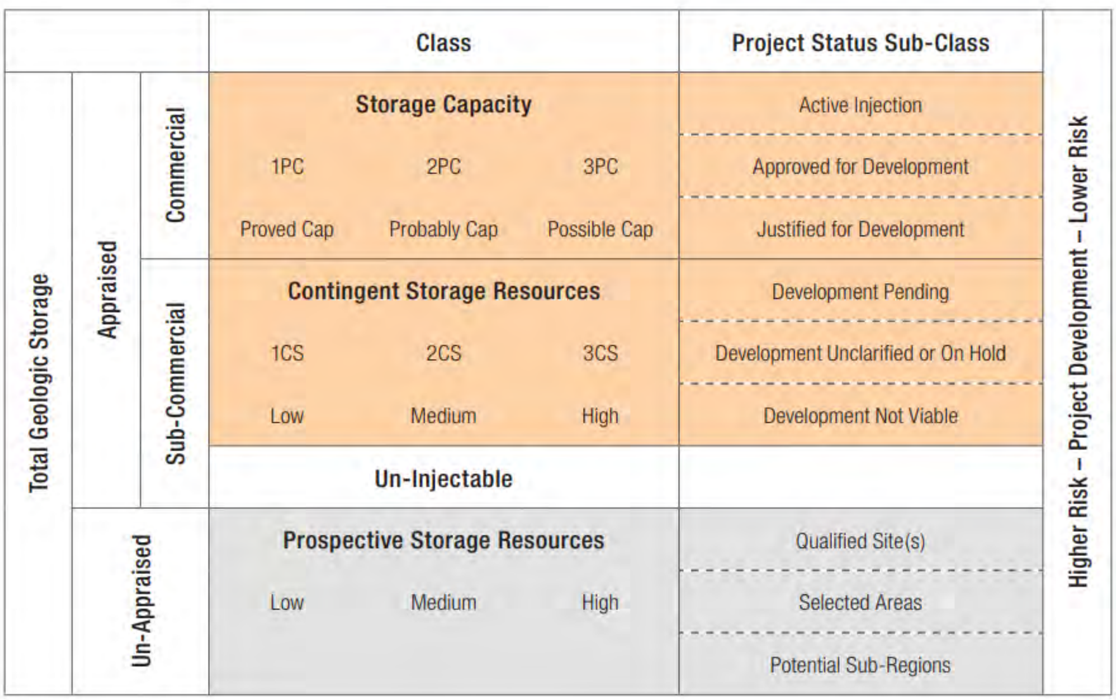


Source: National Energy Technology Laboratory (NETL) [108]

Figure 8. Graphical representation of a geologic storage project from site screening through selection of a qualified site following characterization

Evaluation and appraisal of the region's geologic resource attributes can provide a much more complete picture of the technical merits, risks, and commercial viability of geologic CO_2 storage and utilization opportunities. Additionally, this level of exploration can help high-grade viable storage resource opportunities across the region, help to mature pointed storage options (Figure 9), and explicitly identify qualified sites ready for permitting (i.e., shovel-ready sites). These geologic assessments can also inform more tailored and effective environmental justice, policy, and economic solutions to accelerate the commercial deployment of GCS.

Traditionally, long-term storage and CO_2-EOR operations both rely on the development of building geomodels that represent the candidate site(s) (acquired from characterization data) and performing forward simulations to assess potential site performance to planned injection operations. These efforts include assessing the potential movement of CO_2 and associated pressure buildup and risks given known geologic conditions [76]. Field testing can also be used to infer site performance. For instance, in CO_2-EOR applications, strong prior water flood performance at oil fields that correlates to favorable oil production is a likely indicator that CO_2 flooding could also be beneficial. In new, “greenfield” (previously undeveloped) saline storage applications, well tests like transient pressure tests and injectivity response tests conducted in stratigraphic test wells can be used. Well understood reservoirs reduce the uncertainty related to development and operational costs of injecting and storing CO_2. Additionally, insight from modeling efforts can be used to support site-specific monitoring strategies. Access to geologic datasets is critical to the establishment of site geomodels. CCUS practitioners within the region have indicated that screening for potentially viable storage sites can be facilitated through the availability of existing data [3]. These data comprise well logs, seismic surveys, and even injection/production data from operations analogous to CO_2 injection (including oil and gas production or saltwater disposal operations) afford opportunities to appraise, at a high level, the viability for candidate sites and/or regions for CO_2 storage efficacy. Existing well log (and core) data affords substantial opportunity for mapping subsurface resource storage targets and caprock layer extent and inferring geologic properties. However, existing wells also present potential leakage risks should they penetrate storage and/or caprock formations for potential storage systems. These wells would require appropriate identification and corrective action prior to injection to minimize their leakage risk. Conversely, in many greenfield storage regions, existing wells, presumably from oil and gas operations, may not penetrate to deeper saline formation CO_2 storage targets. As a result, a data gap can exist for these deeper resources and will, therefore, require additional characterization investment to properly appraise.



Modified with permission from Society of Petroleum Engineers [109]

Figure 9. CO_2 storage resource maturity classification

Project practitioners at the Wyoming CarbonSAFE project are helping in this regard as they plan to share their insight and experiences working hand in hand with state regulators during their site characterization efforts aimed toward developing a commercial-scale greenfield CO_2 storage site. Researchers at the University of Utah are aiming to evaluate and identify several qualified storage sites in the state of Utah that can be readily utilized and further developed by industry interested in CCUS. Additionally, independently verified storage sites with sufficient storage capacity may provide an opportunity for storage hubs, which can accommodate CO_2 from multiple sources.

Outreach efforts will be needed to support accelerated CCUS deployment: The impact of climate change on communities in the region is already being felt. With more frequent droughts and wildfires, implementing CCUS in the region will be paramount to mitigating CO_2 emissions now and helping slow these repercussions [110]. To facilitate the development and acceptance of CCUS in these communities, it will be essential for the industry to have a continued public outreach and education effort. It has been recognized through previous field projects that communities that have not been properly educated or informed during all phases of CCUS implementation have the potential to feel they are at a higher risk when these operations are conducted in their vicinity [3]. Landowners can also become concerned that they may be somehow liable if there were to be an operational mishap in “their” pore space. There is also exist a stigma that CCUS is not “green” and only perpetuates the usage of fossil fuels with little impact on carbon emissions. With proper outreach, these concerns and more can be better understood and addressed to provide the knowledge and factual basis necessary to recognize the overwhelming benefits and necessity of these technologies in the near and mid-term. Besides the positive impact on climate change, these projects will save and provide new jobs. Some power plants, slated to be shuttered, will be able to keep their doors open and employees intact with the augmentation of carbon capture equipment (e.g., San Juan Generating Station) [111]. A burgeoning CCUS industry creates new-sector job demand, making use of transferable skills of an oil and gas industry that has been prevalent in the region for decades. Communities need to be engaged to convey these messages and be heard.

3.1.2 CCUS Ramping Up in the Region

In 2021, the Global CCS Institute identified 27 active CCUS facilities around the world with capacity to capture approximately 37 million tonnes of CO_2 each year—13 of these projects operate in the United States [88]. These U.S.-based projects are largely rooted in providing CO_2 supply for EOR operations. The lone dedicated long-term storage project includes the Illinois Industrial Carbon Capture and Storage Project in Decatur, Illinois [112], a project that has received financial support through government subsidies. However, a growing and increasingly urgent demand for reducing greenhouse gas (GHG) emissions is coinciding with an expansion in the operational and in-development CCUS capacity in the United States. As a result, evidence exists that both the private and public sectors in the United State are gradually taking further advantage of low-carbon friendly policies and making investments in CCUS despite explicit penalties or taxes on carbon emissions—a trend not uncommon to the region.

As of March 2022, there are approximately 41 projects in operation or in the planning stages for implementing CCUS within the region. This count does not include earlier initiatives that have been completed, largely funded by the DOE or other federal grants, that explored the viability of CCUS in the region and set the groundwork for the CCUS landscape seen today [113]. These 41 projects range in scale from several hundred thousand tonnes of CO_2 injected per year in an individual acid-gas injection well, to a planned seven to eight million tonnes of CO_2 captured per year at a natural gas processing facility primarily for use in CO_2-EOR. A map showing the location of each project across the region is provided in Figure 10. Key galvanizing attributes of these projects were inferred from publicly available information and are outlined in Table 7. The diverse mix of small- and large-scale CCUS projects has demonstrated that the technology is highly versatile, that significant volumes of CO_2 emissions can be reduced through the technology, and the successful integration of value chain components (capture, transport, and storage) is possible. CCUS, targeting hard to decarbonize industries in the region, will remain essential to meeting net-zero goals.

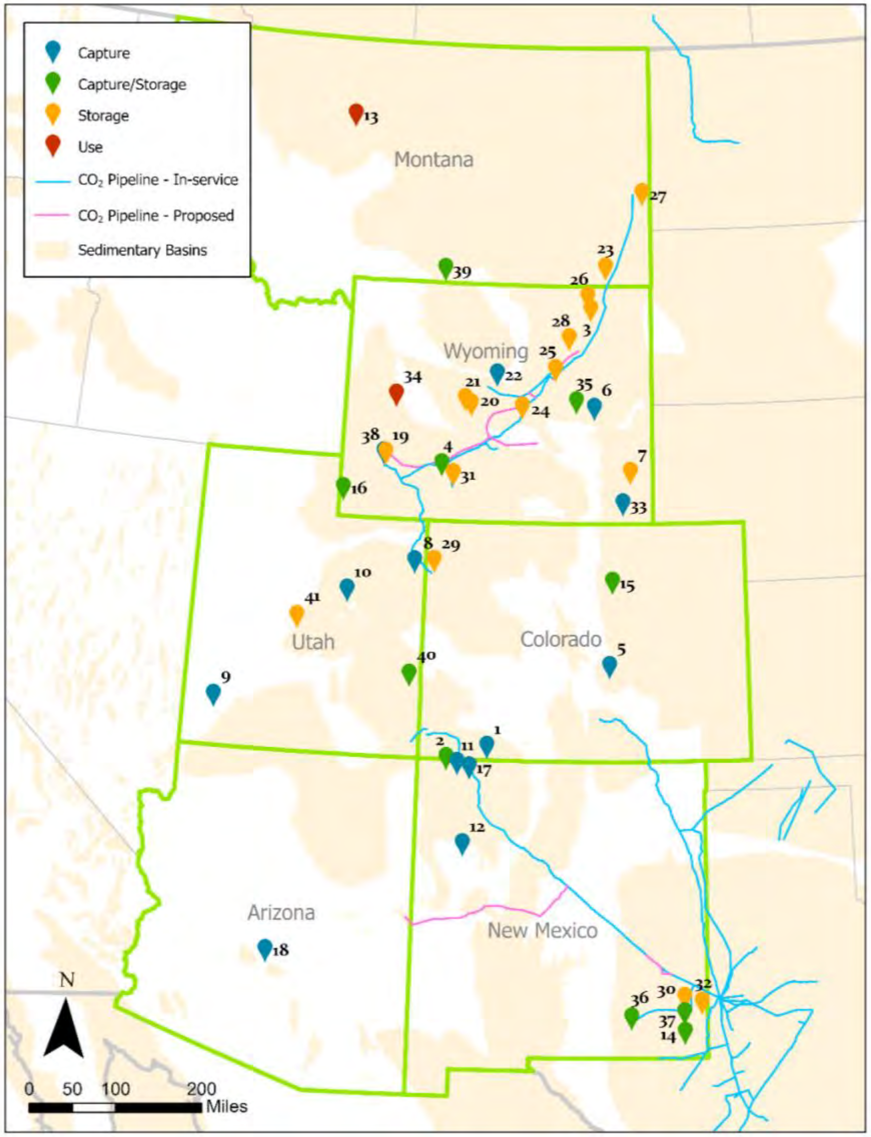


Figure 10. Map of CCUS-related projects on-going or proposed in the region

Project Name	Tax Credit	Grant Funding	Regulatory Requirement or Benefit	Pipeline Quality Requirement	Enhanced Oil Recovery	Vertically Integrated
1) Coyote Clean Power Project	■				■	
2) CarbonSAFE New Mexico: San Juan Basin	■	■			■	■
3) CarbonSAFE Wyoming: Dry Forks Station	■	■			■	■
4) Jim Bridger Plant Capture	■	■	■		■	
5) LH CO_2MENT Colorado Project	■	■				
6) Project Blue Bison (Blue Hydrogen)	■	■				
7) Eastern Wyoming Sequestration Hub	■	■				
8) Bonanza Power Plant CCS Project	■					
9) CCS at Iron Mountain Iron Mine	■		■		■	■
10) Utah Blue Ammonia	■					
11) Libertad Energy Project - Blue Hydrogen	■					
12) Escalante H_2 Power Project	■					
13) Montana Renewables - Renewable Diesel						
14) Red Hills Acid Gas	■			■		■
15) Commerce City Refinery	■		■		■	
16a) North Shore Energy - Clean H_2	■	■				
16b) Project Phoenix	■	■				
17) Big Navajo Hydrogen Pilot Project		■				
18) MechanicalTree - DAC	■	■				
19) Shute Creek Gas Processing Facility	■		■		■	
20) Big Sand Draw Oil Field CO_2-EOR					■	
21) Beaver Creek Oil Field CO_2-EOR					■	
22) Lost Cabin Gas Processing Facility	■				■	
23) Bell Creek Oil Field CO_2-EOR					■	
24) Grieve CO_2-EOR					■	
25) Salt Creek CO_2-EOR					■	
26) Gas Draw CO_2-EOR					■	
27) Cedar Creek Anticline CO_2-EOR					■	
28) Hartzog Draw CO_2-EOR					■	
29) Rangely Weber Sand Unit CO_2-EOR					■	
30) Vacuum CO_2-EOR					■	
31) Patrick Draw Monell CO_2-EOR					■	
32) Hobbs CO_2-EOR	■				■	
33) Wyoming Hydrogen Demonstration Pilot	■	■				
34) Jonah Energy - Green H_2 through Power to Gas		■				
35) Dave Johnson Power Plant capture	■				■	
36) Eddy County, NM Acid Gas Injection				■		■
37) Lea County, NM Acid Gas Injection				■		■
38) Shute Creek Acid Gas Injection				■		■
39) EBET2 001 Acid Gas Injection				■		■
40) Lisbon Unit D-716 Acid Gas Injection				■		■
41) Providence Fed 24-4 CO_2-EOR					■	■

Table 7. List of project attributes from CCUS projects in the region

The most prevalent and longstanding CCUS activity in the Intermountain West has been that of the oil and gas industry (e.g., CO_2-EOR, AGI) due to either regulatory requirements or the inherent financial incentive of improved oil recovery. Historically, these projects have not made an immense impact on carbon emissions mitigation, with CO_2-EOR typically using naturally sourced CO_2 as opposed to anthropogenic and AGI traditionally injecting very low volumes of CO_2. However, this has more recently shifted with companies like Occidental Petroleum having transitioned to only ~25 percent naturally sourced CO_2 in their Hobbs Field-Permian Basin CO_2–EOR operation, with plans to cut that to 0 percent in the near future [21]. Furthermore, Lucid Energy's MRV plan was recently approved by EPA for its Red Hills Gas Processing Plant AGI project in the Permian Basin. This sets the stage for them to inject substantially more CO_2 on site than before (from 0.02 million tonnes per year of CO_2 to 0.5 million tonnes per year of CO_2) and seek approval for the 45Q tax credit from the IRS [103]. This new development may very well pique the interest of other AGI operators in the region seeking additional tax relief.

Aside from oil and gas-related operations, nearly all the CCUS project examples within the region that plan to come online in the near-term are taking advantage of some form of public support. This is largely in the form of capital grants or operational subsidies (Table 7). Federal grant funding has played a particularly important role in this effort, with two out of seven federally funded projects receiving grants of approximately $15.2 million and $17.5 million each in the case of CarbonSAFE Phase III Wyoming and San Juan Basin projects, respectively [114, 115]. Over 20 projects in the region have or are planning access to operational support in the form of tax credits or subsidies.

Complementary to subsurface injection and storage operations, several utilization pathways exist that also offer potential for consuming captured CO_2 and converting it to viable commodities [116, 117]. Several projects in the region are leveraging these technologies and helping to create a marketplace for the derived products. Despite the benefits many of these approaches offer, CO_2 utilization is currently handicapped with limited market potential given the combination of high production costs and enormous energy requirements [118, 87]. Regardless, the technologies for these pathways are being developed, tested, and matured, and may contribute to an increasing portion of the emerging CO_2 economy in the region.

In the near-term, the continued expansion of retrofitting capture equipment to existing point sources coupled with subsurface utilization can take advantage of the enduring capital stock within the region while accelerating decarbonization efforts and at same time delaying asset retirements. New projects can build off the lessons learned and best practices that ongoing or recently completed CCUS projects have generated. As a result, these existing, early-mover projects can serve to accelerate deployment of new-source capture facilities, increase certainty in capacity for subsurface storage and utilization geologic resources, provide a bridge to low-carbon hydrogen, low carbon biofuels, and CO_2 removal technologies like DAC [87], and offer insight that could facilitate the development of supportive policies. The coalescence of these aspects could prompt a more expansive CO_2 economy in the region underpinned by broader CCUS deployment.

Several significant operational milestones across these regional projects were recently achieved:

- The U.S. Environmental Protection Agency has approved **Lucid Energy's** (Targa Resources Corporation) MRV plan relevant to 40 CFR Part 98, Subpart RR regarding its CO_2 injection and storage operations associated with its Red Hills gas processing complex in Lea County, New Mexico [103]. The MRV plan applies to both an existing UIC Class II well at the Red Hills complex and for a planned and permitted second well at the same location. Both wells are designed to inject and store up to 330,000 tonnes of CO_2 per year. Lucid is planning to seek a permit for a third well—enabling a facility-wide injection and storage capacity upwards of 560,000 tonnes of CO_2 per year. As of January 2022, the Red Hills complex captures and stores approximately 45,000 tonnes of CO_2 per year [119]. Additionally, the MRV plan supports secure geologic storage requirements for section 45Q tax credits pertinent to Lucid's existing and permitted disposal wells. The tax credits provide economic incentive to store the CO_2 that was previously vented during the company's operations as well as getting credit for the CO_2 they were already storing as part of their acid gas disposal process. Additional CO_2 capture could be possible in this system if results of techno-economic analysis currently underway point to additional adequate revenue that would justify certain changes to the existing process.

Case Study: Wyoming CarbonSAFE Integrated Commercial CCS Prefeasibility Study at Dry Fork Station, Wyoming

Wyoming CarbonSAFE is one of thirteen original CCUS project sites funded by DOE's CarbonSAFE with the goal of ensuring carbon storage complexes will be ready for integrated CCUS system deployment. The project is working to characterize the geology below the Basin Electric Power Cooperative's 483-megawatt coal-based Dry Fork Station in Gillette, Wyoming, to assess whether potential CO_2 storage zones and caprocks within the study area could accommodate safe and permanent CO_2 storage on a scale of upwards of 50+ million tonnes of CO_2 [159]. Several technical and non-technical conditions co-exist that make the Wyoming CarbonSAFE project highly amenable for CCUS:

- Proximity to EOR, saline storage, and CO_2 transport opportunities (Figure 11)
- Engagement with industry partner that is a coal-fired power plant with an existing connection to the integrated CO_2 capture and utilization test facility (Wyoming Integrated Test Center)
- Minimal transport needs, statewide CO_2 pipeline and pipeline ROW corridors exist
- Industry partner owns the needed pore space
- CCUS-favorable regulatory environment given WY Class VI primacy authorization

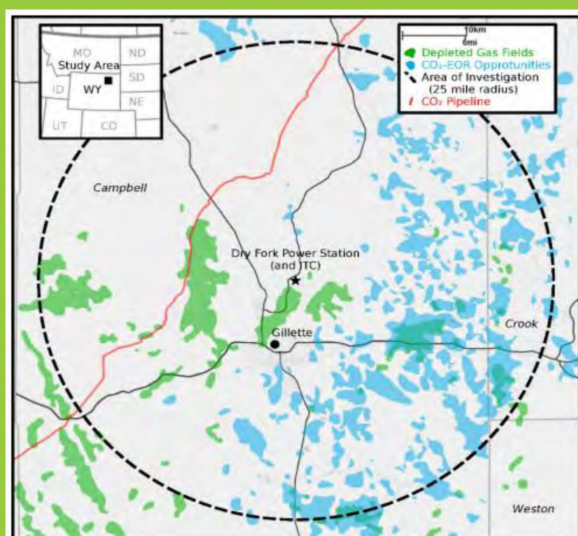


Figure 11. CO_2 storage and transportation opportunities identified within 25 miles of the Dry Forks Station

- The **Wyoming CarbonSAFE project** successfully drilled two test wells near its Dry Fork Station as part of its geologic characterization efforts. These wells enable project operators to collect data including geologic core samples, water samples, and other subsurface data, which offer valuable insight regarding the target storage reservoirs and the caprock seals. Site characterization efforts, like these, are crucial for gaining insight on the feasibility of a candidate site and an understanding for how it may perform when CO_2 injection (for long-term storage or potential CO_2-EOR if applicable) is applied. These wells also allow project investigators to design testing programs to evaluate the response of injection (using water injection tests) within storage reservoirs. Site performance will dictate monitoring strategies, surface and pore space access considerations, risk mitigation approaches, and infrastructure requirements. Similarly, site performance is critical to the permitting process for demonstrating safe operations. These are the first two wells in Wyoming that will be completed to the rigorous standards of UIC Class VI, which necessitate the use of noncorrosive construction materials and an expanded subsurface testing program designed to meet permitting requirements. Following well construction, researchers at the University of Wyoming will work to complete UIC Class VI permit applications in an effort to make the field site the first fully permitted and constructed carbon storage site in Wyoming [120].
- An initial scoping study has been completed for a first-of-a-kind carbon capture application on a cement plant located in Florence, Colorado, that is owned and operated by LaFarge Holcim. Findings from this study, completed in partnership with Electricore, Svante, Oxy Low Carbon Ventures, and Total, support planning for potential capture upwards of 2 million tonnes of CO_2 per year from the cement plant and the natural gas-fired steam generator. The captured CO_2 could be used for either dedicated storage or EOR and would be the largest-scale use of Svante adsorption-based capture technology. The retrofit application of CCUS would also enable receipt of 45Q tax credits. The study indicated an anticipated levelized operating cost for CO_2 removal at $28/tonne CO_2 and net-zero index of 0.85 [121]. The project, titled the "**LH CO_2MENT Colorado Project**," was awarded $1.5 million in federal funding for cost-shared R&D to support the initial engineering analysis [122]. Moving forward, the project anticipates initiating the development of the needed CCUS infrastructure in 2023, with hopes of operations in 2024 [123].
- The **Coyote Clean Power Project** recently filed an interconnection application with the Western Area Power Administration in February 2022. This move marks a major milestone for the project, which aims at delivering a 280-MW gas-fired NET Power plant located on a "brownfield" (previously developed) site on the Southern Ute Indian Reservation in Colorado [124, 125]. The NET Power system applies the Allam-Fetvedt Cycle, which involves combusting natural gas with pure O_2 (versus air) and uses supercritical CO_2 as a working fluid to drive a turbine (opposed to steam) [126]. This process eliminates air pollutants and produces near pipeline-quality CO_2 that can be geologically stored. The project has the potential to capture 786,000 tonnes of CO_2 per year while providing a source of clean power. Coyote Clean Power is a joint venture between 8 Rivers Capital, LLC and The Southern Ute Indian Tribe Growth Fund and was established to build, own, and operate a NET Power plant.

Case Study: San Juan Generating Station & CarbonSAFE San Juan Basin Project

San Juan CarbonSAFE phase III project, funded by DOE and led by New Mexico Tech, focuses on safe subsurface storage of CO_2 that could be captured from the coal-fired San Juan Generating Station in nearby saline reservoirs with the development of 10 UIC Class VI injection wells (Figure 12) [160]. A contingency plan would connect the CO_2 capture units to Kinder Morgan's Cortez pipeline giving access to the Permian Basin for CO_2-EOR. Favorable characteristics support the development of this project:

- Large-scale coal-fired power generation with fuel sourced within basin-bolstering economics
- Existing emissions low in nitrogen oxides, sulfur dioxide, and mercury, requiring only CO_2 mitigation
- Optionality of robust geologic storage options within basin or tying into existing, nearby infrastructure to pipe to the Permian Basin for EOR
- ~$53M annually in property taxes that support San Juan County schools (provided by keeping generating station open)
- Preservation of 1,500 direct and indirect high paying jobs, with simultaneous creation of more than 2 million hours of construction jobs for the capture facility [111]
-

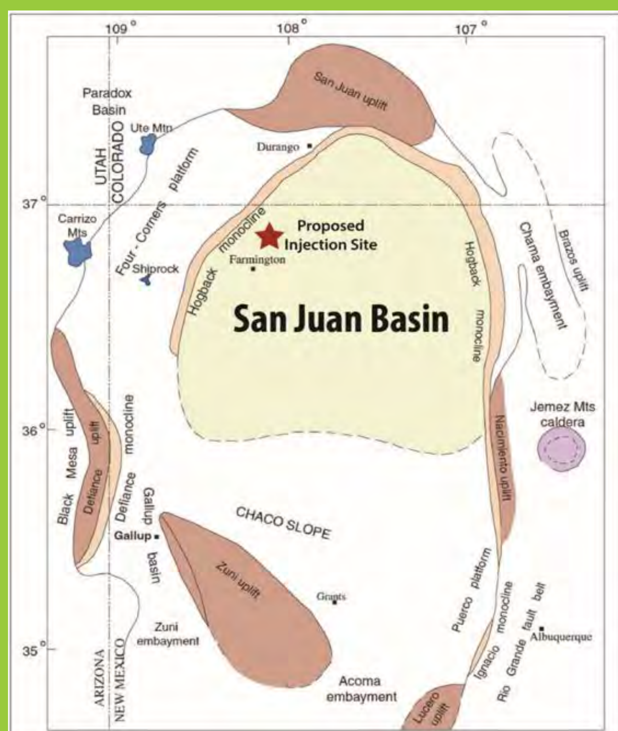


Figure 12. Location of proposed injection site within San Juan Basin [111]

- In April 2021, **Escalante H_2 Power** announced their intent to buy the recently retired Escalante coal-fired Generating Station near Prewitt, New Mexico, from Tri-State Generation and Transmission Association, Inc. Plans are in place to transform Escalante into a clean hydrogen-generating facility leveraging natural gas as a feedstock [127]. The plant is located near gas transmission lines and is situated above geology believed favorable for large-scale CO_2 storage. The project is planning to utilize 45Q tax credits and store the captured CO_2 through a well placed on the Escalante site—minimizing CO_2 transportation expenses [128].
- **Denbury** has recently accomplished several milestones supporting CCUS expansion in the Rocky Mountain region. For example, Denbury completed the 105-mile Cedar Creek

Anticline CO_2 Pipeline in November 2021. The pipeline extends from the Bell Creek oil field in southeastern Montana to the Cedar Creek Anticline in eastern Montana and southwestern North Dakota. The new 16-inch pipeline can transport approximately 7 million tonnes of CO_2 per year. It is an extension of the Greencore CO_2 Pipeline, which supplies CO_2 from various sources to oil fields in Wyoming and Montana [129]. In February 2022, Denbury commenced CO_2 injection into the Red River formation of the Cedar Creek Anticline as part of its first phase of CO_2-EOR development expansion—an effort that includes the Cedar Hills South Unit and East Lookout Butte fields. Denbury's second phase, planned for 2024, would target approximately 100 million barrels of oil via application of CO_2-EOR in the Interlake, Stony Mountain, and Red River formations of the Cedar Creek Anticline [130].

- **Enchant Energy** is designing a CCUS project for the coal-fired San Juan Generating Station in New Mexico, as part of the DOE-sponsored CarbonSAFE initiative. The planned design would be the largest capture project in the world. The effort aims to avert the plant's looming closure announced by majority owner, Public Service Company of New Mexico, to take place near year-end 2022. The generating station is an 847-MW coal-fired electricity generation station built in the 1970s and expanded in the 1980s [115]. The project plans for post-combustion retrofit capture at a rate of six to seven million metric tonnes of CO_2 per year that would be stored in the San Juan basin via EPA class VI injection wells or used for EOR in the Permian Basin. As of March 2022, project partners at the New Mexico Institute of Mining and Technology have undertaken a comprehensive site characterization effort of the storage complex in the San Juan Basin in northwest New Mexico to assess the suitability for commercial-scale CO_2 injection. Part of this work includes the receipt of a permit to drill a stratigraphic test well to facilitate collection of additional geologic and geophysical data and enable well performance testing. These data, in combination with existing well and seismic data, will be used to support the preparation of UIC Class VI permits for upwards of 10 injection wells [111].

3.1.3 Calls to Action Needed to Accelerate CCUS Deployment in the Intermountain West

To deploy CCUS at the necessary rate to align with I-WEST decarbonization targets, private sector investment must increase by orders of magnitude. The private sector is well placed to manage general project risks, such as technical or construction and operational performance risks, and this is common across many large infrastructure projects. At the same time, growth of the CCUS sector is contingent upon there being a stable policy framework in place to support its fruition. By addressing market failures, allocating risks efficiently, achieving economies of scale, and learning by doing, the costs of CCUS could be brought down significantly.

Several near and longer-term technology and/or policy needs were identified by regional stakeholders during the I-WEST CO_2 Storage and Utilization Technical Workshop to further promote CCUS, with noteworthy examples including 1) policies in place for clearly defining long-term liability following site closure and PISC, 2) 45Q applicability over longer timeframes, 3) policies for use of federal lands for CO_2 storage, 4) state-by-state determination of clarity for pore space rights, 5) seismic survey cost reductions to improve the economics for characterization and monitoring, 6) improving opportunities for landowners (assurance against any liability, compensation for pore space leasing, etc.), and 7) establishment of “early wins” consisting of small, but successful projects to build trust and reduce the risk in CCUS.

Federal and state governments have a role to play, by setting the regulatory framework to effectively allow for early deployment of shared transport and storage infrastructure. Policies will be advantaged that place a sufficiently high value on emissions reduction to incentivize investments. Strong policy support, de-risking, and cooperation between potential participants is needed for the proactive development of a CCUS industry. Here features can include the following [13, 87, 131, 132]:

- Pre-investment in independent CO_2 transport and storage capacity as strategic infrastructure to encourage and accelerate interest and investment in CCUS from other emitters
- Scoping of multiple potential storage sites for projects where suitable conditions exist, rather than a focus on a single site
- Financial incentives to optimize state taxes and other policies to drive private investment in projects
- Market development in the form of state and federal procurement programs, portfolio requirements, and mandatory power purchase or offtake agreements to build markets for low- and zero-carbon industrial products and energy, which support private investments in carbon management projects and infrastructure. In the context of CCUS, public procurement policy is most relevant for hard-to-abate sectors, from which governments procure commodities either directly or indirectly in large volume, including cement, steel, paper, and fuel
- Rules for CO_2 ownership, given that, in most cases, the party that captures CO_2 is responsible for its safe disposal. Some states have clarified by law who will be considered the legal owner of captured CO_2 and how parties can transfer ownership of CO_2
- State-established polices in which pore space, where CO_2 is injected and stored, can be owned, and specific rules for transferring the title of pore space to the party performing CO_2 injection. Several states have laws for the unitization of pore space, a process whereby a state recognizes ownership of a given unit of pore space
- State primacy – EPA permits Class VI wells required for CO_2 injection for the purposes of saline and other dedicated GCS under its UIC Program. Given concerns about the timeframe, cost, and complexity of obtaining a Class VI permit, state primacy, and sufficient staffing and resources to evaluate applications, will be important as project developers and investors consider states in which to invest for their initial projects. State primacy for EPA Class VI GCS has been obtained in the region by Wyoming to administer the Class VI UIC Program directly.
- Policy recommendations – In considering policy design to decarbonize existing power plants, policymakers could consider more than just the cost of CO_2 capture. They should

consider ownership structure, fuel type, plant efficiency, and policy mechanisms to achieve the desired outcomes. Policy recommendations should differ for stimulating adoption of carbon capture for coal plants versus gas plants, for ensuring the lowest total system costs, or for realizing the fastest decarbonization potential

- Well-planned, early engagement with stakeholders and the community to better educate them on CCUS, as well as understand and address their collective concerns with CCUS development in the region
- State or federal government assumption of long-term liability for CO_2 storage projects to reduce perceived investment risk and increase private investment on more favorable terms. Certain states have established a fund for long-term site stewardship. These commonly require a nominal fee per ton of CO_2 injected and stored to pay into the fund
- Green bonds, which are a promising investment vehicle that allows investors to attach purpose to their investments, reconnecting finance with hard assets in the economy
- Engagement by banks, which have a critical role in providing debt financing to project developers. As the number of CCUS facilities increases, and through policy de-risking, debt finance will become available for CCUS projects. Future project finance analyses should reflect the presence or absence of CO_2 storage or transportation infrastructure, the vintage and efficiency of specific plants, regional differences in power markets, rapid technology changes available for both new and retrofit plants, and applications outside of power generation

There are no insurmountable technical barriers to CCUS scale-up. The costs are within conventional boundaries of energy investments and the policy options known. The next ten years will prove decisive—to meet climate goals, policies must enter into force and public trust must be gained. Governments will have a role to play to solve the apparent contradiction between urgent investments and remote future impacts on climate change.

4 TRANSITION OUTLOOK FOR CO_2 STORAGE AND UTILIZATION

The potential impact of CCUS in supporting the Intermountain West's carbon-neutral energy and industrial economies could be significant given that approximately 66 percent of the regional CO_2 emissions from point sources are derived from fossil-based electricity generation; roughly 20 percent originate from petroleum and natural gas processing facilities, and a variety of other source types contribute to the remainder of the emissions profile. As a result, downstream storage or utilization of CO_2 must be applicable to a variety of existing and emerging industries (i.e., power generation facilities, industrial facilities, and DAC) that have their own unique and distinctive business cases. However, the opportunity for deployment of CCUS at significant scales in support of the region's low-carbon transition must be caveated with the implications (as well as constraints) expected from utilizing regionally relevant geologic resources to support the abatement of CO_2 emissions from sources within the region. As a result, several pointed questions are worthy of exploring and answering when considering a vision of a low-carbon future in the region where CCUS plays a critical role, including the following:

- Does sufficient, low-cost storage capacity exist within the region to deploy CCUS at scale?
- What percentage of the existing regional point CO_2 emissions profile could geologic resources within the region accommodate via CCUS?
- Does reserve regional storage capacity exist should the volume of CO_2 requiring storage via CCUS increase over time and become augmented with emerging sources (i.e., blue hydrogen and DAC)?
- What relative magnitude of CCUS projects (and location of promising geologic targets) would be deployed based on the volume of CO_2 needing to be managed?
- What magnitude of a CO_2 pipeline network would be needed to connect capturing point sources with viable geologic storage options?
- What are the potential impacts and tradeoffs and job/workforce implications given an emerging regional CO_2 economy where CCUS plays a significant role?

This section provides an analytical evaluation of the opportunity space for CCUS in the Intermountain West (and nearby states—featured in Appendix A: CCUS Technology Readiness Level Matrix) targeted specifically at providing insight and context to the questions postulated above. The analysis provides a quantitative outlook into both technical and economic aspects of the CCUS opportunity space in the Intermountain West given the region's inherent geologic resources and their spatial proximity to known point sources that could capture CO_2. The analytical framework applied leverages mature CCUS analysis tools in combination with regionally relevant geologic data. For instance, both NETL and LANL have developed models and other analytical resources that enable technical and economic evaluation of distinct components (transport and storage/utilization) of the CCUS value chain that can be applied here [53, 133]. These resources were utilized to provide the basis for the bulk of the analyses in the following subsections (with detailed methodology and approach outlined in Supplementary Material by Morgan et al. [134]), mostly by performing CCUS-related modeling of distinct cases through scenario analysis. Each scenario reflects an incremental change to a technical, economic, or policy-related driver relative to a baseline scenario in a way that may impact the outlook of CCUS. The potential variability in the cost of storing captured CO_2 due to changes akin to each scenario are then evaluated for the multitude of geologic reservoirs prominent in the region and nearby states. The result can shed light on the economic and cost implications of deploying CCUS in the region should advancements in supportive policies occur that directly help alleviate the rigor needed to implement storage operations. Analysis intentionally focuses on CO_2 storage in saline reservoirs and via CO_2-EOR given 1) the availability of appraised geologic datasets that enable evaluation of these storage options and 2) the potential for these operations to store large quantities of CO_2. Despite the omission from this analysis, the conclusions are not intended to suggest that technical pathways involving CO_2 as a working fluid in enhanced geothermal applications or via feedstock for conversion do not have a current or future role in the region moving forward.

Analysis Data Available Online

The full set of results data generated as part of the I-WEST Roadmap Initiative that were used to compile figures related to CO_2 transport costs, CO_2-EOR economics, and saline storage economics is available online at NETL's Energy Data eXchange website ***[156]***. These datasets are free and open to use and can provide specific insight at the state-level beyond what is shown in the I-WEST Roadmap.

EDX™ Energy Data eXchange

4.1.1 Perspective on CO_2-EOR

CO_2-EOR is an established, safe, economically viable approach for the region's decarbonization efforts (Figure 7). Additionally, the 45Q tax credit, which can be as high as $130/tonne of CO_2 for DAC with storage in EOR applications, is prompting interest from industry. It is important to note that CO_2 storage associated with CO_2-EOR described in the context of this section differs from CO_2 storage in "oil and natural gas reservoirs" discussed in Section 2.1 and 3.1.1 (e.g., Table 2), in that CO_2-EOR uses CO_2 as a working fluid in tertiary oil recovery efforts, which results in incidental CO_2 storage, while CO_2 storage in oil and natural gas reservoirs assumes CO_2 is injected strictly for storage.

In this analysis, an opportunity case for CO_2-EOR was evaluated using the DOE FECM and NETL Onshore CO_2-EOR Evaluation System (Evaluation System) [135, 136, 137]. The Evaluation System comprises a Fortran-based streamline/stream tube pattern-based reservoir simulator coupled with a cash flow model for brownfield or greenfield CO_2-EOR projects. A publicly available Energy Information Administration (EIA) dataset of onshore U.S. conventional oil fields, wloil.txt, was 1) filtered to include only oil fields within region and their bordering basins (Intermountain west EOR Region), 2) screened for oil-miscible water-after-gas (WAG) CO_2-EOR technical feasibility, and 3) assessed for CO_2 storage capacity, annual CO_2 injection rate, and incremental oil production with respect to CO_2 cost at set oil prices.

The Evaluation System was run using three modeling scenarios that reflect different market prices for oil ($50, $70, and $120 per bbl). Potential variability in the cost of storage and economic viability of regional oil fields under application of CO_2-EOR can be evaluated based on an oil price outlook. Detailed methodology and expanded results for the Intermountain West CO_2-EOR Region are included in the accompanying Supplementary Material [134]. A CO_2-EOR abatement curve in Figure 13 illustrates the cumulative storage potential for the oil fields evaluated in the region that exist with the EIA dataset. Each bar along the supply curve illustrates the first-year break-even price of CO_2 stored (Y-axis) for a single oil field. The width of the bar reflects the CO_2 storage capacity within each field— each bar is colored by its associated state. Within the six Intermountain West states, results demonstrate that roughly 1.9 gigatonnes of CO_2 storage capacity are technically feasible across 326 oil fields under application of CO_2-EOR (Figure 13).

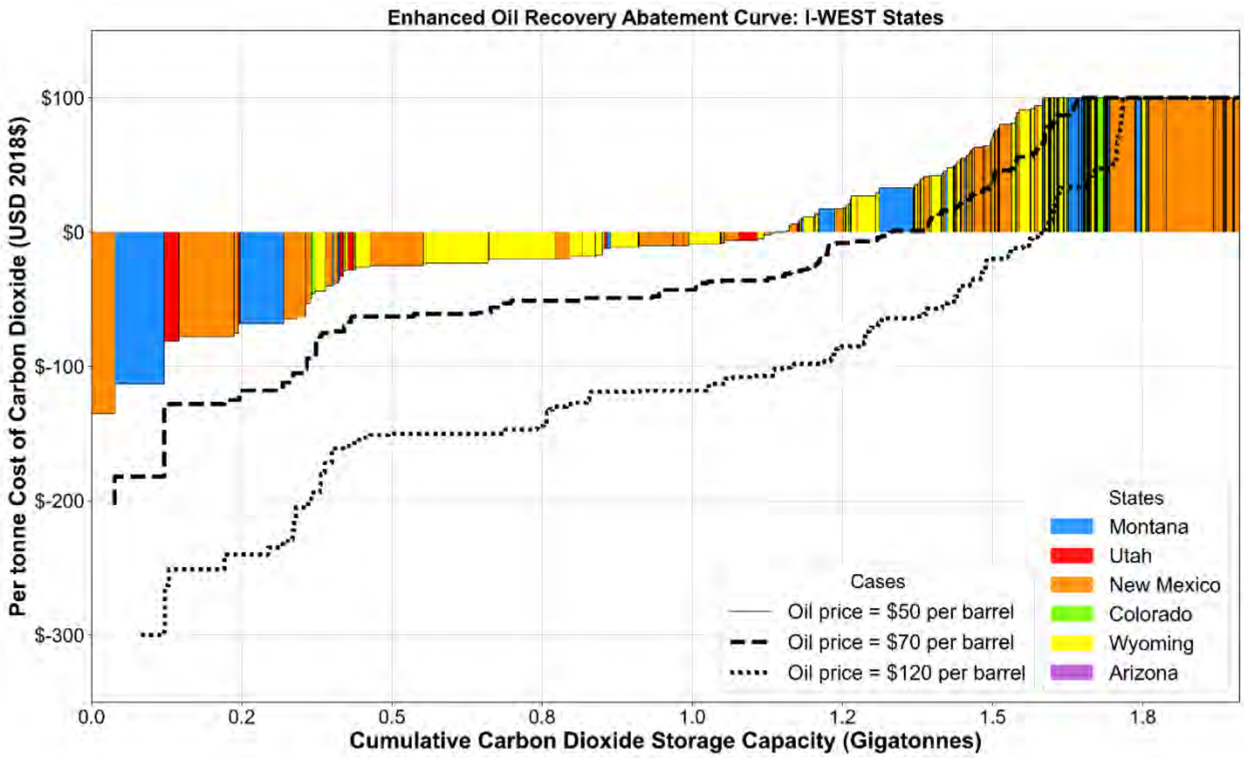


Figure 13. CCUS abatement curve applicable to CO_2-EOR in the region

In the six states, assuming a "conventional economic scenario" where EOR operators receive $70 per stock tank barrel (STB) for incremental oil produced, and pay $25 per tonne of CO_2 for CO_2 delivery (prices in real 2018$):

- 70 oil fields are economically viable, representing 1.2 gigatonnes of CO_2 storage capacity, equivalent to a total annual injection rate of 40.2 million tonnes per year, averaged for 30 operating years. These oil fields represent a total of 3.7 billion STB of incremental oil production.
- 8 oil fields are "shovel-ready" (likely to deploy CO_2-EOR in the near-term) based on oil saturations reported in the onshore U.S. conventional oil field database. These fields represent 216 million tonnes of CO_2 storage capacity, equivalent to a total annual injection rate of 7.2 million tonnes per year, averaged for 30 operating years. These oil fields represent a total of 664 million STB of incremental oil production.
- 88 percent of the "shovel-ready" CO_2 storage capacity resides in four oil fields in New Mexico: 146 million tonnes of CO_2 storage capacity from two oil fields in New Mexico's

Permian Basin province, and 46 million tonnes from two oil fields in New Mexico's San Juan Basin province. Figure 14 demonstrates that among the Intermountain West state's provinces, the shovel-ready oil fields in New Mexico's provinces are, on average, the largest with respect to acre-feet of porosity, and the most homogenous with respect to reservoir permeability; relative to other states' provinces, New Mexico's shovel-ready oil fields are geologically larger reservoirs that can be more efficiently swept by CO_2, resulting in quantitatively larger, and more efficient, CO_2 storage and incremental oil production.

The outlook for CO_2-EOR within the region improves given a higher market price for oil as shown by the additional scenario curves in Figure 13.

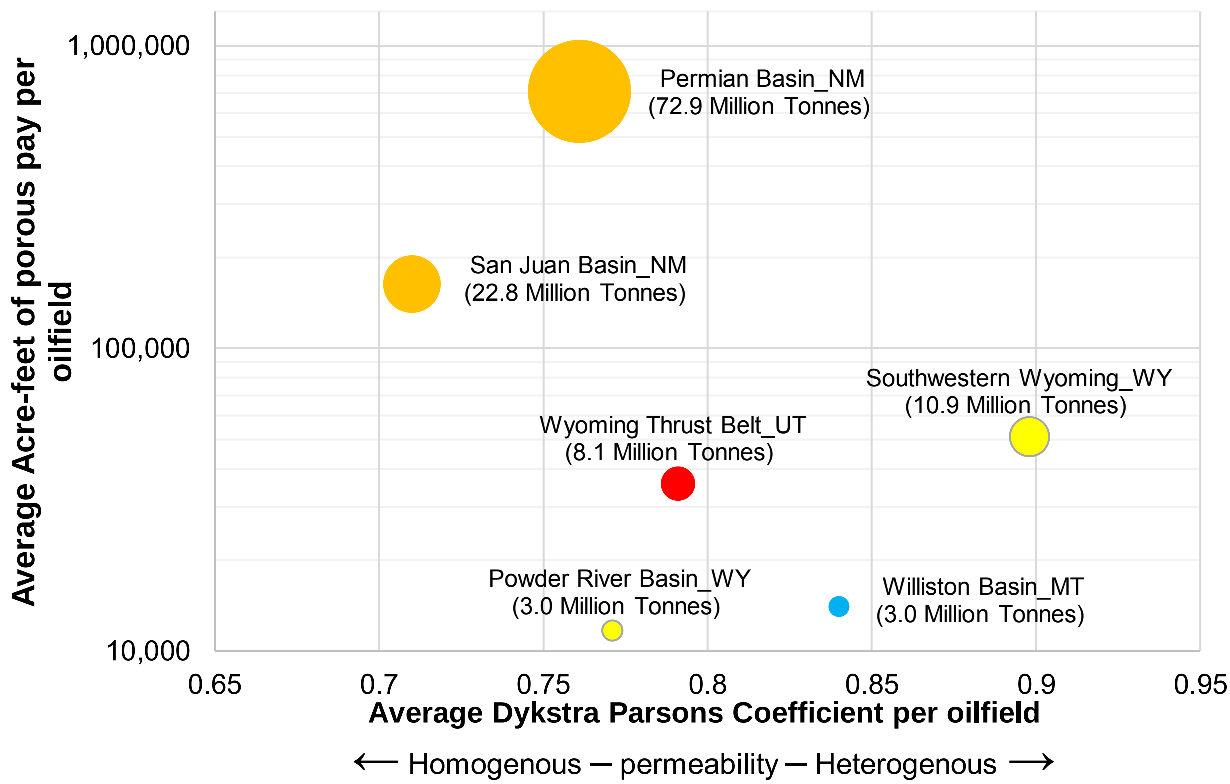


Figure 14. Average shovel-ready oil field reservoir quality for oil fields economical at \$70/STB and \$25/tonne CO_2 for transportation by province-state combination, sized by average purchased CO_2 per field

A cumulative annual injection rate of 7.2 million tonnes per year for shovel-ready CO_2-EOR projects, assuming \$70/STB and -\$25/tonne CO_2, is unlikely to support a sustained large-scale decarbonization effort given the existing point source fleet in the region but affords substantial potential as an early-mover opportunity. Economic and shovel readiness feasibility aside, 1.9 gigatonnes of technically feasible CO_2 storage is equivalent to ~64 million tonnes, still short of a volume approaching 219.5 million tonnes—a value approaching the region's 45Q-eligible point source emissions fleet using the Bipartisan Budget Act (BBA) standards. Expanding capacity estimates to include oil fields outside the six I-WEST states, i.e., the Intermountain West EOR Region greatly increases CO_2 storage and injection rate capacity, as shown in Appendix B: CO_2 Storage Resources Results – States Proximal to (e.g., Figure 22). CO_2 storage in saline-bearing formations provides an additional CO_2 storage capacity opportunity toward supporting the region's CO_2 emissions reduction timeline and targets.

4.1.2 Perspective on CO_2 Storage in Saline-Bearing Formations

The estimated CO_2 storage capacity of saline formations in the region, as well as across the United States, is believed to be extensively large and are often co-located with stationary point sources, making them an enticing long-term storage resource solution. Additionally, the 45Q tax credit value of \$85/tonne or \$180/tonne CO_2 (depending on capture technology used) for storage in saline formations, is an enticing incentive garnering interest in non-CO_2-EOR related CCUS. The opportunity case for CO_2 storage in saline formations was evaluated using the FECM/NETL CO_2 Saline Storage Cost Model (CO2_S_COM). This model is a Microsoft Excel®-based cost model that estimates the first-year break-even price (2018\$) to store a tonne of CO_2 in an onshore deep saline-bearing reservoir [138].

This model incorporates the labor, equipment, and technology costs as well as the financial instruments needed to meet regulatory requirements set out in EPA's UIC Class VI regulations. Also, the model accounts for the equipment and technology needed for compliance with Subpart RR of the Greenhouse Gas Reporting Rule [54]. The financial assumptions utilized in the model are those for a high-risk investor-owned utility. Storage break-even prices are estimated for reservoirs compiled with the model's geologic database. The storage resource volume in the CO2_S_COM's geologic database approximately aligns with median capacity estimates from DOE's 2015 Carbon Storage Atlas [8]. A total of 121 reservoirs with the CO2_S_COM geologic database fall within the states of the region. An additional 104 reservoirs in states proximal to the Intermountain West (California, Texas, Kansas, North Dakota, South Dakota, Oklahoma, Nevada, and Nebraska) were also evaluated to infer opportunities located nearby.

CO_2 storage cost and associated capacity result data at the reservoir-level was generated using the CO2_S_COM to gain insight to the scale at which the region may support CO_2 storage in known saline bearing formations—a factor largely dependent on the scale of CO_2 capture (detailed methodology described in Supplementary Material [134]). The CO2_S_COM was run using four distinct modeling scenarios. Each scenario reflects an incremental change to CO_2 storage-related policy or operational conditions from the baseline scenario. Potential variability in the cost and the economic implications of storage due to changes akin to each scenario can then be evaluated for the geologic reservoirs prominent in the region and nearby states. The four scenarios evaluated include the following:

- **Baseline Case:** Derived largely from the EPA "Pro Forma" analysis of the costs expected for implementing CO_2 storage when the initial Class VI regulations were proposed. The Pro Forma analysis provides insight into EPA's initial rational about how the regulations might be implemented. However, the assumptions in the Pro Forma analysis are often not explicitly derived from the regulations, so they are not legally required. Also, the regulations provide room for negotiation with the permit applicant. This scenario assumes fairly extensive site monitoring efforts along with 50 years of PISC.
- **Enhanced Policy Case 1:** Includes operational changes to make them more consistent with current expectations as influenced by approved monitoring strategies for CCUS projects

that have acquired UIC Class VI permit approval [139]. Financial responsibility assumptions are assumed the same as baseline.

- **Enhanced Policy Case 2:** Operational changes held the same as Enhanced Policy Case 1 except PISC is reduced to 15 years instead of 50 years. Financial responsibility is a trust fund, but payment period is 10 years rather than 3 years. The changes are believed to be more consistent with recent experience.
- **Enhanced Policy Case 3:** Assumptions are the same as Enhanced Policy Case 2 except financial responsibility instrument is self-insurance for corrective action, injection well plugging, and PISC and site closure.

The saline storage CCUS abatement curve in Figure 15 illustrates the cumulative storage potential for all 121 reservoirs analyzed in the region that exist with the CO2_S_COM database. Each bar along the supply curve illustrates the first-year break-even price of CO_2 stored (Y-axis) for a single storage project in a specific regional reservoir. The width of the bar reflects the CO_2 storage capacity that exists for each reservoir—each bar is colored by its associated Intermountain West state. An imposed capacity constraint as proposed by Teletzke et al., 2018 was utilized to account for potential pressure interference that may occur from multiple CO_2 storage projects operating in a common formation in proximity [140]. Any economic influence from a 45Q tax credit transferred to a storage operator is not considered part of the economic evaluation here.

The results from this analysis are encouraging, suggesting that the region is believed to contain ample CO_2 storage resource potential given the prevailing geology when considering saline formations only, completely in isolation from CO_2-EOR or other subsurface utilization opportunities. For instance, the Intermountain West states contain well over 130 gigatonnes of storage potential in saline reservoirs, a conservative estimate considering 1) that it includes the dynamic capacity adjustment factor proposed by Teletzke [140] and 2) water production and subsurface pressure alleviation was not considered in this analysis. Regardless, these results indicate regional CO_2 storage capacity exists on the order that could accommodate the entirety of CO_2 generated from the current fleet of regional point sources eligible for 45Q per BBA (roughly 219.5 million tonnes per year) for upwards of 600 years. Results also suggest that the region could support the storage of CO_2 from new or emerging sources in addition to the current regional source fleet, like new DAC, hydrogen, or even point sources located in states outside of the Intermountain West A substantial portion of the capacity (approximately 40 gigatonnes) is near or below $10/tonne. The enhanced policy scenarios demonstrate how the cost to store is drastically reduced relative to the baseline case when key cost drivers related to PISC duration, the volume of sites needing screening, monitoring intensity are lessened, and the type of operational financial assurance instrument applied. As an example, the regional storage capacity that is near or below $10/tonne under the Enhanced Policy Case 3 scenario is roughly 100 gigatonnes—a 60 gigatonne improvement relative to the baseline scenario. Items listed in the "Calls to Action" in Section 3.1.3 will be critical in advancing and supporting the technical and non-technical factors that can make CCUS, in general, a more economically viable low-carbon strategy.

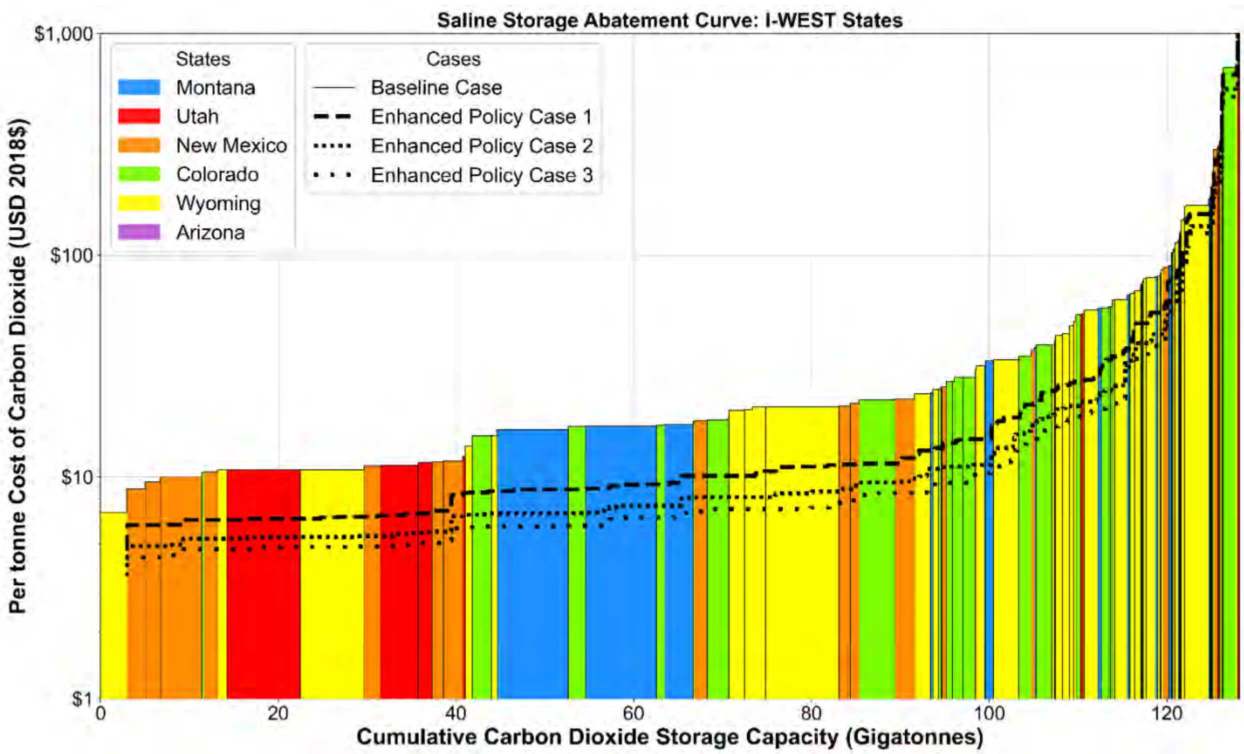


Figure 15. CCUS abatement curve applicable to saline storage resources in the region

An additional key takeaway from Figure 15 is that a rank order of storage capacity as a function of storage costs exists, which ultimately highlights how reservoirs common to each state stack up to each other. This outcome is largely influenced by the geologic attributes affiliated to each reservoir that have been shown to strongly correlate to the cost of storage. Geologic properties, such as reservoir depth, thickness, porosity, and permeability define the quality of a potential storage reservoir and can strongly impact the cost to store CO_2 [57, 56, 53, 5]. These properties vary significantly across potential storage reservoirs and have a direct impact on the capacity, injectivity, and containment properties of sites [107] as well as the resulting CO_2 plume movement and pressure evolution in the subsurface. For example, reservoir depth impacts the drilling and operational costs of both injection and monitoring wells as deeper wells generally cost more than shallower wells. Reservoir thickness and permeability affect injectivity which, in turn, may influence the number of injection wells needed to inject the annual volume of CO_2 delivered to a storage site. Reservoir thickness and porosity, along with storage efficiency [141] and areal extent, determine the reservoir's overall storage capacity, which directly dictates the volume of CO_2 a reservoir can accommodate. Storage reservoirs with larger storage capacities can typically attain unit cost savings (i.e., $/tonne basis) via economies of scale by storing larger volumes of CO_2 than smaller reservoirs. Reservoirs depicted in Figure 15 (and for the Intermountain West region and proximal states in Figure 23 in Appendix B: CO_2 Storage Resources Results – States Proximal to the Intermountain West) that typically contain higher reservoir quality attributes correlate to the lower cost options in general.

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Table 8 highlights how collective reservoir quality attributes impact first-year break-even storage costs, with higher-quality reservoirs providing lower storage costs and lower-quality reservoirs resulting in higher storage costs. Red and green coloration is used in a bar-chart format to assist visual comparison of inter-attribute values. For instance, attributes in green, when increased, tend to reduce unit costs of storage. Storage reservoirs that are thicker, more porous, and extend over a large area can reduce unit costs of storage due to 1) potentially smaller CO_2 plumes, monitoring areas, and area of review footprints and 2) economy of scale cost advantages by offer more prospective storage resource and enabling larger injection projects. Conversely, attributes in red increase unit costs when their values similarly increase. Deeper reservoirs, for instance, tend to increase the costs of drilling and completing wells. Several studies exist that outline key factors analyzing unit costs of storage [5, 53, 57, 56].

Table 8. Top five lowest cost storage reservoir by state with accompanying project and reservoir characteristics

State	CO2_S_COM Reservoir Name	Basin	1st-year breakeven CO_2 price (2018$/tonne)	Max Number Injection Projects	CO_2 Storage Capacity (Million tonnes)	Depth to top of formation (ft)	Thickness (ft)	Porosity	Horizontal permeability (mD)	Area (mi^2)
NM	Seven Rivers2	Permian	9	16	2,064	3,064	516	19.0%	22	9,342
	Morrison2	San Juan	9	13	1,677	5,511	883	13.0%	15	8,518
	Wolfcamp2	Tucumcari	10	36	4,644	3,663	1,000	12.5%	100	8,495
	Leonard2	Permian	11	12	1,548	5,808	1,000	9.0%	10	9,342
	Canyon2	Tucumcari	11	14	1,806	5,517	724	8.5%	42	8,495
WY	Frontier3	Big Horn	7	23	2,967	3,280	740	22.1%	73	4,073
	Lance1	Wind River	11	8	1,032	7,394	1,000	17.5%	16	3,927
	Tensleep4	Wyoming Thrust Belt	11	56	7,224	6,375	440	22.0%	150	6,903
	Fort Union2	Wind River	14	6	774	5,966	1,000	8.4%	8	6,324
	Entrada6	Denver	15	5	645	7,163	382	15.7%	31	5,031
CO	Morrison1	San Juan	10	2	258	5,390	846	13.0%	15	1,960
	Morrison8	Piceance	15	17	2,193	6,382	435	14.0%	30	17,368
	Arbuckle2	Las Animas Arch	17	15	1,935	5,890	260	14.0%	60	11,610
	Entrada8	San Juan	17	7	903	3,391	161	20.0%	370	1,707
	Hermosa1b	Paradox	18	1	129	8,275	1,000	7.5%	9	1,467
MT	Minnelusa2	Powder River	16	22	2,838	8,000	295	19.0%	200	3,611
	Madison Gp-Mission Canyon Fm4	Williston	16	40	5,160	6,500	545	12.0%	8	42,151
	InyanKara1	Williston	17	62	7,998	5,000	250	18.0%	100	27,105
	Red River2	Williston	17	25	3,225	9,500	360	14.0%	35	21,306
	Duperow-Lower1	Kevin Dome	24	2	258	3,800	300	12.5%	20	4,804
UT	Entrada2	Uinta	11	64	8,256	7,240	670	16.5%	100	10,798
	Tensleep5	Wyoming Thrust Belt	11	33	4,257	6,780	420	22.0%	145	4,435
	Morrison7	Uinta	12	12	1,548	6,858	804	13.0%	21	8,004
	Navajo01	San Rafael Swell	12	2	258	6,500	420	23.5%	15	1,830
	Dakota5	Uinta	54	2	258	8,640	130	12.0%	20	10,678

Table 8 depicts the top five reservoirs, based on lowest first-year break-even price (2018$), for each state in the region under the "Baseline case" scenario. Arizona is notably absent as no reservoirs of substantive capacity have been comprehensively evaluated or identified to date [8]. However, it is worth noting though that an effort is currently underway to characterize the CO_2 storage potential in the Harquahala basin, western central Arizona, as part of the Carbon Utilization and Storage Partnership of the Western United States [21]. Reservoir attributes listed in Table 8 include depth, thickness, porosity, permeability, area, and storage capacity specific to the CO2_S_COM's geologic database. Note that, in general, as reservoir depth decreases and reservoir thickness, porosity, permeability, area, and storage capacity increase, break-even costs come down. From the table, greater values of porosity are one of the more consistent reservoir properties of the top reservoirs in each state. It is also clear that New Mexico is the best of the best for high-quality, low-cost saline storage in the region, with key differentiating reservoir characteristics being consistently thicker reservoirs that are typically shallower than reservoirs in adjacent states. Nonetheless, there are extremely viable saline storage options throughout the region and proximal to emissions sources.

Integrated analysis results that include both the Intermountain West CO_2-EOR and saline storage reservoirs are presented in the abatement curve in Figure 16. Storage costs and capacity result data at the field (EOR) or reservoir (saline) are differentiated by color. Certain baseline and policy scenarios for the saline storage analysis have been married to oil price conditions relevant to CO_2-EOR to explore various integrated policy/market conditions. The integration of these data re-emphasizes the contribution of potential negative cost (i.e., oil fields where operators would be willing to pay a capture source the equivalent dollar per tonne for CO_2 given specified market conditions for oil) CO_2-EOR capacity up to one gigatonne of storage potential across several EOR fields. At capacities greater than one gigatonne, storage in saline reservoirs dominates the curve, but comes as an expense (i.e., positive per tonne cost) to a source capturing CO_2.

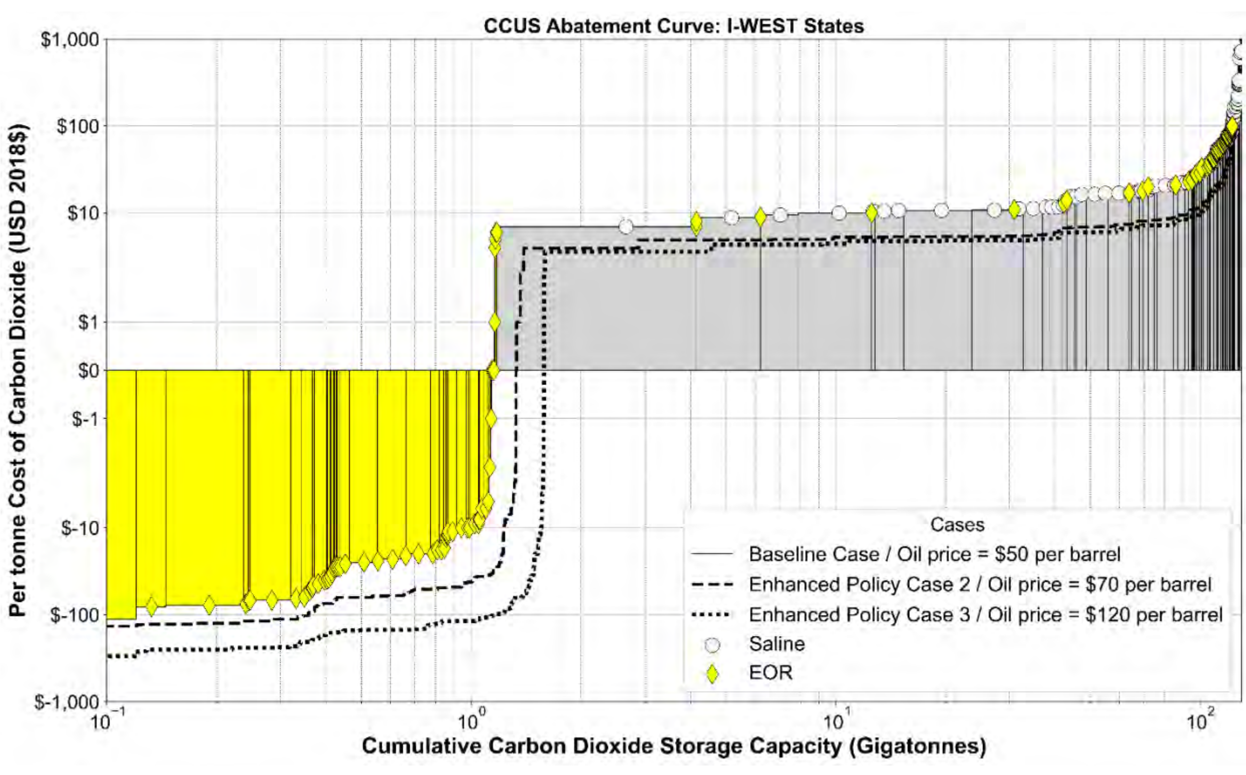

Figure 16. CCUS abatement curve applicable that includes both saline storage and CO_2-EOR in the region

Omitted from the discussion thus far has been the cost of CO_2 transportation and integrating point sources capturing CO_2 with viable geologic storage options. The proximity of sources to sinks is also a critical cost driver and logistical challenge, aspects that directly affect the transportation component of the CCUS value chain. Depending on a given source or sources spatial location in relation to subsurface storage and utilization resources, the most economic storage resources for CO_2-EOR and saline storage that have been aggregated into Figure 16 are not necessarily the first movers given other decision influencing criteria. Also needed when considering evaluating regional CCUS development, the scale of CCUS projects needing to be deployed based on the volume of CO_2 requiring management, and the volume of the CO_2 pipeline network needed to connect capturing point sources with viable geologic storage options. Both of which have cost and logistical aspects requiring consideration in the design and operations of functioning integrated CCUS systems.

4.1.3 CO_2 Transportation Network Outlook – Integrating Sources and Sinks

To determine the potential scale of CCUS-related infrastructure that would be required to transport captured CO_2 at different volumes within the region, LANL's *SimCCS* model [133, 142] was utilized to simulate pipeline buildouts. *SimCCS* aims to optimize networks of CO_2 sources, CO_2 storage and utilization options, and connecting pipelines needed to handle the total volume of CO_2 captured from all point sources included as part of a CCUS network. *SimCCS* was implemented to target a net-zero regional emission goal from all BBA 45Q-eligible point sources from the current Intermountain West fleet using CCUS—an annual CO_2 emission volume of roughly 219.5 million tonnes per year [143]. The *SimCCS* model optimizes pipeline buildouts to create integrated CCUS networks with the objective of generating CO_2 transportation routes based on the most cost-effective integrated system designs, which include capture, transport, and storage. To do so, the model accounts for CO_2 source locations, emission volumes captured per each source, source type and associated unit costs of CO_2 capture, and topography (which impacts pipeline routing considerations), as well as key geologic storage/utilization criteria (location, depth, area, thickness, porosity, permeability, and unit storage cost). The analyses in Section 4.1.1 and Section 4.1.2 offer a glimpse at geologic storage opportunity potential in saline storage formations and hydrocarbon bearing storage reservoirs (under application of CO_2-EOR) in the region. This section expands on those analyses to approximate the potential extent of pipeline network needs given regional CO_2 point sources, storage formations, and CCUS deployment at a level that could enable full decarbonization of 45Q-eligible point sources from the current Intermountain West fleet.

4.1.3.1 Regional CO_2 Point Sources and Cost Supply Curve

The U.S. EPA's Greenhouse Gas Reporting Program has identified 695-point sources in the region with cumulative CO_2 emissions of 247.4 million tonnes per year (2020 year) (Figure 17A). Out of all the sources, 204 are sufficiently large and have the potential to capture and store CO2 at volumes at or above the minimum eligibility requirements specified in the BBA for the 45Q tax credit. These 45Q-eligible sources emit a total of 219.5 million tonnes of CO_2 per year (Figure 17B). These source types largely include coal- and gas-fueled power generation sources, natural gas processing, mining, and chemical manufacturing. A CO_2 supply curve is presented in Figure 18 and is used to assume unit costs of capture for SimCCS based on source type. Figure 18 depicts 1) the unit costs to capture CO_2 emissions from regionally relevant source types and 2) displays the annual CO_2 emissions capacity contribution from each type of source. Figure 18 shows that the median cost to capture for regional CO_2 emissions is roughly $50 per tonne of CO_2.

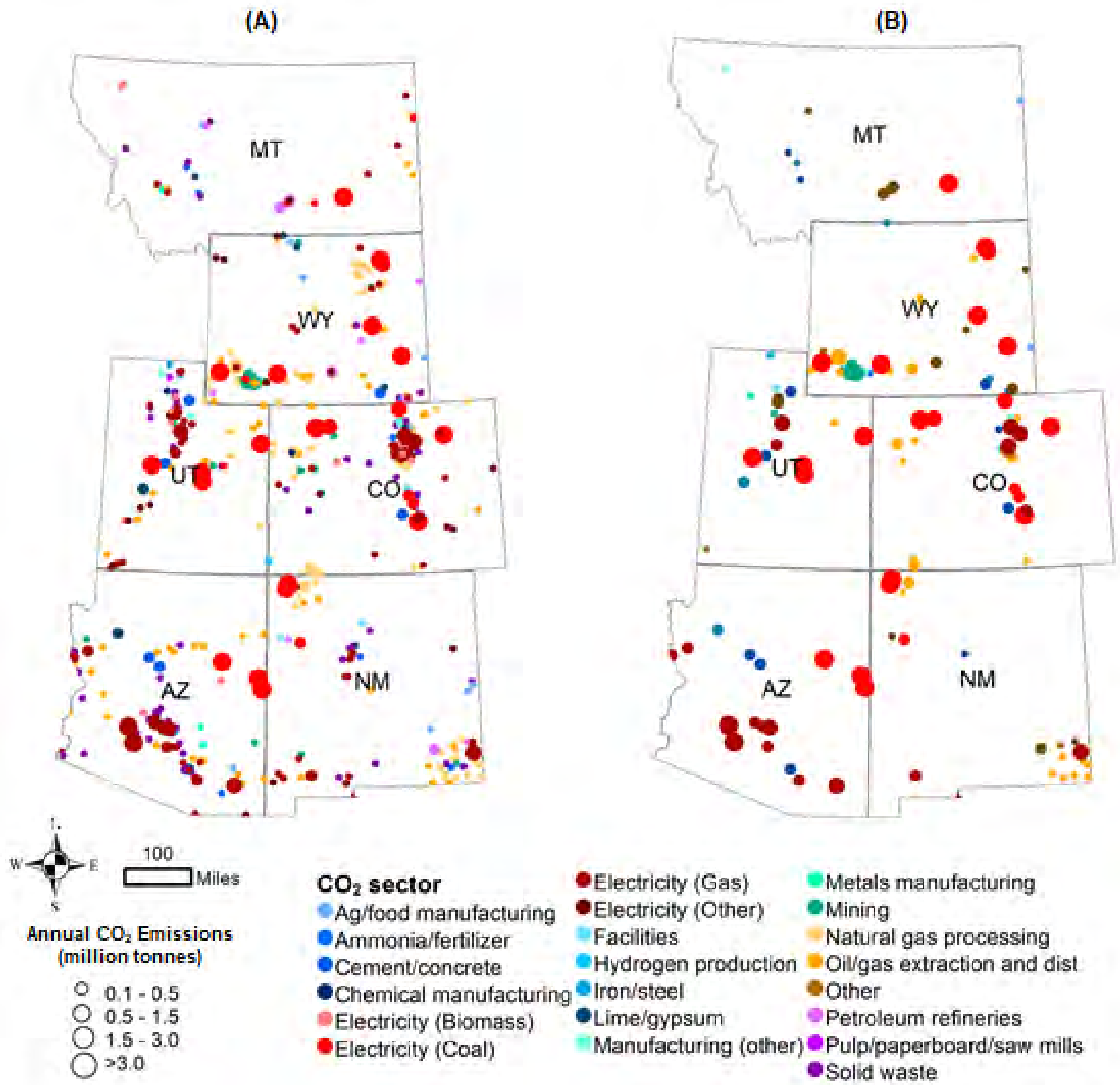

Figure 17. Maps showing all point source CO_2 emitters in the region (A) and those that meet 45Q eligibility (B)

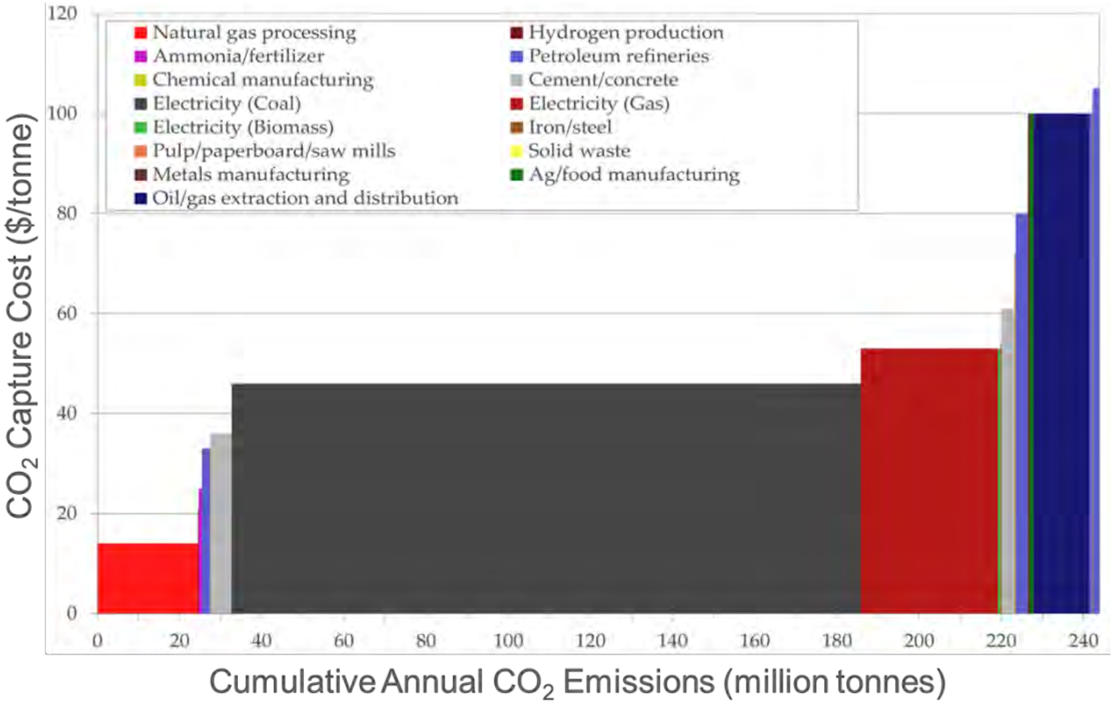

Figure 18. CO_2 supply curve for the CO_2 sources and associated costs of capture in the region

4.1.3.2 Single Phase Pipeline Network Outlook

A series of CCUS network development outlooks were generated, the first of which assume full abatement of all BBA 45Q-eligible sources in the region during a single development phase. This approach provides perspective on full-scale integration of CCUS across the region from the onset of a low-carbon transition. As a result, the decarbonization timeline here would not directly coincide with the phased approach proposed in the I-WEST Roadmap; however, the outlooks are intended to show a fully matured network of pipelines integrating CO_2 sources with storage options in order to gain a sense of the potential pipeline scale needed. Three scenarios were evaluated to assess sensitivity of results to environmental and justice (E&J) restrictions that could influence source-to-sink routing considerations—storage cost assumptions use the $70 per bbl oil case for CO_2-EOR fields per Figure 13 and the Enhanced Policy Case 1 costs for saline formations in Figure 15:

- Scenario 1 - CO_2 storage in saline formations without E&J routing restriction
- Scenario 2 - CO_2 storage in saline formations with E&J routing restriction
- Scenario 3 - CO_2 storage in saline and via CO_2-EOR

The E&J-sensitive regions are associated with disadvantaged communities and tribal land as described in DOE's Justice40 Initiative [144]. They are prominent throughout the region. A disadvantaged community is one affected by one or several social, economic, environmental, or health burdens. These burdens may include poverty, high unemployment, air and water pollution, and presence of hazardous wastes, as well as high incidence of asthma and heart disease [145]. These communities may have been or continue to be subjected to a disproportionate amount of impact from one or more environmental, social, or economic burdens compared to other community types in regard to energy or industrial development. E&J is needed to support a fair and equitable low-carbon transition and to avoid any future unfair treatment of disadvantaged communities or tribal lands. Scenario 2 and Scenario 3 exclude pipeline mapping through these communities.

Table 9 presents *SimCCS* outlooks for potential new pipelines, as well as capture and storage formation and field counts approximated under each single-phase scenario. The resulting regional CCUS pipeline infrastructure is mapped out in Figure 19. The quantity of saline storage formations and CO_2-EOR fields required to store 219.5 million tonnes of CO_2 per year varies as the specifications; therefore, pipeline routing changes with each scenario. The variation of pipeline thickness (i.e., green lines) in Figure 19 reflect pipe diameter, which ranges 4–42 inches. Pipeline diameters scale according to the volume of CO_2 throughput. Trunklines that carry CO_2 from multiple sources tend to have larger relative CO_2 throughput capacity than single source-to-sink pipelines. Analysis results suggest new pipeline infrastructure needs on the order of 4,882–6,836 miles to connect Intermountain West sources to regional storage options. This volume of new pipelines would roughly double the amount of current CO_2 pipeline infrastructure that exists in the United States [146, 147], which as of the year 2021 sits at 5,339 miles long. Note that with E&J considerations applied, pipeline networks grow in length in order to avoid surface crossings with disadvantaged communities and across tribal land. For instance, the CO_2 pipeline volume under Scenario 2 is roughly 11 percent longer than the pipeline length under Scenario 1. Many of the pipeline networks approximated under Scenario 1 and Scenario 2 are largely the same. However, the presence of an E&J-sensitive community along source-to-sink routes prompts alternative pipeline routing, resulting in longer segments of pipeline. One example exists as shown in Figure 19B where a major trunkline in northwestern New Mexico routes around the E&J communities in Scenario 2 and Scenario 3 instead of passing through them.

Table 9. Optimal solutions including pipeline length and costs under different scenarios

Economic Results	Scenario		
	Scenario 1 Saline storage without E&J restriction	Scenario 2 Saline storage with E&J restriction	Scenario 3 Saline + EOR storage with E&J restriction
Number of capture sites	204	204	204
Captured amount of CO_2 (million tonnes/year)	219.5	219.5	219.5
Resulting new pipeline installed (miles)	4,882	5,433	6,836
Weighted average unit capture cost ($/tonne CO_2)	46.87	46.87	46.87
Number of saline storage formations utilized	15	14	11
Number of CO_2-EOR fields utilized for storage	0	0	41

The inclusion of CO_2-EOR as storage options adds to the volume of pipeline needs in the region. For instance, comparing Scenario 2 and Scenario 3 shows that the total potential pipeline network length would be significantly longer, on the order of 1,400 miles, when the CO_2-EOR fields are included as storage options. This additional length is attributed to the extra pipelines needing constructed to transport CO_2 from sources to EOR fields. For example, a pipeline from Arizona to an EOR site in southern Utah (Figure 19C) is an incremental construction not shown under outlooks for Scenario 1 and Scenario 2. Similar examples exist in Montana and Colorado.

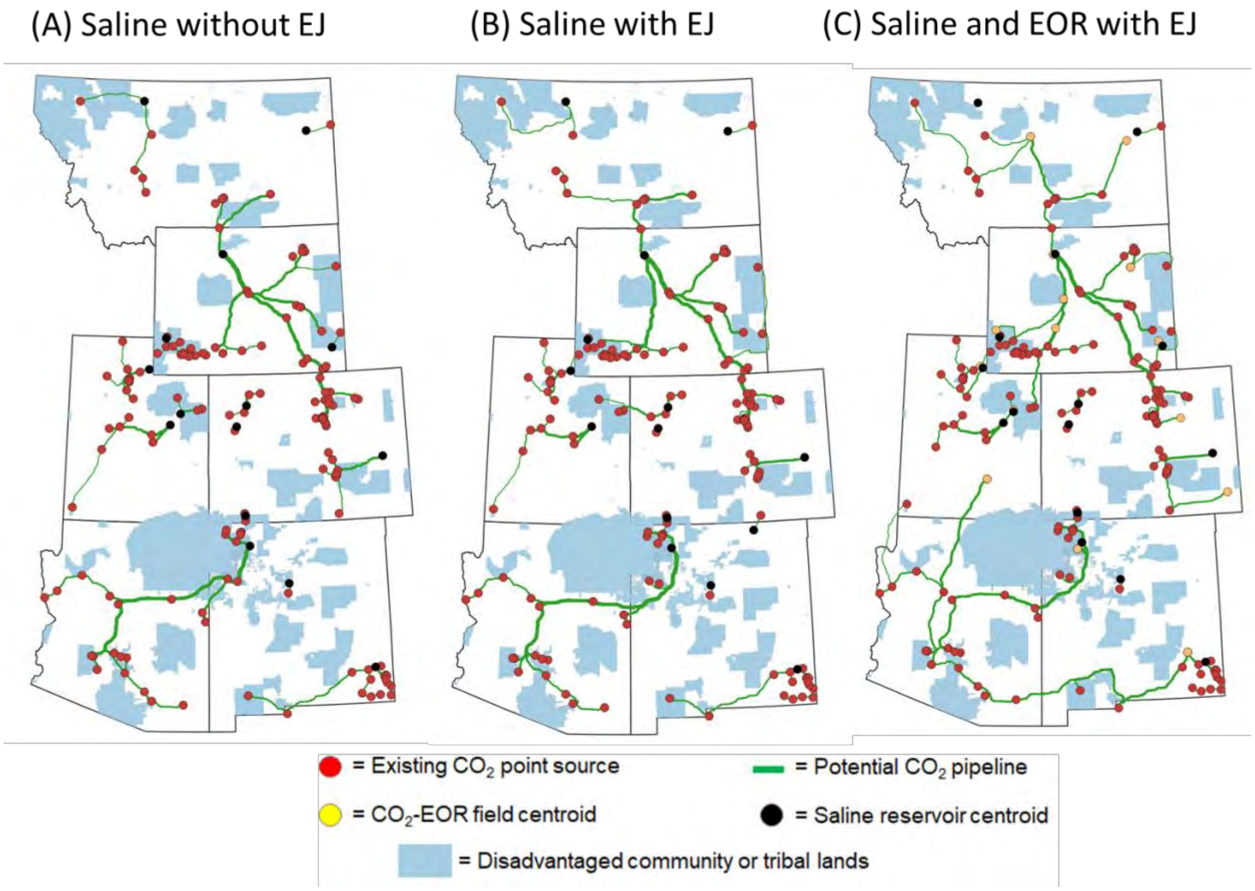

Figure 19. Pipeline network outlook connecting point sources and sinks under the three single phase scenarios

4.1.3.3 Phase-Based Pipeline Network Outlook

An additional CCUS network development outlook, rooted in a phased development approach, was generated for comparison to the single-phase scenarios. The phase-based outlook similarly assumes full abatement of all BBA 45Q-eligible sources in the region but does so over a 20-year development scale-up timeframe. The development timeframe was evaluated under four distinct phases, where each phase spans five years and reflects the incremental scale-up of CCUS deployment in the region over time. The volume of CO_2 assumed captured and stored in each phase is 50, 100, 150, and 219.5 million tonnes per year respectively. These volumes more closely coincide with the I-WEST Roadmap's phased decarbonization timeline than under the single-phase development outlooks.

For each of the four phases, a CCUS network development outlook was generated, where outlooks for each proceeding phase build off prior CCUS network development from earlier phases. Both saline formations and EOR fields were considered as potential storage reservoirs and their respective counts required to handle each phase's CO_2 volumes were noted in Table 10. The *SimCCS*-temporal model was leveraged in the phased pipeline network modeling. This aspect of *SimCCS* enables pipeline networks to build out sequentially overtime. E&J restrictions were also incorporated as part of the outlook.

The phase-based CCS infrastructure predicted by *SimCCS* is mapped out in Figure 20. Most of the captured CO_2 in the early phases (Phase 1 and Phase 2) is projected to be transported to a mix of EOR fields and saline storage reservoirs in Montana, Colorado, Utah, and New Mexico. Latter phase development (Phases 3 and Phase 4) largely involves connecting sources far from storage reservoirs, mostly in Arizona and New Mexico, with storage options. The length of new pipeline needed under each phase grows rapidly from 3,447 miles in Phase 1 to over 6,600 miles by Phase 4 (Table 10). As the phases progress, CO_2 source types with higher costs of capture become more integrated into the network, as a result the regional weighted average unit capture cost increases over time. A summary of the constitution of pipeline development for each phase is summarized in Figure 21 showing a largely unchanging composition of pipeline sizes overtime.

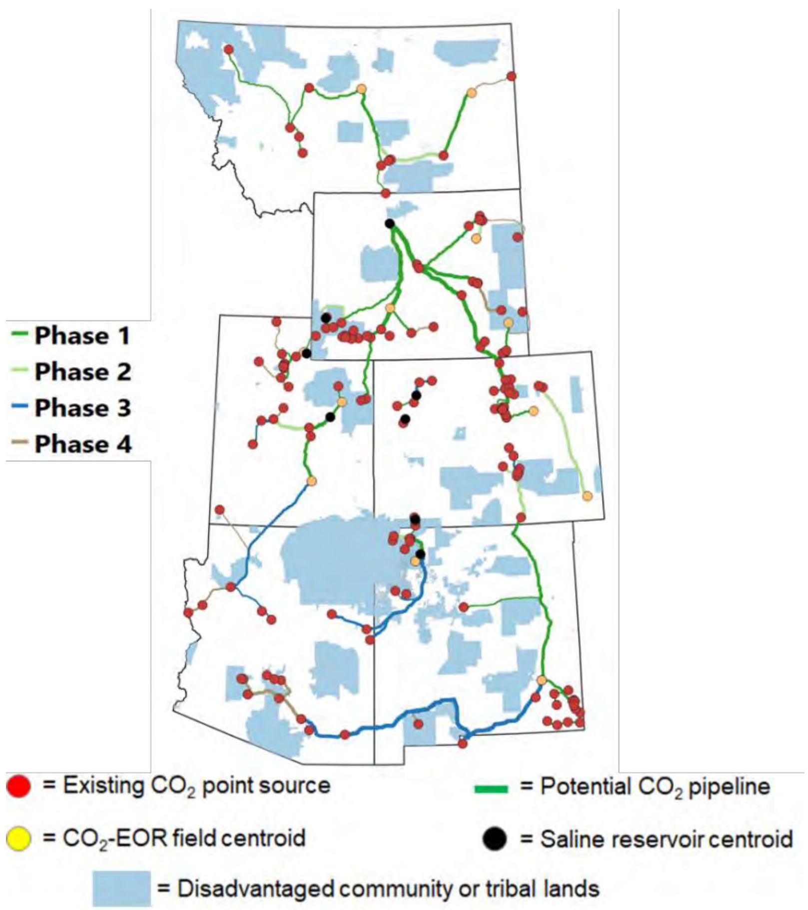

Figure 20. Phased pipeline network buildout connecting point sources and sinks

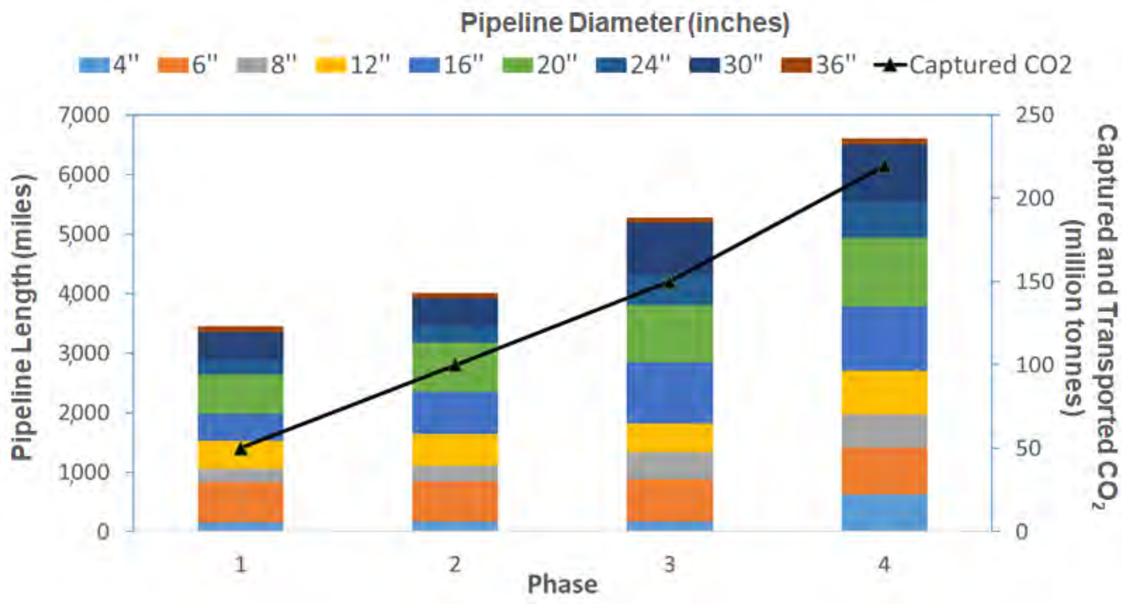

Figure 21. Pipeline length and annual CO_2 capture volume for each buildout phase

Table 10. Optimal solutions including pipeline length and costs under four different phases

Result Output	Buildout Phase			
	Phase 1	Phase 2	Phase 3	Phase 4
Number of capture sites	81	98	115	204
Captured amount of CO_2 (million tonnes/year)	50	100	150	219.5
New pipeline installed (miles)	3,447	4,010	5,278	6,601
Weighted average unit capture cost ($/tonne CO_2)	$28.37	$37.17	$40.11	$46.87
Number of saline storage formations utilized	7	8	8	8
Number of CO_2-EOR fields utilized for storage	12	15	17	25

While the results shown throughout this section demonstrate the potential scale of the pipeline infrastructure that may be needed should wide-spread CCUS deployment occur in the region, the results are not intended to suggest a single viable CCUS deployment scale-up strategy. For instance, the explicit pipeline routes and sizes approximated, as well as the specific source-to-sink connections (and locations) projected in these outlooks are driven by the data available and modeling approaches applied. Stakeholders in the region with an interest in integrating CCUS would be expected to pursue pathways and apply business models most suitable to their current and future circumstances. However, these analyses are informative for regional planning and in understanding the scale to which the region can support CCUS, what a fully integrated and BBA 45Q-eligible source decarbonized region looks like in terms of CCUS infrastructure needs, and approximately where suitable geologic storage targets exist in relation to known sources of CO_2.

It is worth noting that this modeling was based on the BBA 45Q qualifications framework. Since the original drafting of this document, the IRA has passed, loosening the capture requirement thresholds for 45Q qualification. These capture requirement reductions plus additional "sweeteners" for 45Q in IRA drive the number of 45Q-eligible projects to over 450 with a potential capture volume upwards of 225 million tonnes per year. Accommodating these increased project counts and volumes would require an expanded pipeline network, over-and-above what was modeled here.

4.1.4 Potential Impacts to Workforce and Economics

The benefits of regional CCUS deployment may reach beyond its emission reduction potential. CCUS is a technology that is believed to provide clean growth opportunities, produce and sustain jobs, and support a just and sustainable transition for communities. For instance, CCUS would expect to create new jobs and economic opportunities during the construction and the operation of new facilities, as well as in the materials supply chain. Additionally, CCUS affords the potential for high emitting industries and the jobs they require to continue as part of supporting efforts to meet emissions reduction targets. It's also believed that broader deployment of the technology can generate new opportunities that spill over to tangential areas, including the supply of infrastructure and technology, the delivery of supporting and enabling services and finance, the production of low-carbon products [14].

To enable CCUS deployment (focusing on the transportation and storage/utilization components here) upwards of the regional magnitude potential described in Sections 4.1.2 and Section 4.1.3 will require substantial growth in dedicated employment. A skilled and capable workforce will be needed for site construction and maintenance, as well as for appraising, developing, and operating sites, and implementing permitting oversight and due diligence. Jobs are expected to span a mix of skill levels as well [148]. Table 11 approximates the magnitude of the potential annual CO_2 transportation and storage economy in the region based on various scales of deployment. Revenues were approximated for transportation and storage/utilization components as the product of a notional dollar per tonne of CO_2 value and the annual volume of CO_2 managed. The CO_2 storage/utilization values at given deployment scales were compiled by integration using a weighted average approach based on the dollar per /tonne cost in Figure 16 that intersects with a capacity threshold as specified by the yearly CO_2 transported and stored targets in Table 11. The capacity thresholds were generated by multiplying the yearly CO_2 transported and stored volume listed in Table 11 to span an assumed 30 years of operation to align with total capacity values depicted on the x-axis in Figure 16. Negative CO_2-EOR prices (which equate to a CO_2 purchase price from the oil field operator) are considered positive values for this analysis in order to approximate revenue. A fixed $10 per tonne of CO_2 for transportation was assumed. In this example, results approximate roughly a $3.9 billion per year economy for a 150 million tonnes per year deployment in the region.

Table 11. Approximation of the size of a regional CO_2 transportation and storage/utilization economy

Analog Industry	Existing Industry (U.S. Total)	Average Yearly Revenue of Existing Industry 2010–2021 (USD)	50 million tonnes CO_2 per year transported and stored		150 million tonnes CO_2 per year transported and stored		219.5 million tonnes CO_2 per year transported and stored	
			2018$/ tonne assumed	Analog Revenue (% of existing industry)	2018$/ tonne assumed	Analog Revenue (% of existing industry)	2018$/ tonne assumed	Analog Revenue (% of existing industry)
CO_2 Transportation	Natural Gas Distribution	$106 Billion	$10	$500M (0.5%)	$10	$1,500M (1.5%)	$10	$2,195M (2.2%)
CO_2 Storage/ Utilization	Oil and Gas	$157 Billion	$39	$1,950M (1.2%)	$16	$2,400M (1.5%)	$14	$3,073M (2.0%)

Table 11 also provides an approximation of the yearly revenues generated by existing industries from which CCUS is somewhat analogous to enable comparison based on different scales of CCUS deployment in the region. The natural gas distribution and oil and gas industries were utilized as existing industry analogs. Revenue data from these industries (nationwide) [149, 150] was compiled to show the potential relative size of a CCUS economy in the region. Depending on the deployment scale, the CO_2 transportation and storage/utilization economy would be at or below 2 percent of the size of its industry analogs nationwide.

To estimate CCUS's potential impact on jobs, a methodology was adapted from Størset et al. (Equation 1) [151]. It relies on scaling job counts proportionally to millions of tonnes of CO_2 stored per year, while being reduced to reflect efficiencies of scale, as is injected CO_2 increases (Equation 1).

$$E_t = E_p \frac{C_t S_t}{C_p S_p} \qquad \textbf{\textit{Equation 1}}$$

Where:

- E_t = Total number of people employed from transport and storage
- E_p = Total number employed for a single isolated project
- C_t = Transport and storage cost per tonne for Intermountain West scenario (2018$)
- S_t = Stored CO_2 in Intermountain West scenario (million tonnes per year)
- C_p = Transport and storage cost per tonne for single isolated project (2018$)
- S_p = Stored CO_2 in single isolated project (million tonnes per year)

In Equation 1, a single isolated project is used as the base case. This base case assumes an injection rate of 1.4 million tonnes of CO_2 per year and 95 persons employed, which is consistent with Størset et al. (Table 12). The transport and storage cost (2018$) for this case was calculated from Størset et al.'s base case by subtracting out the capture cost, which was assumed to be 65 percent of the total integrated CCUS cost as suggested by literature [152, 57]. Cost was converted from Norwegian Krones to U.S. Dollars using the average exchange rate for 2018 [153]. CO_2 values used were those listed in Table 11. Equation 1 was then used to calculate total persons employed for each scenario. It has also been established that industries can have a ripple effect on employment; where persons may not directly be employed by a specific industry, but their existing jobs are realized by the proliferation of a tangential industry. To account for this dynamic, the petroleum industry was used as a proxy, of which it has previously been suggested that the ratio between people directly employed to the sum of directly and indirectly employed persons is about 1.8 [151]. If 150 million tonnes of CO_2 per year are stored, it is estimated that 4,411 persons would be employed directly for supporting CO_2 transportation and storage and 7,825 persons would be employed directly or indirectly via ripple effects (Table 12).

Table 12. Approximation of employment numbers both directly and indirectly related to transportation and storage scenarios in the Intermountain West

CCUS Volume in region (million tonnes/year CO_2)	Average Transport & Storage/Utilization Cost ($2018/tonne CO_2)	Direct Persons Employed (count)	Persons Employed including Ripple Effects (count)
1.4	60	95	169
50	49	2,771	4,916
150	26	4,411	7,825
219.5	24	5,958	10,570

Overall, this analysis aims to provide a glimpse of the potential economic and workforce outlook as a function of transporting and storing/utilizing CO_2 at different scales. The basis for approximating the scale of CCUS in this analysis is largely contingent on the notional per tonne value of CO_2. It is worth noting that "as-built" values from actual CCUS deployment endeavors in the region could vary substantially from the notional estimates used here for a variety of reasons. For instance, the various scenarios evaluated in Figure 16 (as well as for transportation per Figure 3) have shown that factors like the price for oil can affect the market for CO_2-EOR within the region significantly and that key operational aspects related to CO_2 storage, when implemented, can reduce the costs of implementation. Additionally, the approach strategy tends to focus on utilization of highest quality storage options with most favorable $/tonne storage values identified in the region. These storage/utilization options may not necessarily translate to the first-mover resources utilized as CCUS deployment scales in the region. As a result, the notional value per tonne of CO_2 for storage could ultimately fluctuate along with associated revenue projections. The 45Q tax credit was not directly applied in this analysis either. However, it is expected that 45Q would improve the economic bottom-line for entities capturing (and ultimately storing or utilizing) CO_2 and might be required as critical to any business case that includes CCUS.

5 CONCLUSION

The portfolio of technologies that constitute CCUS are expected to be critical for supporting the Intermountain West's low-carbon transition. CCUS is a proven and mature emissions reduction solution that can support CO_2 management from a multitude of power and industrial point-source capture facilities and DAC projects. The region is rich with a myriad of attributes amenable to storing captured CO_2 in subsurface resources. Firstly, the region contains abundant geologic resources that offer ample CO_2 storage resource potential. For instance, the region contains, on average, upwards of 1,278 gigatonnes of storage potential across the saline reservoirs, unmineable coal seams, and oil and gas reservoirs within the region [8]. This volume of storage capacity is sufficient to store all the existing regional annual point sources eligible for Section 45Q credit for carbon oxide sequestration (45Q) for over 5,700 years. However, opportunities exist to improve the certainty on storage capacity that co-exists with viable containment strata as part of identifying "shovel-ready sites" to enable rapid project deployment. Additionally, there are several projects in the region already leveraging CCUS or are proposing to integrate CCUS as part of their existing business cases—approximately 40 projects have been identified in total. The projects are highly diverse and include EOR using CO_2 separated from natural gas processing sources, and also include CO_2 capture on coal power, hydrogen, and cement facilities with long-term CO_2 storage. The enabling drivers for these projects are equally diverse, but the 45Q tax credit has shown to promote CCUS interest from industry even absent federal subsidies. And with its recent expansion under IRA, CCUS investment and development is expected to reach an all-new high. As the volume of projects implementing CCUS increases, regional needs remain related to improving the understanding of pressure changes in the subsurface as influenced by proximally located projects and ensuring future coordination under multi-project deployment conditions. Moreover, regional attributes are affording early-mover project opportunities, most notably in the form of CO_2-EOR expansion in Wyoming and Montana, as well as CO_2 separation and storage associated with oil and gas processing sources in New Mexico. Oil and natural gas processing sources are prominent across Intermountain West; aside from power generation, they remain the second largest set of regional CO_2 emitters. Industry is taking advantage of 45Q by storing the separated CO_2 from these processes in multiple cases. An opportunity exists for CCUS aligned to regional oil and natural gas processing facilities to scale up in the short term. However, despite the progress made and the opportunity facing the region, several enabling technical, workforce, and policy needs still exist and must be addressed to enable accelerated CCUS development. Workforce human capital will be needed to explore, characterize, develop, and implement permit oversight of candidate geologic storage sites. Policy frameworks must also continue to evolve to support CCUS acceleration, including aspects such as pore space rights, clarity on long-term site liability, 45Q tax credit, and landowner rights. Lastly, CCUS would benefit from continued R&D investment to improve processes and materially lower implementation costs.

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APPENDIX A: CCUS TECHNOLOGY READINESS LEVEL MATRIX

Table 13 through Table 17 provide technology readiness levels (TRLs) for multiple technology pathways relevant to the carbon capture, utilization, and storage (CCUS) value chain. The pathways and associated TRLs are based largely on the International Energy Agency's Energy Technology Perspectives Clean Technology Guide [9] and consider context from other publicly available CCUS resources [4, 154]. TRLs range 1–11 (the definition for each TRL is defined in Table 5). Important to note is that this TRL scale proposed by the International Energy Agency spanning 1–11 differs among other analyses. For instance, the Global CCS Institute [154], National Petroleum Council [4], and United States (U.S.) Department of Energy (DOE) [155] have all used a 1-to-9-point scale. Collectively, these tables can provide stakeholders with the most current, concise information on the maturity of CCUS-related technologies and pathways.

Table 13. TRL levels for power generation and fuels production CO_2 point source pathways

Technology Grouping	Subsector	Technology Area	Sub-Technology	CO_2 End Use	TRL
Generation	Power	Coal	Post-combustion/chemical absorption	CO_2 transport and storage/ utilization	9
			Post-combustion/membranes polymeric		6
			Oxy-fuel		7
			Pre-combustion/physical absorption		7
			Chemical looping combustion		5
		Natural gas or coal	Supercritical CO_2 cycles		6
		Natural gas	Post-combustion/chemical absorption		8
		Biomass	Pre-combustion/physical absorption		3
			Post-combustion/chemical absorption		8
Production	Biofuels	Biomethane	Biomass gasification and methanation		7
			Anaerobic digestion and CO_2 separation		7
		Biodiesel	Gasification and Fischer-Tropsch		4
	Hydrogen	Biomass/waste gasification			7
		Coal gasification			5
		Steam methane reforming			10
		Natural gas autothermal reforming			10
		Natural gas autothermal reforming with gas heated reformed			7
	Synthetic hydrocarbon fuels	Liquid fuels	Liquid fuels from hydrogen and CO_2		6
			Concentrating solar fuels		4
	Refining	Process heaters, hydrogen production			8
		Fluid catalytic cracker	Post-combustion		4
			Oxy-fuel		5

Table 14. TRL levels for industrial CO_2 point sources

Technology Grouping	Subsector	Technology Area	Sub-Technology	CO_2 End Use	TRL
Production	Ammonia	Fossil- or biomass-based	Chemical absorption	CO_2 transport and storage / utilization	11
			Physical absorption		5 to 9
	Methanol		Chemical absorption		9
			Physical absorption		7 to 8
	High value chemicals		Chemical absorption		7
			Physical absorption		7
	Iron and steel	Blast furnace	Hydrogen enrichment +CO_2 removal → use of works arising gases		5
			Conversion of steel works arising gases to fuel		8
			Conversion of steel works arising gases to chemicals		7
		Direct reduced iron	Chemical absorption		9
			Physical absorption		5
		Smelting reduction	Enhanced smelting reduction		7
	Aluminum	Primary smelting			2
	Cement	Cement kiln	Chemical absorption, partial capture rates (less than 20 percent)		8
			Chemical absorption (full capture rates)		7
			Calcium looping		7
			Oxy-fueling		6
			Novel physical absorption (silica or organic-based)		6
			Direct separation		6
			Membrane separation		4
		Concrete curing	CO_2 storage in inert carbonate materials		10

Table 15. TRL levels for DAC

Technology Grouping	Subsector	Technology Area	Sub-Technology	CO_2 End Use	TRL
Direct air capture	CO_2 Removal	Solid DAC		CO_2 transport and storage/ utilization	6
		Liquid DAC			6

Table 16. TRL levels for CO_2 compression and transportation

Technology Grouping	Subsector	Technology Area	Sub-Technology	CO_2 End Use	TRL
CO_2 transport	Capture and separation	Compression		CO_2 storage or utilization end-user location	10
	Onshore	Pipeline			10
		Truck			10
		Rail			9
	Offshore	Pipeline			5
		Ship transport	Port to port		7
			Port to offshore		5

Table 17. TRL levels for subsurface storage and utilization

Technology Grouping	Subsector	Technology Area	Sub-Technology	CO_2 End Use	TRL
CO_2 storage or subsurface utilization	Subsurface utilization	CO_2-enhanced oil recovery		Working fluid usage and incidental CO_2 storage	11
		Geothermal working fluid and reservoir storage			3
		Enhanced coal bed methane			3
	Storage	Saline formations		Long-term storage	9
		Depleted oil and gas reservoirs			7
		Mineral storage	Basalt and ultra-mafic rocks		3
			Other		3
		Advanced monitoring technologies			7

APPENDIX B: CO_2 STORAGE RESOURCES RESULTS – STATES PROXIMAL TO THE INTERMOUNTAIN WEST

The analytical evaluation of the opportunity space for carbon capture, utilization, and storage (CCUS) in the Intermountain West presented in Section 4 provide a quantitative outlook into both technical and economic aspects of the CCUS opportunity space in the region given the region's inherent geologic resource attributes. The analytical framework applied (that utilized the CCUS analysis tools) by the National Energy Technology Laboratory (NETL) as it relates to CO_2 storage and associated economics for saline bearing formations and CO_2-enhanced oil recovery (EOR) in the region was similarly applied to nearby states. Those states included California, Nevada, North Dakota, South Dakota, Nebraska, Texas, and Kansas. This appendix presents combined results from the Intermountain West and proximal states. This expanded analysis offers additional perspective to the geologic storage and utilization options that exist in nearby states and could be used to supplement the regional subsurface resource base. The abatement curves in Figure 22 (CO_2-EOR only),

Figure 23 (saline storage only), and Figure 24 (CO_2-EOR and saline combined) illustrate the first-year break-even price of CO_2 stored (Y-axis) as a function of cumulative storage potential for all reservoirs within the region and proximal states. Each bar is colored by its associated state, and proximal states are demarcated by a gray coloring. The full set of results data used to compile these figures is available online [156]; these datasets can also provide specific insight at the state-level beyond what is shown in the figures provided in this appendix.

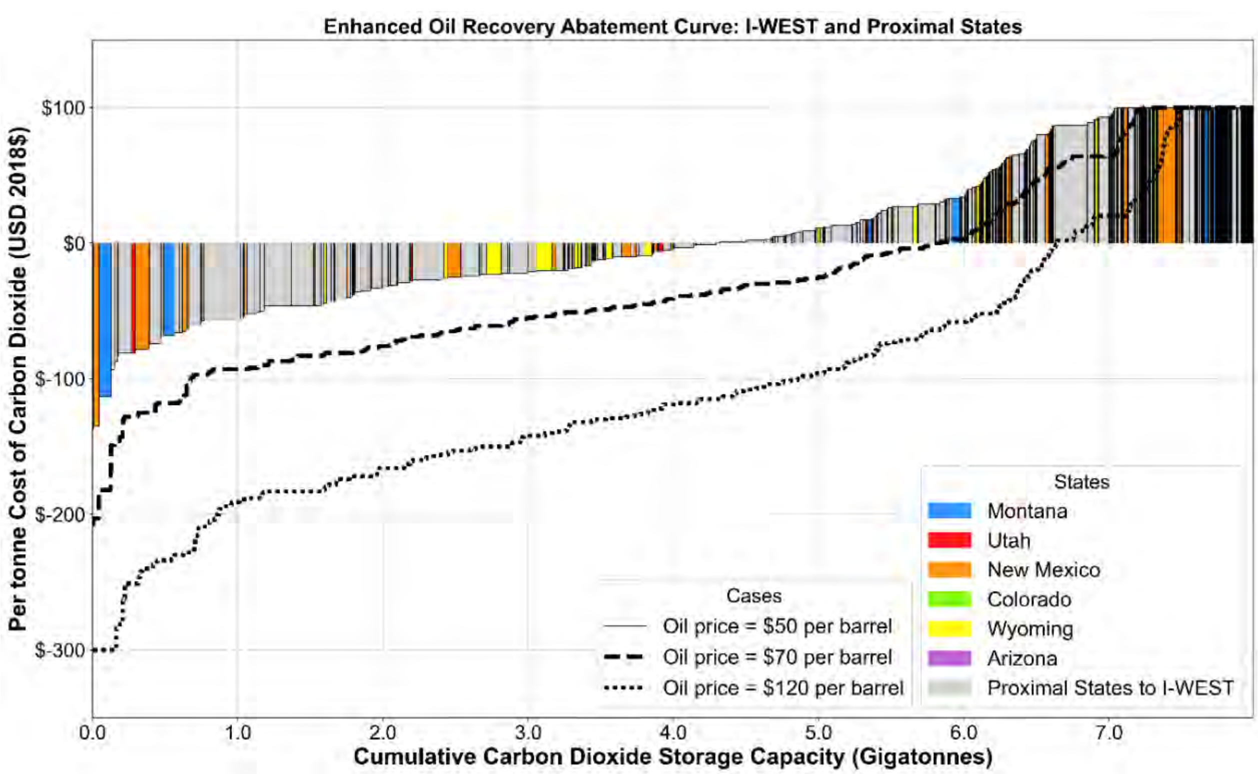


Figure 22. CCUS abatement curve applicable to CO_2-EOR in the region and proximal states

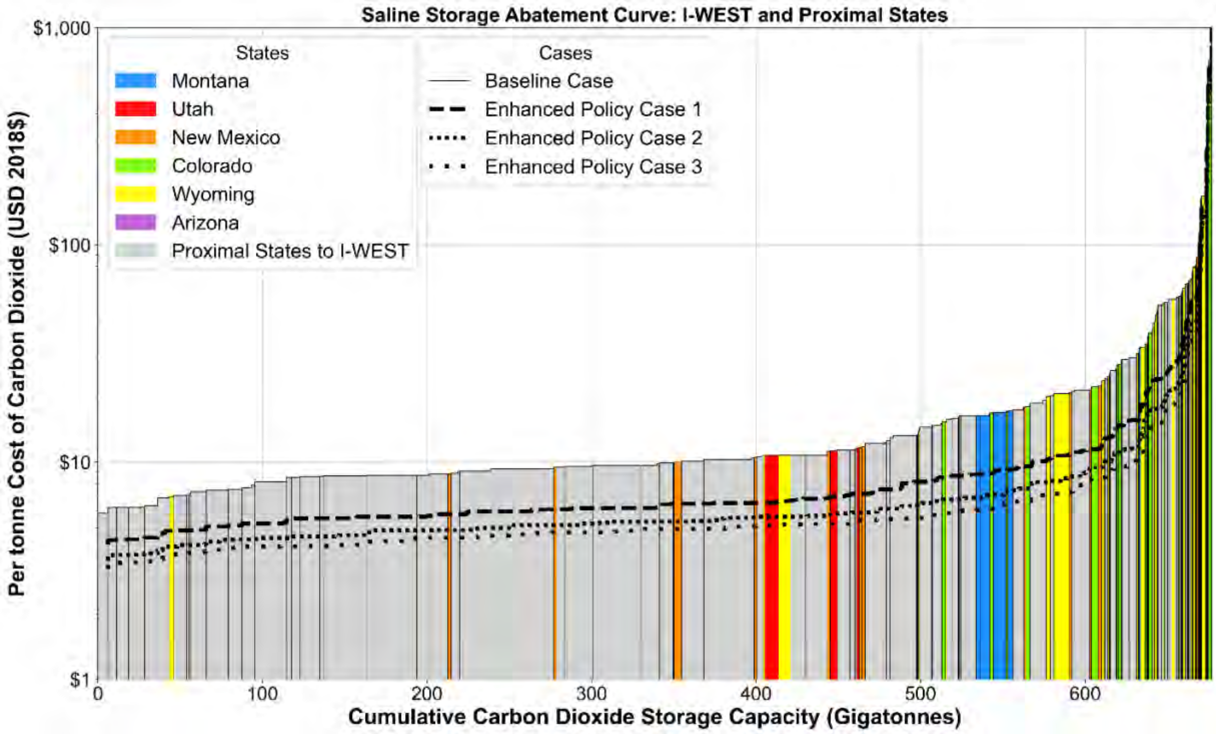


Figure 23. CCUS abatement curve applicable to saline storage resources in the region and proximal states

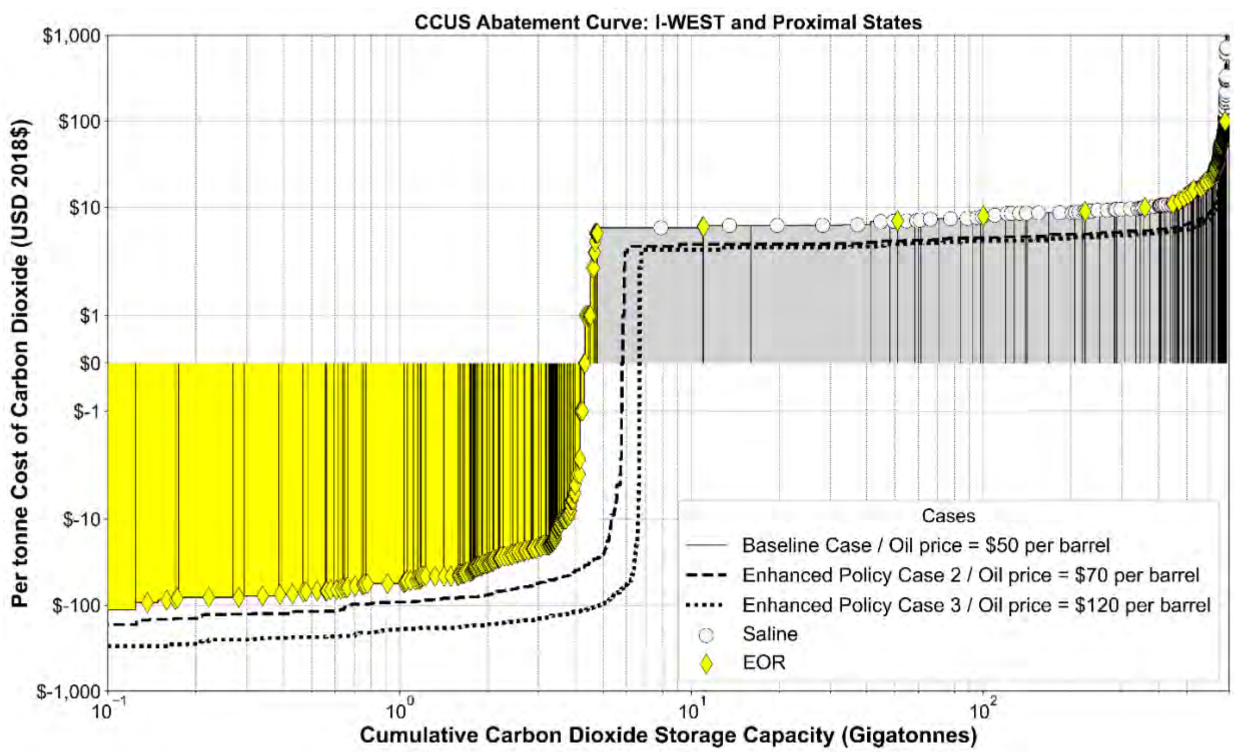
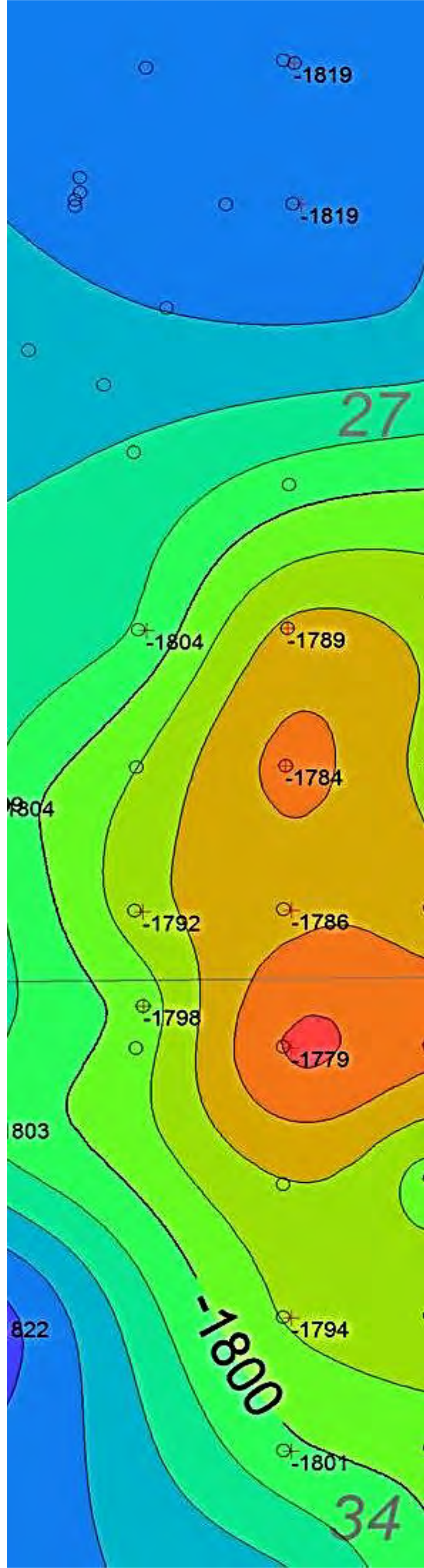


Figure 24. CCUS abatement curve that includes both saline storage and CO_2-EOR in the region and proximal states



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Phase One Final Report | Detailed Chapter

Certification for Decarbonization Technologies

VERSION 2.0

ARIZONA STATE UNIVERSITY

JUNE 2023

About this chapter

The Intermountain West Energy Sustainability & Transitions (I-WEST) initiative is funded by the U.S. Department of Energy to develop a regional technology roadmap to transition six U.S. states to a carbon-neutral energy economy. I-WEST encompasses Arizona, Colorado, Montana, New Mexico, Utah, and Wyoming. Each state is represented in this initiative by a local college, university, or national laboratory. Additional partners from beyond the region were selected for their expertise in applicable fields. In the first phase of I-WEST, the team built the foundation for a regional roadmap that models various energy transition scenarios, including the intersections between technologies, climate, energy policy, economics, and energy, environmental, and social justice. This chapter presents work led by an I-WEST partner on one or more of these focus areas. A summary of the entire I-WEST phase one effort is published online at www.iwest.org.

Authors

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Table of Contents

1 Certification: a social contract to improve quality, protect, and build trust

Consumers and industry are in a better place because of protocols, standards, and certification. We expect cars to not fall apart, outlets to not electrocute us, and food to be fit for human consumption. Every sector of the economy relies on protocols, standards, and certification to ensure materials, products, processes, and services are fit for their purpose. Protocols, standards, and certification together aim to provide standardization within industries to create equal playing fields, prevent consumer deception, ease logistical procedures, and improve quality. However, improvement in quality is not an automatic result of standardization. Quality will only be achieved when the advocated standard is a "high" standard, where the requirements are an improvement in relation to common practice. Standardization is also not always the goal of protocols, standards, and certification which may sometimes only aim to make improvements. For example, protocols, standards, and certification in agriculture are generally developed to improve customer choice on products that have an environmental and social sustainability quality such as being ‘organic’.

Protocols, standards, and certification also have a wider purpose. In addition to preventing consumer deception and improving quality they can protect the public who is external to the product, process, or service. This is particularly salient in activities that may affect the environment and public safety because of their scale, supply chain, or waste production. Extractive industries, construction, agriculture, nuclear energy would be examples. In this context, protocols, standards, and certification are necessary to protect the public. Thus, they are a social contract that activities, products, and services are delivered properly acting on behalf of both purchasers and the public.

Protocols, standards, and certification are required to build trust and to meet legal obligations, which is critical for any industry (Lazarte, 2016). Trust is the basis of transactions, progress, and business performance. Trust can be fostered from many actions and behaviors that display integrity, social responsibilities, transparency, compliance, fairness, and meeting expectations. Industries that see low levels of trust often face significant backlash from the public and investors.

Lastly, it is worth noting that the failure to certify properly can have significant consequences. Inadequate standards can lead to mispricing of assets, wasting time and resources, scams and fraud, harm to communities and the environment, and general failures of the implicated industry. In the context of decarbonizing the economy, inadequate standards can lead to the proliferation of boondoggles, loss of credibility and investments[1], environmental destruction[2], human rights violations[3] as well as the potential failure of tackling climate change (Figure 1).

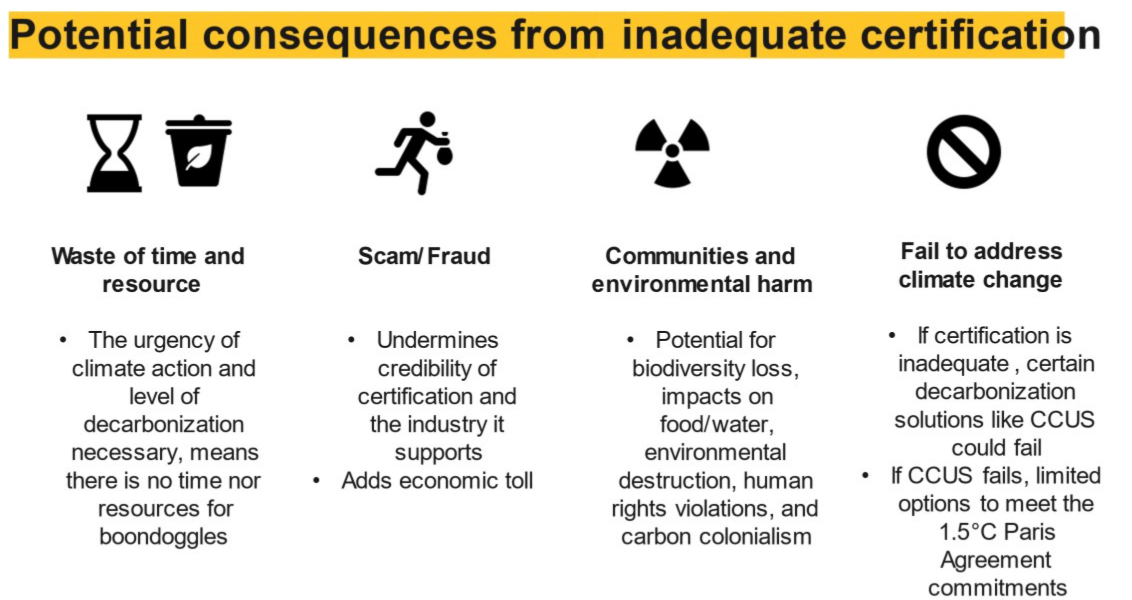

Figure 1. The potential consequences of inadequate certification of decarbonization solutions.

Not all products, services, or persons will need protocols, standards, and certification to guarantee quality. However, the least risky action would be to track and verify. Therefore, certification requires a level of verification which must be combined with remedial action for products/activities that do not meet the requirements. This is to reduce genuine mistakes, but also to minimize fraud. A product, service or activity that does not meet the requirements of certification by mistake and

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[1] Morton, A. (2022). Australia's carbon credit scheme 'largely a sham', says whistleblower who tried to rein it in. The Guardian, March 23, 2022. Available at: https://www.theguardian.com/environment/2022/mar/23/australias-carbon-credit-scheme-largely-a-sham-says-whistleblower-who-tried-to-rein-it-in

[2] Song, L. (2019). Why Carbon Credits For Forest Preservation May Be Worse Than Nothing. ProPublica, May 22, 2019. Available at: https://features.propublica.org/brazil-carbon-offsets/inconvenient-truth-carbon-credits-dont-work-deforestation-redd-acre-cambodia/

[3] Nelsen, A. (2011). Carbon credits tarnished by human rights 'disgrace'. Euractiv, October 3, 2011. Available at: https://www.euractiv.com/section/climate-environment/news/carbon-credits-tarnished-by-human-rights-disgrace/

remediates against it, is acceptable. Not remediating or not meeting the requirements by design is fraudulent behavior that is punishable through the courts if the legal standard from which “fraud” can be measured has been established. After all, the credibility of the certification and the industry it supports is dependent on it.

In the context of decarbonizing the economy, consumer and public trust in the industry and trust in protocols, standards, and certification have an important role. Technologies and activities researched by the I-WEST initiative, including Point Source Capture and Sequestration (PSCS), Direct Air Capture and Sequestration (DACS), Biomass Carbon Removal and Sequestration (BiCRS), Hydrogen, and DAC to synthetic fuels, will all need to be fit-for-purpose and will all have environmental and safety considerations due to their anticipated large scale, infrastructure, material requirements, and waste production. Consumers and the public alike will want to ensure activities and products are fit-for-purpose in an environmentally and socially sound manner.

2 Definitions, organization, and actors

Protocols and standards are tightly linked and can reflect the interests of industry. Protocols are the technical specifications on how to perform measurements, exchanges, and behaviors. Standards are documented agreements containing protocols to be used consistently to ensure a desired outcome is reached. Standards are best thought of as mechanism architectures. Standards may be product or process based. Product standards set the outcome characteristics to be attained by a product. Process standards set the criteria for how products and services are performed. Process standards can be sub-categorized as management system standards, which set the management procedures, and performance standards, which set verifiable requirements. Protocols and standards are developed by standard developing organizations (SDO) which may represent or be the industry itself. SDOs may also be composed of environmental and social non-profit organizations who may develop standards independently or in collaboration with industry.

Certification is a procedure by which a third party gives assurance that a product, process, or service is in conformity with certain standards. The certification programs are the system of rules, procedures, and management for carrying out certification, including the standards against which it is being certified. Certification bodies ought to always be independent from the industry, buyers, and standard developing organizations. If the SDO and certification body are the same, this can cause conflicts of interest and internal confusion as to the ultimate objectives. The SDO would like to see high implementation rates of its standard or have a bias against certain types of producers for ideological reasons, which can influence decisions. Certification bodies are usually accredited by an authoritative body which may be governmental or parastatal that they can carry out certification programs.

3 Certification characteristics pertinent to decarbonization technologies and activities

Certification programs can cover a range of product, process, and service characteristics. The main characteristics pertinent to decarbonization technologies and activities may be safety, performance, and origin. These would be in addition to more common measures pertinent to any industry, including quality management, occupational health and safety, and information security. Local and national regulations may also dictate additional certification requirements. Certification will involve methodological protocols as well as standards detailing the mechanism architecture to deliver specific outcomes.

3.1 Safety

Safety usually refers to the minimization of risk. Risks are often not zero but are usually minimized with the level of risk being a societal decision. When product or service risk is too high, safeguards can be implemented to reduce it to a tolerable level. For example, road fatalities in Germany decreased by 72% between 1994 and 2020 but decreased by 24% in the US over the same period, and road fatalities even increased 17% between 2010 and 2020 in the US (OECD, 2022). In the US, road fatalities per 100,000 inhabitants only slightly trailed behind heart disease and cancer in 2020 (Murphy et al., 2021). The current level of road fatalities represents a safety threshold that the American public has accepted as tolerable. The certification process may help determine that a product or service is within agreed safety levels, or that safeguards are adequately implemented.

In the context of decarbonization activities and technologies, safety may be a certifiable characteristic of carbon sequestration and its infrastructure as well as, for example, hydrogen storage. The Intermountain West's projected carbon sequestration volumes in geologic formations to reach carbon neutrality is on the order of 30 Gt over the next century. With such enormous volumes, safety in geologic sequestration cannot be compromised. Instances of safety compromise occurred with the Hutchinson, Kansas salt cavern natural gas storage incident (Bérest and Brouard, 2003). Pipes carrying CO_2 will need to be manufactured to meet higher standards than those for natural gas (National Petroleum Council, 2019), as displayed in the Satartia, Mississippi pipeline incident (Zegart, 2021). Equally large volumes of hydrogen are anticipated. Similarly, hydrogen production, transport, and storage come with significant safety risks (BARPI, 2020). The hydrogen explosion in 2019 at a filling station in Santa Clara, California, demonstrates that certification of personnel is as critical as technical protocols (Hydrogen Safety Panel, 2021). A thousand consumers lost access to hydrogen fuel and nearby businesses and homes were evacuated. Safety is an issue for both consumers and the public. Standard developing organizations are beginning to grapple with the question of safety in such activities, as will be discussed in section 4.

3.2 Performance

Performance refers to the specific level of quality or condition that is expected by consumers and the public through the lifetime of a product or service. Protocols describe the equipment and procedures to be followed. Standards use those protocols in addition to rules, guidance, and definitions to ensure there is minimal failure or replacement needed. This in turn improves efficiency and minimizes the waste of time and resources.

Performance has a time component which can be treated in various ways. For products, certification can be awarded following extensive testing over the product's lifetime. The consumer would then receive a form of guarantee of repair or replacement should the product fail to meet the certification standards. A new car's 3-year warranty is an example.

For ongoing services, certification can be conditional on the requirement of ongoing monitoring and verification. Monitoring would observe metrics that would indicate if the service were failing to meet the certification requirements. Verification from a third party, independent of the manufacturer, service provider, standard developer, or funder would ensure that the metrics are measured properly. Failures would trigger agreed remedial action. Another option is to require recertification through time. For example, LEED building certification must maintain their certification through time by going through a recertification process annually or at distinct intervals. Continuous monitoring, repeated verification, and remedial action would take care of certification for ongoing services.

In the context of decarbonization technologies and activities, performance is a certifiable characteristic of carbon sequestration. Carbon sequestration requires proof that a volume of carbon or CO_2 has been added to a reservoir and that this carbon will need to remain stored indefinitely or be remediated in the case of release. On-going monitoring of all reservoirs would observe potential changes in the reservoir content, verification from an independent party would ensure the measurements are accurate, and remedial action is triggered by the monitoring and verification. In this context, remedial action ought to be the remediation of the escaped carbon to ensure the integrity of the carbon that was paid for.

3.3 Origin

Finally, the origin of a product is another attribute that is certifiable. This is pertinent for the producer, purchaser, and the public. Certification of origin creates greater awareness, provides customers with the opportunity to choose, and signals this choice to the market. It also provides credible and verifiable documentation for auditing, fuel mix disclosures, and feed-in tariffs levelisation. For example, in France, agricultural products can be granted a certification of authenticity called "appellation d'origine contrôlée (AOC)". The AOC protects producers by only allowing products from a certain region and method to use a recognized name like "Roquefort" cheese, consumers by guaranteeing the product will meet expectations, and the public who may be attempting to eat local products and will want to know their behavior changes will be supporting a local industry.

The certification of origin can target a few narrow characteristics, such as the source of raw material. One example is the Forest Stewardship Council® which provides certification for wood produced in forests that are managed to preserve biodiversity and benefits the lives of local communities. Producers undergo certification, consumers expect their purchases to meet the certification requirements, and the public, in this case the local communities, the host country population, and the world are protected.

In the context of decarbonization solutions, certification of origin is called a Guarantee of Origin (GO) in the European Union[4] and is pertinent to renewable energy and biofuels. Certification of origin would also be pertinent to Carbon Dioxide Removal (CDR) approaches, for example, to guarantee carbon was captured from a certain source.

4 Certification requirements and status

The I-WEST initiative is assessing several decarbonization activities and technologies that require certification programs. Most pertinent activities and technologies include carbon sequestration in the form of geologic formations, mineralization, forestry, and soils. Oceanic reservoirs are not

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[4] The EU Renewable Energy Directive (2009/28/EC) refers to GOs as proof to the final consumer that a given quantity of energy was produced from renewable energy sources. Available at: http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2009:140:0016:0062:en:PDF

considered given the intermountain states are landlocked. Whether the CO_2 is sourced from the environment or at the flue-stack will change the certification needs. Products that use carbon sourced from the environment either for sequestration or utilization will also need certification. Products used as reservoirs for sequestration will need to meet different requirements than products for utilization, particularly when it comes to synthetic fuels. Finally, hydrogen is another category of activities that will require certification. Here we analyze the certification needs for each of the aforementioned technologies and activities and review the current status of certification for each.

4.1 Sequestration

Sequestration concerns itself with the durable storage of carbon in oceanic, biotic, and geologic reservoirs or in products (IPCC, 2022). Carbon may be captured from the environment through CDR approaches which include the DAC technologies considered by the I-WEST initiative. Or, it may be captured from the flue-stack of industrial processes, referred to as Point Source Capture (PSC) including fossil fuel or biomass power generating stations, and heavy industries such as cement and steel; another technology considered by I-WEST. Sequestration has a multigenerational time commitment. All storage should be deemed temporary, or provisional, until they can be proven to sequester carbon durably.

The objective of the certification of carbon sequestration is not universally agreed. In carbon markets, a popular mantra is, certification *must ensure that the resulting carbon credits are real, measurable, additional, not resulting in leakage, not double-counted, and permanent* (McDonald et al., 2021). A supplemental objective is to achieve wide-scale implementation to maximize potential impact on the climate (McDonald et al., 2021; Ruseva et al., 2020; Thamo and Pannell, 2016). The two objectives are often seen as a tradeoff between participation level and program stringency (Miltenberger et al., 2021; Ruseva et al., 2017). An alternative objective sees sequestration as a service which results in a commodity that can match an emission (past or future) and looks for a guarantee that carbon remains safely sequestered indefinitely to satisfy the polluter pays principle (Arcusa and Lackner, 2022). The principle of the polluter pays, also known as the producer's responsibility (Jenkins et al., 2021), would simply indicate that the producer of waste, or carbon in this context, has taken the necessary steps to dispose of the waste in a safe and permanent way (Khan, 2015). Satisfying the producer's responsibility also implies that future generations will not be burdened by the waste, nor the maintenance of the disposal (Wong, 2014).

4.1.1 Considerations

For carbon sequestration, the certification criteria that matter for performance, safety, and origin include evidence of carbon sequestration (including evidence of carbon source for CDR), mechanisms to support long-term sequestration, and implementation of safeguards against harm. These require methodological protocols as well as standards that detail the architecture of mechanisms to support the intended goals. The facets of certification meeting those criteria include (i) the demonstration of being fit-for-purpose, (ii) the origin of carbon, (iii) measurement protocols, (iv) monitoring plans, (v) safety protocols, (vi) mechanisms to ensure durable storage, (vii) verification mechanisms, and (viii) tracking. Each facet ought to be addressed for any reservoir, although the specific methods and equipment will vary by reservoir type and by site, with differences highlighted for PSC and CDR. We note that this analysis often does not reflect the current certification ecosystem which is explored in detail in **section 4.1.2**.

- Because CDR is a promise to clean up the environment, its **certification ought to consider the environmental impact of the entire proposed carbon removal activity**. Fit-for-purpose CDR will not damage the environment. Damage in this context may mean biodiversity loss, nutrient or water diversion, or pollution, amongst others. For example, enhanced weathering should not originate from rocks containing heavy metals; forestation should not be attempted in unsuitable locations or destroy species habitat; BiCRS (Biomass carbon removal and storage) should not source combustion materials from projects that cut forests or from projects that displace food production; the source of the wood for building material should not destroy mature forests. PSC activities do not have this requirement because PSC is part of the decarbonization phase and is an addition to existing activities that presumably have already met environmental regulations. The sequestration phase of PSC and CDR ought to consider the environment like any other industry would. Other fit-for-purpose requirements may consider whether the reservoir can spontaneously fill up or has large natural fluctuations, and whether the CDR approach can reach negative emissions in its design. Reservoirs that are not well understood ought to be researched further before being deemed fit-for-purpose. For example, the National Academy of Science, Engineering, and Medicine has begun targeting basic research with their reports (NASEM, 2022; NASEM, 2019).

- Whether the CDR activity can reach negative emissions in its design is critical. Consider the case of a system that captures carbon from the environment and sequesters it in a product that releases fossil carbon in its process. To result in a certifiable negative emission, emissions and removals from the whole CDR consequential process, from
- construction to operation to end of life, would need to be carbon negative (Brander et al., 2021). Thus, robust, standardized, consequential Life Cycle Assessments (LCA) is critical during the design phase to ensure the CDR activity will remove more carbon than it emits. However, although LCA is critical at the design phase, it is inadequate for the accounting of carbon removal due to its subjectivity and impossibility to standardize across CDR activities, as will be discussed in **section 4.1.2**. Activities that produce more emissions than they remove are not fit-for-purpose in a system that does not penalize for carbon emissions.

- Alternatively, a system could be devised to require that carbon waste be safely disposed of. The Carbon Take Back Obligation[5] would require that carbon extraction and import would need to be matched by carbon removal (Jenkins et al., 2021) which ought to be done at the source to simplify the accounting as any product or use downstream would become carbon neutral (Lackner and Wilson, 2008). A transition period could be devised at the end of which 100% of all carbon extracted and imported would be matched by sequestration. The result of such a system would ensure that activities that produce more emissions than they remove would not become the norm.

- **The certification of CDR ought to consider the carbon source** for one obvious reason. CDR is a promise to dispose of carbon that has already been emitted by influencing the atmospheric carbon stock. It is impossible to reach a state of negative emissions if carbon is captured from activities that use fossil carbon. Carbon must be sourced from the environment to be considered a negative emission. Consideration of the carbon source also matters for environmental impact. For example, the origin of the biomass ought to be considered for BiCRS to avoid incentivizing the growth of energy crops instead of food, or incentivizing deforestation or habitat destruction. This ought to be a requirement if a policy like the CTBO is not implemented.

- **Both sequestration from CDR and PSC need robust, evidence-based measurement protocols**. The protocols ought to have specific methods and equipment for each reservoir but ought to meet certain uniform criteria. Protocols must include (i) a method to delineate the boundaries of the reservoir, (ii) a method to quantify the addition of carbon to the reservoir, (iii) a method to quantify the change in reservoir content on non-instantaneous, but rapid demand, and (iv) a method to quantify the measurement uncertainty. The level of sufficient measurement certainty would need to be determined. Measurement protocols ought not to be based on LCA nor counterfactuals, to result in measurable and verifiable carbon sequestration.

[5] Carbon Take Back Obligation. https://carbontakeback.org/about/

- In addition to the measurement protocols, **sequestration from CDR and PSC both will need monitoring plans specific to the reservoir and site**. These plans ought to collect the measurements necessary to observe a change in the reservoir content. All reservoirs need ongoing monitoring for several decades, only after which monitoring frequency could be reduced if observations do not find significant changes in that time. Process times, the times when the carbon in the reservoir undergoes physical changes, ought to trigger a change in the monitoring plan. For example, in underground mineralization, the process time may be the transition from carbon in a supercritical state to carbonated mineral. The monitoring plans are one of two critical requirements to ensuring the durability of sequestration. The second requirement being remediation, as discussed in paragraph (vi).

- **Both sequestration from CDR and PSC need safety protocols and safeguards specific to the reservoir type**. Safety is a concept that can extend to safeguarding the environment from harm which was discussed above. Here safety is discussed in relation to minimizing risks to human life. For many types of reservoirs, the risks are likely minimal. For example, safety is a less applicable criteria for biotic and oceanic reservoirs where environmental harm will be more important, than for geologic reservoirs or products. Nevertheless, all reservoirs and their carbon removal operations should be considered from a safety lens. Extensive research and experience exist for sequestration in geologic formations. The EPA's Class VI wells put safety at the forefront. The National Energy Technology Laboratory's (NETL) Carbon Storage Program offers a wealth of information on best practices and risks assessments[6].

- **All sequestration will need to have mechanisms to ensure the durability of the sequestration**. Several constraints ought to be considered. First, the urgency of the climate crisis requires rapid, large-scale deployment of carbon sequestration activities (Lackner et al., 2012). Second, sequestration activities have different maturities, costs, and capacities (Bey et al., 2021; Fuss et al., 2018; McLaren, 2012). Third, to uphold the principles of the producer's responsibility and intergenerational equity, sequestration

[6] NETL Carbon Storage Program. Available at: https://netl.doe.gov/carbon-management/carbon-storage

duration ought to be commensurate to the residence time of CO_2 in the component of the climate system from which society wishes to avoid damages (Arcusa and Lackner, 2022). It is well understood that CO_2 will remain in the atmosphere for hundreds of thousands of years causing damage from temperature increases (Archer et al., 2009). The oceans will absorb some of it on millennia timescales causing ocean acidification (Hoegh-Guldberg et al., 2017). To avoid damages from ocean acidification, sequestration ought to continue for tens to hundreds of thousands of years to match the weathering and carbonation slow cycles (Archer et al., 1998; Arcusa and Lackner, 2022). Considered altogether, these constraints would suggest that all fit-for-purpose sequestration options ought to be considered, if mechanisms to guarantee durable storage are included in their deployment. These mechanisms can be implemented through the certification programs. One proposed mechanism is discussed below, and existing mechanisms are discussed in **section 4.1.2**.

The simplest solution to meet those constraints is to require the storage operators to monitor their reservoirs and to remediate any release (Arcusa and Lackner 2022). If a release is observed, the operator would simply be required to purchase new sequestration to cover the losses. These requirements ought to be included in the business plans of the storage activities before they can be allowed to be certified. Storage operators could be required to insure their activities, to protect themselves, investors, purchasers, and the public. The shift in responsibility from the buyer of sequestration to the storage operator allows for longer term management and removes the burden on the buyer who cannot control the reservoir.

After a certain number of decades of monitoring, it may be conceivable to transfer the responsibility of the storage operator to a willing party at a fee paid upfront. The willing party could be for example, a nation state or parastatal entity. The willing party would then take over the responsibility of the sequestration system until the next transfer. In some reservoirs, after a certain number of decades of monitoring without observation of release, monitoring frequency may reduce and eventually the storage operator may make the scientifically supported and accepted case that the carbon should be deemed durable. Durable storage in this context would thus be defined as a condition where the probability weighted damage (risk) of full or partial reversal during the required sequestration duration falls below a threshold of concern, e.g., the expected average loss from a reservoir must less than a few percent of the amount stored over tens of thousands of years. Both the duration and threshold of concern would need to be determined but this solution would treat all reservoirs equally and allow for the immediate deployment of sequestration without sacrificing the future. Other mechanisms have been proposed over the past decades (Moura Costa and Wilson, 2000; Whitmore and Aragones, 2022) but fail to meet the constraints outlined above, for reasons detailed in **section 4.1.2**.

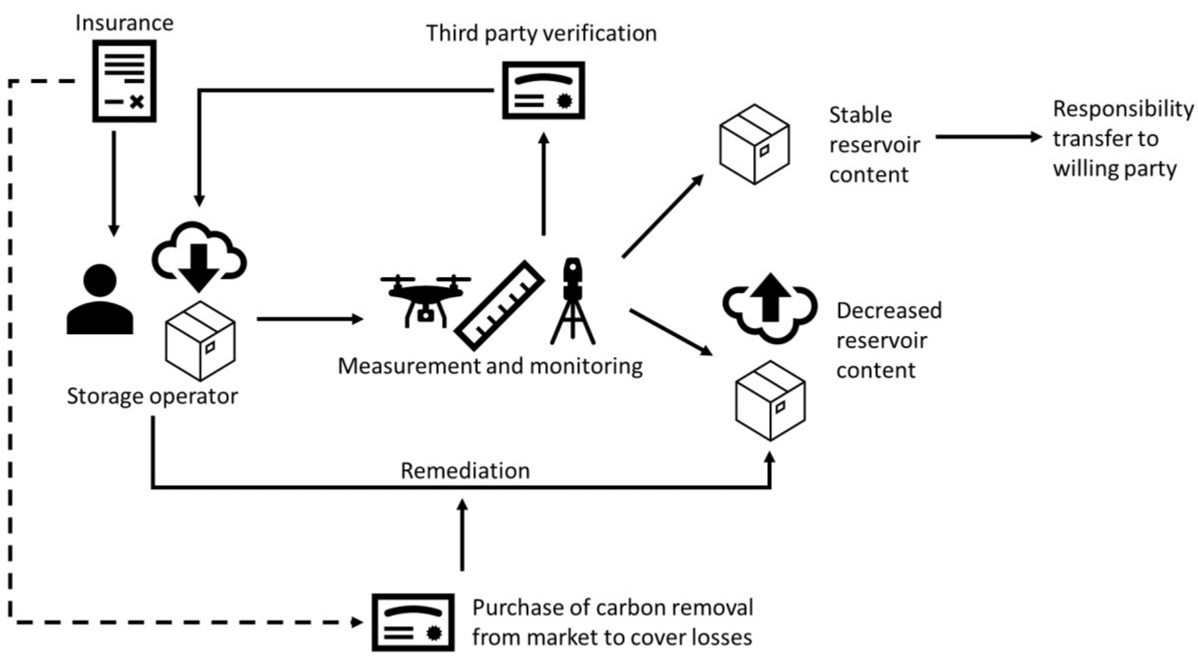

Figure 2. Simplified depiction of the certification program.

- **All measurements need reporting to a central database and verification from an independent entity**. Reporting is usually considered a minimum requirement in multilateral agreements because of the perceived low burden (Breidenich and Bodansky, 2009). Verification usually refers to independently checking the accuracy and reliability of reported information or the procedure to report that information (Breidenich and Bodansky, 2009). Strong verification regimes are important to build confidence. The verification regimes for arms control and nuclear non-proliferation are two examples of the essentiality of verification (Breidenich and Bodansky, 2009). In the context of certifying carbon sequestration, the data that standards rely on to issue certification need to be made available for verification purposes. Verification and eventual certification will need to assign a unique digital identifier to each ton of carbon removed for the purpose of tracking (**paragraph viii**). Verification cannot be performed by the entity receiving the certification nor the entity producing the standards. Verification must be independent and free from conflicts of interests, or even the appearance of conflict. This means that carbon sequestration accounting must use data that can be measured, reported, and verified. It also means that a strong and independent verification regime must be included.

- **Once carbon removal is verified by a third party and certified, it will need to be tracked.** Tracking is the traceability of each ton of carbon removed, from production to purchase including the metadata associated with the sequestration activity. The metadata will need to include incidences of release and remediation. To increase efficiency and transparency, tracking could be done through digital ledger technology and an open-source and centralized double ledger. An international system that works across jurisdictions would help ensure that double counting is eliminated.

4.1.2 State of certification

We restrict the summary of available standards and certification to voluntary or compliance, regulated or unregulated, state, U.S. national or voluntary international programs for the CDR that may be applicable to the Intermountain West region. Programs that are developed in other countries for compliance purposes are not listed, e.g., the Alberta Emission Offset Program. This summary draws from Arcusa and Sprenkle-Hyppolite (2022) who collected a more complete database of available standards and certification worldwide.

The availability of standards and certification schemes depends on the reservoir type and whether the activity is developing for compliance or voluntary purposes, and whether it is regulated or not (**Table 1**). More standards exist for agriculture for soil carbon than any other reservoir. No standard currently exists for enhanced weathering and only one for sequestration in long-lived plastics. The availability of more than one standard for a certain reservoir allows for comparisons, resulting in the conclusion that the programs do not certify the same outcome. For example, CarbonPlan reviewed 14 soil carbon certification protocols, finding wide variety in the rigor of measurements, treatment of durability, and safeguards along other metrics (Zelikova et al., 2021). Similarly, McDonald et al. (2021) reviewed 12 standards across carbon reservoirs and found significant differences in methodologies even for the same reservoirs. These studies raise questions regarding quality, and further, whether standardization across standards ought to be the logical next step to ensure integrity of the certification foundation of the carbon sequestration industry (Arcusa and Sprenkle-Hyppolite, 2022).

Performance, safety, and origin are three key criteria for the certification of carbon sequestration from CDR, with only the first two mattering for PSC except in the case of BiCRS. Above we listed that evidence of carbon sequestration (including evidence of carbon source for CDR), mechanisms to support long-term sequestration, and implementation of safeguards against harm are three facets that ought to be considered for the certification of sequestration. The facets and principles discussed in the previous **section 4.1.1** do not align well with existing research that analyzes the quality of standards and certification programs (e.g., EDF-Oko Institute[7], McDonald et al., 2021; Plastina, 2021; Zelikova et al., 2021). The reason being that the underlying objectives and criteria of certification are perceived differently. Our criteria focus on the demonstration of measurability at the stage of standard development; the existing research focuses on working within the system. However, some commonalities can be drawn in that transparency through reporting and independent verification are important.

Two aspects that deserve special attention in our analysis of existing standards and certification programs are measurements and durability. On the former, current standards for nature- or technology-based reservoirs generally estimate removals from Life Cycle Analysis (LCA) compared to a counterfactual baseline. Although efforts have been made to standardize LCAs (e.g., NETL's LCA Toolkit[8], the International CCU Assessment Harmonization Group[9], ISO 14040:2006[10]), LCA remains a subjective analysis when applied to accounting (Ekvall, 2020). Similarly subjective is setting a counterfactual baseline (Lohmann, 2009). Meanwhile, the counterfactual baseline represents an alternative world where the sequestration project is absent, or business as usual practices continue. Counterfactuals are by nature unverifiable and unmeasurable (Lohmann, 2005), which do not lend to robust carbon sequestration accounting. As detailed in the previous section, measurement protocols for carbon sequestration ought to be designed to be rigorous by including (i) a method to delineate the boundaries of the reservoir, (ii) a method to quantify the addition of carbon to the reservoir, (iii) a method to quantify the reservoir content on (non-instantaneous, but rapid) demand, and (iv) a method to quantify the measurement uncertainty to result in measurable and verifiable carbon removal. As discussed in **paragraph (i) in section 4.1.1**, LCAs remain important at the stage of activity design, but not for accounting.

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[7] Carbon Credit Quality Initiative. Available at: https://www.edf.org/climate/carbon-credit-quality-initiative
[8] National Energy Technology Laboratory Life Cycle Analysis Toolkit. Available at: https://netl.doe.gov/LCA/CO2U
[9] Global CO2 initiative. International CCU Assessment Harmonization Group. Available at: https://www.globalco2initiative.org/evaluation/
[10] ISO. Environmental management — Life cycle assessment — Principles and framework. Available at: https://www.iso.org/standard/37456.html

On the topic of storage durability, what is meant by durable storage has been debated for decades without satisfying resolution (Dornburg and Marland, 2008; Dynarski et al., 2020; Fearnside, 2002; Fearnside et al., 2000; Herzog et al., 2003; Kirschbaum, 2006; Ruseva et al., 2020; Thamo and Pannell, 2016). Durable storage has been left undefined by the Intergovernmental Panel on Climate Change (2022). The term also varies greatly across existing standards (Arcusa and Sprenkle-Hyppolite, 2022). The reasons for why durable storage matters also remain inadequately articulated and inadequately treated in certification (Arcusa and Lackner, 2022). **Section 4.1.1** argued that durable storage is the point at which the producer of carbon emissions can be lifted the responsibility for their carbon waste in a manner that does not sacrifice future generations. This implies that all carbon reservoirs must meet this aim, and certification ought to be the mechanism to implement this objective. Current practices use long project durations varying between 10 and 100 years, discounting, buffers, or legal approaches (McDonald et al., 2021), but none of these approaches internalize the potential failure of sequestration to be permanent (Arcusa and Lackner, 2022). The few that attempt to internalize impermanence are the Kyoto Protocol's Joint Implementation[11] and Clean Development Mechanism[12] which require perpetual liability on the part of the buyer to remediate for any carbon release.

The carbon sequestration industry moves odorless, colorless gas into reservoirs. For this reason, and the additional safety concerns, the public's trust is primordial. Certification (measurement, tracing, and verification) is key to providing support for the industry. Therefore, ensuring that certification is robust, measurable, and verifiable is a critical endeavor for carbon sequestration.

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[11] Joint Implementation Guidelines. Available at: http://unfccc.int/resource/docs/2005/cmp1/eng/08a02.pdf#page=2

[12] Clean Development Mechanism modalities and procedures. Available at: https://cdm.unfccc.int/Reference/COPMOP/08a01_abbr.pdf

Table 1. Available certification schemes for carbon reservoirs pertinent to I-WEST

PSC and sequestration in geologic formations	DAC and sequestration in geologic formations	Soil carbon – biochar burial or in products	Soil carbon – agriculture for soil carbon	Enhanced weathering	Afforestation, reforestation, or forest restoration	Long-lived products – wooden building material	Long-lived products – plastics	Long lived products – carbonated building materials
Environmental Protection Agency[13] (national, compliance, regulated)	California Air Resource Board Low Carbon Fuel Standard[14] (state, compliance, regulated)	Puro.earth[15] (international, voluntary, unregulated)	Puro.earth[16] (international, voluntary, unregulated)	Under development – Open Natural Carbon Removal Accounting[17] (international, voluntary, unregulated)	PlanVivo[18] (international, voluntary, unregulated)	Puro.earth[19] (international, voluntary, unregulated)	Verra[20] (international, voluntary, unregulated)	Puro.earth[21] (international, voluntary, unregulated)
American Carbon Registry[22] (national, voluntary, regulation approved)	Verra CCS+ [23] (international, voluntary, unregulated)	Ithaka Institute[24] (international, voluntary, unregulated)	Food and Agriculture Organization of the United Nations[25] (international, voluntary, unregulated)	Verra CCS+ [26] (international, voluntary, unregulated)	Regional Greenhouse Gas Initiative[27] (regional, compliance, regulated)	Under development – Open Natural Carbon Removal Accounting[28] (international, voluntary, unregulated)		Verra[29] (international, voluntary, unregulated)
Verra CCS+ [30] (international, voluntary, unregulated)	International Organization for Standardization[31] (international, voluntary, unregulated)	Verra[32] (international, voluntary, unregulated)	BCarbon[33] (international, voluntary, unregulated)		Climate Action Reserve[34] (national, voluntary, unregulated)			Gold Standard[35] (international, voluntary, unregulated)
DNV [36] (international, voluntary, unregulated)		Climate Action Reserve[37] (national, voluntary, unregulated)	Nori[38] (international, voluntary, unregulated)		American Carbon Registry[39] (national, voluntary, unregulated)			
			Regen Network[40] (national, voluntary, unregulated)		California Air Resource Board Cap-and-trade[41] (state, compliance, regulated) *			
			American Carbon Registry[42] (national, voluntary, unregulated)					
			Climate Action Reserve[43] (national, voluntary, unregulated)					
			Verra[44] (international, voluntary, unregulated)					
			PlanVivo[45] (international, voluntary, unregulated)					
			Gold Standard[46] (international, voluntary, unregulated)					

[13] Environmental Protection Agency (EPA) Class VI wells. https://www.epa.gov/uic/class-vi-wells-used-geologic-sequestration-carbon-dioxide
[14] California Air Resource Board (CARB) Low Carbon Fuel Standard. https://ww2.arb.ca.gov/sites/default/files/2020-03/CCS_Protocol_Under_LCFS_8-13-18_ada.pdf]
[15] Puro.Earth [https://static.puro.earth/live/uploads/tinymce/Puro_Documents/Puro-Rules-CO2-removal-marketplace_v2.0_final.pdf]
[16] Puro.Earth https://puro.earth/articles/introducing-corc20-and-the-soil-amendment-methodology-647]
[17] Open Natural Carbon Removal Accounting (ONCRA). https://climatecleanup.org/accounting/
[18] PlanVivo [https://www.planvivo.org/Handlers/Download.ashx?IDMF=5b30948b-26f3-4d7a-803f-0fcce593acbd]
[19] Ibid 16.
[20] Verra. [https://verra.org/methodology/vm0040-methodology-for-greenhouse-gas-capture-utilization-plastic-materials/]
[21] Ibid 16.
[22] American Carbon Registry (ACR). [https://americancarbonregistry.org/carbon-accounting/standards-methodologies/carbon-capture-and-storage-in-oil-and-gas-reservoirs]
[23] Verra CCS+. https://www.ccsplus.org/
[24] Ithaka Institute. [https://www.european-biochar.org/en/ct/139-C-sink-guidelines-documents]
[25] Food and Agriculture Organization of the United Nations (FAO). [https://www.fao.org/3/cb0509en/cb0509en.pdf]
[26] Ibid 24.
[27] Regional Greenhouse Gas Initiative (RGGI). [https://www.rggi.org/sites/default/files/Uploads/Design-Archive/2012-Review/2013-later-materials/Forest_Protocol_FINAL.pdf]
[28] Ibid 18.
[29]Verra. [https://verra.org/wp-content/uploads/2021/07/Methodology-for-CO2-Utilization-in-Concrete-Production-Carbon-Cure.pdf]
[30] Ibid 24.
[31] International Organization for Standardization (ISO). [https://www.iso.org/obp/ui/#iso:std:iso:tr:27915:ed-1:v1:en]
[32] Verra. [https://verra.org/request-for-proposals-development-of-a-vcs-biochar-methodology/]
[33] BCarbon. [https://static1.squarespace.com/static/611691387b74c566a67f385d/t/622f8af172db6730a9a21db7/1647282930779/031422_Soil_Metrics_Protocol.pdf]
[34] Climate Action Reserve (CAR). [https://www.climateactionreserve.org/wp-content/uploads/2014/07/Urban_Tree_Planting_Project_Protocol_V2.0.pdf]
[35] Gold Standard. [https://globalgoals.goldstandard.org/432_cdr_carbon-sequestration-through-accelerated-carbonation-of-concrete- aggregate/]
[36] DNV. DNV-SE-0473, DNV-RP-F104, DNV-RP-J203, DNV-RP-J201. https://www.dnv.com/oilgas/download/dnv-rp-j201-qualification-procedures-for-carbon-dioxide-capture-technology.html https://www.dnv.com/oilgas/download/dnv-rp-f104-design-and-operation-of-carbon-dioxide-pipelines.html https://www.dnv.com/oilgas/download/dnv-se-0473-certification-of-sites-and-projects-for-geological-storage-of-carbon-dioxide.html https://www.dnv.com/oilgas/download/dnv-rp-j203-geological-storage-of-carbon-dioxide.html

* CARB uses standards from CAR and ACR for this type of reservoir. PSC = point source capture. CCS+ = carbon capture and storage plus.

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[37] Climate Action Reserve (CAR). [https://www.climateactionreserve.org/how/protocols/biochar/dev/]

[38] Nori. [https://nori.com/documents]

[39] American Carbon Registry (ACR). [https://americancarbonregistry.org/carbon-accounting/standards-methodologies/afforestation-and-reforestation-of-degraded-lands]

[40] Regen Network [https://regen-registry.s3.amazonaws.com/Methodology+for+GHG+and+Co-Benefits+in+Grazing+Systems.pdf]

[41] California Air Resource Board (CARB) cap-and-trade. . [https://ww2.arb.ca.gov/our-work/programs/compliance-offset-program/compliance-offset-protocols/us-forest-projects/2015]

[42] American Carbon Registry (ACR). [https://americancarbonregistry.org/carbon-accounting/standards-methodologies/methodology-for-avoided-conversion-of-grasslands-and-shrublands-to-crop-production]

[43] Climate Action Reserve (CAR). [https://www.climateactionreserve.org/wp-content/uploads/2020/10/Soil-Enrichment-Protocol-V1.0.pdf]

[44] Verra. [https://verra.org/methodology/vm0042-methodology-for-improved-agricultural-land-management-v1-0/; https://verra.org/methodology/vm0017-adoption-of-sustainable-agricultural-land-management-v1-0/; https://verra.org/wp-content/uploads/2021/06/VM0026-Methodology-for-Sustainable-Grasslands-Management-v1.1.pdf; https://verra.org/wp-content/uploads/2018/03/VM0021-Soil-Carbon-Quantification-Methodology-v1.0.pdf; https://verra.org/wp-content/uploads/2018/03/VM0032-Meth-for-the-Adopt-of-Sustain-Grasslands-through-Adj-of-Fire-and-Grazing-v1.0.pdf]

[45] PlanVivo [https://www.planvivo.org/Handlers/Download.ashx?IDMF=5b30948b-26f3-4d7a-803f-0fcce593acbd]

[46] Gold Standard. [https://globalgoals.goldstandard.org/402-luf-agr-fm-soil-organic-carbon-framework-methodolgy/; https://globalgoals.goldstandard.org/402-1-luf-agr-am-soc-module-improved-tillage/; https://globalgoals.goldstandard.org/402-2-luf-agr-am-soc-activity-module-application-organic-soil-improvers/]

4.2 Utilization

The utilization of carbon refers to the use of CO_2, at concentrations above atmospheric levels, directly or as a feedstock in industrial or chemical processes, to produce valuable carbon-containing products (Metz et al., 2005). Feedstocks including non-fossil carbon from the air, biomass, or algae can be transformed into short life products including chemicals and fuels (Hepburn et al., 2019) for various usage, including sustainable aviation fuels and alternative fuels for land transportation. These pathways have limited potential to sequester carbon as the carbon is released upon use. However, they have the potential to reduce emissions and create a circular carbon economy, and therefore have an important role to play in decarbonization.

4.2.1 Considerations

To support the role of carbon utilization, the criteria that need consideration in its certification are origin, performance, and safety. In the transition to a zero or net negative emission economy, the origin of carbon will matter. For example, purchasers and the public may wish to be able to differentiate between fossil and non-fossil-based products. This is pertinent for all carbon products, including synthetic fuels and chemicals and short-lived materials.

In the context of utilization, performance would refer to the net decrease in emissions from using the substitution. Until the transition to a net zero or negative emissions world is complete, the production of non-fossil carbon products has the potential to produce more emissions than continuing with the fossil-based product. Regulation akin to the Carbon Take Back Obligation[47] at the source of carbon extraction (Lackner and Wilson, 2008) may need to take effect to handle this for each product and process.

Safety in carbon utilization would refer to analyzing that the substitute product is fit for purpose and that the source of the carbon is not damaging the environment. An example of the former, alternative aviation fuels are often designed to be “drop-in” fuels that can be used in

[47] Carbon Take Back Obligation. https://carbontakeback.org/about/

existing aircrafts and infrastructure. ASTM International has been developing certification programs for this purpose (e.g., ASTM D7566, Standard Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons[48]). An example of the latter is the EU's negative impact on food, the environment, and land through first generation bioenergy crops (Hein and Leemans, 2012; Rulli et al., 2016). Certification of safety criteria is supposed to consider environmental harm - if that criterion is not considered at other points in the certification program.

As concluded by National Academies of Sciences, Engineering, and Medicine (2016), only with verifiable data on carbon utilization can economic value, reliability, safety requirements and climate targets be ensured to stakeholders. The certification of performance, origin, and safety is one system.

4.2.2 State of certification

Certification of carbon utilization in the context described above is limited in the US to fuels and to the Environmental Protection Agency (EPA) and California's Air Resource Board's (CARB) Low Carbon Fuel Standard (LCFS). The EPA administers the Renewable Fuel Standard which requires a minimum volume of renewable fuels to be sold in the US. The renewable fuels are biomass-based, and the certification of performance is determined through a Life Cycle Analysis compared to a 2005 petroleum baseline. The EPA tracks compliance using a Renewable Identification Number[49], like a certificate of origin. Targets have not been met since 2014 met due to underproduction of advanced biofuels (Bracmort, 2022).

California's regulation certifies the performance, safety in terms of responsible biomass sourcing, and origin to some extent of alternative fuels. To certify performance, the California's Air Resource Board's (CARB) Low Carbon Fuel Standard (LCFS)[50] uses Life Cycle Assessments to examine the direct and indirect greenhouse gases associated with the production, transportation and use of alternative fuels expressed as a carbon intensity compared to gasoline and diesel fuels. A declining benchmark assigns credit generations and deficits. Since its inception, the LCFS has reduced the carbon intensity of California's fuel pool by about 7% (2011-2020)[51]. The LCFS offers pathways to

[48] ASTM International. ASTM D7566: Standard Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons. Available at: https://www.astm.org/d7566-21.html
[49] Renewable Identification Number in the Renewable Fuel Standard. More information available at: https://afdc.energy.gov/laws/RIN.html
[50] CARB's Low Carbon Fuel Standard Program basics. Available at: https://ww2.arb.ca.gov/sites/default/files/2020-09/basics-notes.pdf
[51] CARB Data Dashboard. Available at: http://www.arb.ca.gov/fuels/lcfs/dashboard/dashboard.htm

certify the carbon intensity for common low carbon fuels (e.g., landfill gas, cooking oil biodiesel, corn ethanol, gasoline blend stock) as well as next-generation fuels including DAC. Regarding safety, the LCFS contains regulation on the types of crops and residues that can be used in fuel production, for example used cooking oil, tallow, corn extracted from distiller grains and oils from fish processing. With the certification, the LCFS offers a form of guarantee of origin. Certification of origin is more prevalent in the EU where every member state must have a Guarantee of Origin system under the Renewable Energy Directive (2009/28/EC)[52].

Other standards and certification programs relevant to carbon utilization may include standards for fair comparisons between products (e.g., ASTM International), and the LCA standardization efforts referred in the previous section (e.g., NETL's LCA Toolkit, the International CCU Assessment Harmonization Group, ISO 14040:2006).

The certification of non-fossil carbon utilization meets similar issues as the certification of carbon sequestration discussed previously. Similar issues with LCA's apply for carbon sequestration as well as carbon utilization: without regulation such as the CBTO applied upstream, the accounting will continue to be challenging in its attribution of ownership and responsibility. Guarantees of origin have also been criticized for their lack of environmental integrity, having no or worse impact on emissions, and double counting (Jansen, 2017).

Table 2. Certification programs available for carbon utilization

Organization	Certification program	Certification criteria	Reference
CARB	Low Carbon Fuel Standard	Fuel carbon intensity – performance and safety	https://ww3.arb.ca.gov/regact/2009/lcfs09/lcfs09.htm
EPA	Renewable Fuel Standard	Biofuel market penetration -origin	https://www.epa.gov/renewable-fuel-standard- program/overview-renewable-fuel-standard
ASTM International	ASTN E3066-20: Standard Practice for Evaluating Relative Sustainability Involving Energy or Chemicals from Biomass	Comparison practice	https://www.astm.org/e3066-20.html
ISO	Environmental management — Life cycle assessment — Principles and framework	LCA	https://www.iso.org/standard/37456.html
National Energy Technology Laboratory	Life Cycle Analysis Toolkit	LCA	https://netl.doe.gov/LCA/CO2U
Global CO2 initiative	International CCU Assessment Harmonization Group	LCA	https://www.globalco2initiative.org/evaluation/

[52] Ibid 4

4.3 Hydrogen

4.3.1 Considerations

Safety and origin are two criteria that matter for the certification of hydrogen. Hydrogen has ignition, combustion and pressure characteristics that make safety a priority, despite being a promising energy efficient and clean fuel. Safety concerns arise during production, transmission, use, and storage (Najjar, 2013). Hydrogen can be produced in various ways (e.g., from hydrocarbons, coal, nuclear energy, wind energy by electrolysis, thermos-chemical biomass processing, solar energy and hydrogen separation and purification), each having their own hazards. In general, the main hazard is through leakage (Najjar, 2013), although combustion also may be a safety hazard.

Because hydrogen can be produced from many sources, the origin of the energy used and the process to produce the hydrogen matters in the context of decarbonizing. Hydrogen can be used to reduce emissions in sectors with no other pathways, for example steel making. In a world of negative emissions, hydrogen production must either not produce emissions or emissions will have to be removed using CDR. Hydrogen produced from steam methane reform will need to be successfully fitted with CCS technology. However, the Rocky Mountain Institute found that in many natural-gas economies, such as the US, the predominantly SMR (small modular reactor)-based existing hydrogen production plants are quickly on track to become less CO_2-efficient than electrolysis[53]. Therefore, using the cleanest energy possible in hydrogen production could avoid stranded assets and accelerate decarbonization. Certifying the source of the energy will play a critical part to tracking this clean hydrogen, and support decarbonization claims.

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[53] Koch Blank, T. and P. Molly (2020). Hydrogen's Decarbonization Impact for Industry. Rocky Mountain Institute Insight Brief, January. Available at: https://rmi.org/wp-content/uploads/2020/01/hydrogen_insight_brief.pdf

4.3.2 State of certification

Certification programs for hydrogen origin and safety exist (**Table 3**). The only available certification of energy origin for hydrogen is from the organization TÜV SÜD, an international and independent testing, inspection, and certification organization[54]. TÜV SÜD's Production of Green Hydrogen Standard is based on European Union legislation but is in principle applicable worldwide. TÜV SÜD can issue a GreenHydrogen certificate if the basic requirements are met, and the hydrogen has a greenhouse gas reduction potential of at least 70 % compared to a fossil fuel benchmark for fuels or combustibles. If additional requirements are met, TÜV SÜD can issue a GreenHydrogen+ certificate and this is proposed to promote greater use of renewable energy. The TÜV SÜD standard will eventually be superseded by the CertifHy™ GO (Guarantee of Origin) but will remain as an additional quality scheme. CertifHy™ was formed in response to EU legislation to reduce emissions continent wide with hydrogen a key technology. The mission of CertifHy™ is to develop an EU-wide system with a unique registry and unique standard compliant with the EU's Guarantee of Origin regulation (Art. 19 from RES Directive 2018/2001/EC (REDII)). The CertifHy™ will not be available outside of the EU.

More standards and certification are available regarding safety (**Table 3**). Organizations such as the National Institute of Standards and Technology (NIST), the American Society of Mechanical Engineers (ASME), the SAE International (SAE), and the International Organization for Standardization (ISO) provide hydrogen safety standards at the various stages of hydrogen production. For example, NIST has statutory responsibility under the US's Pipeline Safety Act of 2002 to develop research and standards for gas pipeline integrity, safety, and reliability for hydrogen. ASME expanded on data gathered by NIST to design pipeline construction code. The PSC certification programs identified in the previous section would provide the standards (e.g., pipelines and storage) which are pertinent to CCS for biomass or fossil-based hydrogen.

Table 3 (continued on next page). Certification programs available for hydrogen

Organization	Certification program	Certification criteria	Reference
TÜV SÜD	Production of Green Hydrogen Standard	Renewable energy origin	https://www.tuvsud.com/de-de/-/media/de/industry-service/pdf/broschueren-und-flyer/is/energie/tv-sd-standard-cms-70_grund–und-zusatzanforderungen-deutsch-englisch.pdf

[54] TÜV SÜD. Available at: https://www.tuvsud.com/en-us

CertifHy™	EU Voluntary Scheme for the certification of hydrogen as RFNBO (Renewable Fuel of Non-Biological Origin) according to the European Renewable Energy Directive	Renewable energy origin "Guarantees of Origin"	https://www.certifhy.eu/
NIST	Measurement Quality in Hydrogen Storage R&D	Storage measurement	https://www.nist.gov/programs-projects/measurement-quality-hydrogen-storage-rd
ASME	Hydrogen Piping and Pipelines B31.12 – 2019	Pipeline safety	https://www.asme.org/codes- standards/find-codes-standards/b31- 12-hydrogen-piping-pipelines
ISO	ISO 14687:2019 Hydrogen fuel quality — Product specification	Fuel quality	https://www.iso.org/standard/69539.h tml
ISO	ISO 13984:1999 Liquid hydrogen — Land vehicle fueling system interface	Fueling interface safety	https://www.iso.org/standard/23570.h tml?browse=tc
ISO	ISO 13985:2006 Liquid hydrogen — Land vehicle fuel tanks	Fuel tanks	https://www.iso.org/standard/39892.h tml?browse=tc
ISO	ISO/TR 15916:2015 Basic considerations for the safety of hydrogen systems	Basic safety	https://www.iso.org/standard/56546.h tml?browse=tc
ISO	ISO 16110-1:2007 Hydrogen generators using fuel processing technologies — Part 1: Safety	Generator safety	https://www.iso.org/standard/41045.ht ml?browse=tc
ISO	ISO 19880-1:2020	Fueling station safety	https://www.iso.org/standard/71940.ht
ISO	ISO 19881:2018 Gaseous hydrogen — Land vehicle fuel containers	Fuel containers (vehicles)	https://www.iso.org/standard/65029.h tml?browse=tc
ISO	ISO 26142:2010 Hydrogen detection apparatus — Stationary applications	Detection apparatus	https://www.iso.org/standard/52319.ht ml?browse=tc
SAE International	J2719 Hydrogen Fuel Quality for Fuel Cell Vehicles	Vehicle safety	https://www.sae.org/standards/conte nt/j2719_202003/

5 Gaps, needs, and recommendations in the context of I-WEST

5.1 Carbon sequestration (including long-lived products)

5.1.1 Gaps

- The situation with the certification of carbon sequestration currently depends on the reservoir type. The certification of sequestration ought to result in an equal outcome that ought to be clearly stated, which may require different treatments for each reservoir type. Guidelines on how this could be done do not currently exist and the considerations in **section 4.1.1** may offer a starting point.
- One of the region's main considerations is point source capture into geologic reservoirs. For this type of decarbonization solution, the EPA's Class VI wells permitting is available. The main issues have so far been related to the time and effort needed to get through the process, exacerbated by the limited staffing. Lessons learned from the Illinois Basin – Decatur Project are detailed in Van Voorhees et al. (2021). The remedial action requirements of the Class VI wells may not be consistent with ensuring the integrity of the sequestration as a decarbonization solution, i.e., by requiring an equal amount of re-sequestration to match lost carbon, and may need further exploration.
- For other carbon sources injected into geological reservoirs, a few protocols are available (e.g., the California Air Resource Board Low Carbon Fuel Standard allows for carbon from DAC whereas Verra CCS+ initiative is developing voluntary, unregulated standards for DAC, CO_2-rich gases, biogenic sources, and oil and gas production into aquifers and depleted oil and gas fields[55]). Protocols ought to result in the certification of the same outcome to be considered equivalent. Guidance on what that ought to be is generally lacking, unless the EPA's Class VI Guidance also applies to CO_2 streams that are not captured from an emission source.
- Protocols are available for Enhance Oil Recovery activities through the California Air Resource Board and the American Carbon Registry.
- Emission accounting that relies on LCAs and counterfactuals are inadequate for delivering measurable and verifiable estimations of sequestration. Alternative approaches that use direct measurements are limited, except for certain standards covering geologic sequestration.

[55] Verra CCS+ Initiative. Available at: https://verra.org/wp-content/uploads/2021/10/Verra-RFP-Meth-CCS.pdf

- Most standards of sequestration do not internalize the potential failure that sequestration will not be durable. Guidance on what is satisfactory is generally lacking.

5.1.2 Recommendations

The I-WEST initiative is explicitly focused on the Intermountain West region. The following recommendations are pertinent to geologic sequestration in the region.

- As recommended elsewhere, support the streamlining of EPA permitting process and increase of EPA staffing.
- Determine if bio-oil injection is a fit-for-purpose CDR approach.
- Develop standards that safeguards against poorly sourced biomass.
- Develop certification of origin for biomass used for BiCRS.
- Ensure the EPA Class VI permit includes CO_2 streams from non-point sources such as DAC and BiCRS.

Although I-WEST is not explicitly assessing forestry, soils, enhanced weathering, and mineralization in the decarbonization pathways, a plethora of protocols are available on a voluntary basis for these types of reservoirs. For these, there is no coherency in the protocols either in terms of performance, safety, or origin. Many are of questionable integrity in terms of their rigorousness of measurement, monitoring plans, and remedial action. They also have limited oversight and restricted verification activities. Recommendations for non-geologic reservoir certification are the following.

- Create independent oversight of standards development to ensure standards represent the same outcome.
- Develop an independent system for verification that eliminates conflicts of interests.
- Develop accounting protocols that use direct measurements to meet measurability and verification requirements.
- Identify what reservoirs need further research and target basic research towards reservoirs with large uncertainties or costly measuring equipment.
- Require the separation of certification and verification from the financial gain of the activity or product.
- Support the development of a framework for the certification of carbon sequestration that is equal across reservoirs, produces measurable and verifiable accounting of sequestration, and allows deployment today without compromising the future.

5.2 Utilization

5.2.1 Gaps

- The LCFS (Low Carbon Fuel Standard) and the EPA's RFS (Renewable Fuel Standard) are the only two standards covering carbon utilization as a fuel. The EPA narrowly focuses on biofuels demand, whereas the LCFS offers some opportunities to expand to DAC-to-fuel production.
- The LCFS is for now restricted to California, although it does provide for the import of fuels into the state. This could benefit alternative fuel production in the intermountain west.
- Existing standards are focused on land and air transport, with none appearing to exist for watercrafts, which are important to support recreational activities, a lucrative sector for the Intermountain West.
- No standard appears to exist for fuels outside of the transport sector. For example, to replace residential and commercial heating fuel.
- No standard appears to exist for carbon utilization in other non-fuel, short-lived products.
- Criticisms of GO systems are similar to those of the carbon sequestration: poor environmental credibility, over supply, and double counting will weaken the system.
- Carbon accounting at the product level is challenging in terms of attribution, has large uncertainties in terms of quantification, and is a burden on product manufacturers. It is unclear how the current strategy would support an expansion of carbon neutral or negative products.

5.2.2 Recommendations

- Expand a standard like the LCFS to the Intermountain West.
- Develop an independent verification regime.
- Support regulation like the CBTO and require that accounting be done at the point of carbon extraction or import to create a demand and simplify accounting systems, respectively.

5.3 Hydrogen

5.3.1 Gaps

- The scaling of clean hydrogen will require adequate certification infrastructure which is inexistent or nascent. Buyers will want to report their purchases of clean hydrogen either for reporting or to make claims towards sustainable practices and clean hydrogen production will need to be tracked to target hard infrastructure development and market development.

- A portion of the challenge is the various naming designation for hydrogen based on the source. In some cases the naming of the hydrogen (green, blue, etc.) serves to obfuscate the origin and as such hide the actual CO_2 impact of the hydrogen, both its formation and application.
- No standard for hydrogen energy origin currently exists to do that for the US, but the TÜV SÜD standard is a priori applicable.

5.3.2 Recommendations

The certification of hydrogen activities ought to be a priority to support the development and scaling of the hydrogen industry in the US to the extent envisaged by the I-WEST initiative. Recommendations to do so are the following.

- Like the CertifHy Initiative, create a unique hydrogen Guarantee of Origin registry that would span across states.
- Build on the TÜV SÜD standard.
- Adopt one hydrogen Guarantee of Origin standard.
- Develop a strategy using certification to reach 100% renewable energy hydrogen source.
- Develop an independent verification regime.
- Develop a naming system that identifies the source of the hydrogen and the CO_2 created by the different sources.

6 Conclusions

Certification is the social contract that protects the public and consumers. Certification will be critical for decarbonization activities to gain and keep the public's trust. Some decarbonization activities have the added complexity of being invisible to the consumer, either because they are far removed, or because they move gases without physical properties that can be sensed and have limited immediate impacts on the public. For these reasons, certification is important for decarbonization with the understanding that certification must be actively shielded from the potential to be gamed in its development but also in its verification. Strong verification regimes ought to be developed for all the decarbonization activities that require certification.

Geologic storage is largely governed by the EPA Class VI well permitting process. The process has limitations as discussed but provides a robust procedure that results in measurable and verifiable data, along with long-term commitments to monitor. Ensuring that released carbon would be remediated by re-sequestration would continue the integrity of the sequestration as a decarbonization solution.

Alternative sequestration options may be sought by the region in the future, including mineralization, enhanced weathering, soil carbon, and forestation. For these types of activities, the status of certification highlights several urgent needs that ought to be addressed before implementation begins. These include a need for oversight so the plethora of unequal protocols are reformed to meet a minimal level of quality that can be trusted, a need for the establishment of independent certification without financial link to decarbonization products or activities or to the standards, and a need for independent verification that can make sure the certification is applied properly.

Other decarbonization activities, such as synthetic fuels, hydrogen, and biomass utilization, have either nascent or inexistent certification programs, particularly when it comes to certification of origin. To support the development of these industries, there is thus a need for urgent development of rules in a U.S. context.

Targeted basic research will support the development of certification programs. For carbon sequestration, basic research on the various reservoirs and technology cost reduction will add additional suitable reservoirs, will help protect communities and the environment, and will reduce the cost of certification. For hydrogen, basic research should focus on reaching the DOE targets for hydrogen systems[56].

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[56] DOE Hydrogen Shot Program. Available at: https://www.energy.gov/eere/fuelcells/hydrogen-shot

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I-WEST

Phase One Final Report | Detailed Chapter

Hydrogen Supply

About this chapter

The Intermountain West Energy Sustainability & Transitions (I-WEST) initiative is funded by the U.S. Department of Energy to develop a regional technology roadmap to transition six U.S. states to a carbon-neutral energy economy. I-WEST encompasses Arizona, Colorado, Montana, New Mexico, Utah, and Wyoming. Each state is represented in this initiative by a local college, university, or national laboratory. Additional partners from beyond the region were selected for their expertise in applicable fields. In the first phase of I-WEST, the team built the foundation for a regional roadmap that models various energy transition scenarios, including the intersections between technologies, climate, energy policy, economics, and energy, environmental, and social justice. This chapter presents work led by an I-WEST partner on one or more of these focus areas. A summary of the entire I-WEST phase one effort is published online at www.iwest.org.

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Table of Contents

Introduction

Currently, about 10 million tons of hydrogen (H_2) is produced in the U.S. annually, predominantly for use in industrial processes and fertilizer production. With water being the only product of its combustion, H_2 is a clean energy carrier and is expected to play a significant role in achieving carbon neutrality. Given the presence of large natural gas (NG) reserves in the Intermountain West, the region has potential to emerge as a leader in H_2 production for local use, as well as for export to other regions. While H_2 itself is a “clean” fuel, there are greenhouse gas emissions associated with certain types of hydrogen production; specifically, carbon dioxide (CO_2) released during steam methane reforming (SMR), and fugitive methane during the production of natural gas. Integrating carbon capture and sequestration (CCS) is a potential pathway to mitigate CO_2 emissions from the SMR process, and siting SMR process units near regional natural gas wells would mitigate methane emissions. Water electrolysis is rapidly emerging as a hydrogen production technology for CO_2-free hydrogen production via integration with renewable solar and wind power sources. It is anticipated that H_2 production from fossil fuels, as well as from water electrolysis, will be the two key pathways to meeting existing industrial needs and future transportation sector needs for H_2 over the next five years.

Methodology

In this report, we briefly discuss various H_2 production routes, namely SMR process with and without carbon capture, renewable-energy-driven H_2 production from natural gas, and water electrolysis. A detailed analysis of blue hydrogen was conducted to quantitatively determine its potential to reduce regional carbon emissions. Finally, a preliminary assessment of H_2 production in the Intermountain West region is presented.

Steam methane reforming

Steam methane reformation (SMR) is the industry standard for H_2 production. In current standard process schemes, CO_2 generated during the SMR process is emitted into the atmosphere—this is commonly referred to as “grey hydrogen.” Grey H_2 production is environmentally polluting and has a higher carbon footprint than direct methane burning. However, if the CO_2 generated during this type of H_2 production is captured and sequestered, then it is referred to as “blue hydrogen.”

Figure 1(a) shows the schematic for grey H_2. The natural gas feed along with steam is heated to 700-900 °C, and flows into the steam methane reactor where the methane is reduced to synthesis (syn) gas:

$$CH_4 + H_2O = CO + 3H_2 \quad \text{Eq. (1)}$$

The syngas then flows into the water gas shift reactor where CO is reacted with steam to produce additional H_2:

$$CO + H_2O = CO_2 + H_2 \quad \text{Eq. (2)}$$

The shifted syngas mixture then flows into pressure swing adsorption (PSA) for H_2 purification generating >99% H_2. The natural gas is used as a fuel source for the SMR process. The overall reaction taking place can be written as:

$$CH_4 + 2H_2O = 2CO_2 + 4H_2 \quad \text{Eq. (3)}$$

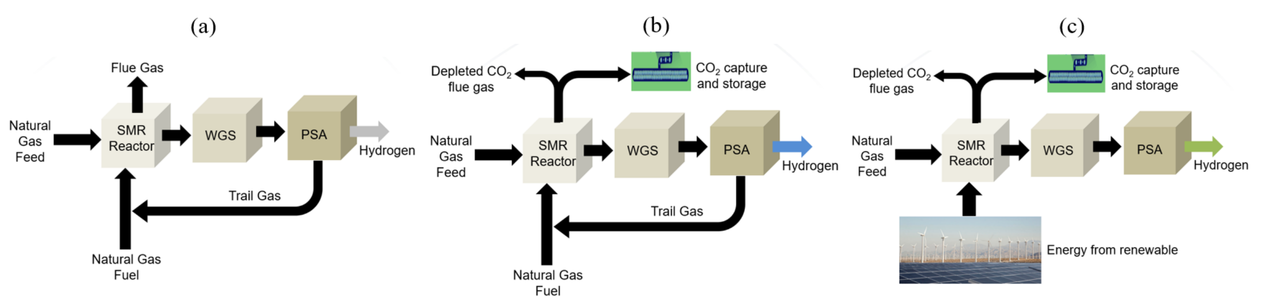

Figure 1: Schematic for different hydrogen production process schemes as a function of carbon capture and energy source: (a) grey hydrogen (b) blue hydrogen, and (c) turquoise hydrogen.

For grey H_2, the CO_2 is produced by the SMR process as well by the heating fuel. The CO_2 coming out from the SMR process is at high concentration and can be readily separated and captured. The H_2 produced by this process is blue hydrogen with SMR CO_2 capture.

Using natural gas as a fuel source is polluting; additionally, the chances of methane leakage always exist. Use of renewable energy as a fuel source can help in reducing the carbon footprint. In this study, we used solar photovoltaics (PV), wind energy, and concentrating solar thermal (CST) as a heat source for "turquoise hydrogen" production.

We have used a cradle-to-grave approach for life cycle assessment. The process involved in natural gas (NG) derived H_2 production includes NG extraction, NG processing and treatment to produce pipeline grade NG, NG transportation, H_2 production, CO_2 capture and sequestration and H_2 utilization. There are leakages associated with NG extraction, compression, transportation, and storage. Detailed analyses of H_2 production from NG, including influence of several process parameters such as NG leak rate, process efficiency, and carbon capture rate, are provided in the Appendix.

Case study

We have considered the Intermountain West as a case study for decarbonizing regional energy sectors, including transportation and electricity generation.

Transportation

The two major contributors to the Intermountain West transportation sector are gasoline and diesel. Gasoline contributes 60.8%, diesel 30.9%, natural gas 5.3% and propane 0.023% of the net fuel energy in the region, with net energy content of ca. 408 TWh/yr (Figure 2(a)) [1]. The net CO_2 emission is 101.2 million ton/yr, with gasoline contributing 58%, diesel 32% and natural gas 10%. For natural gas we have assumed 3.5% methane leakage for 100 years of lifetime.

Fuel production is a water-intensive process, with gasoline consuming 0.84 kg/kWh, diesel 0.98 kg/kWh, and natural gas 0.21 kg/kWh. Note, the natural-gas-specific water consumption is 70-80% lower as compared to gasoline and diesel. The net water consumption for fuel production is 283k acre-feet/yr (349.39 million ton/yr).

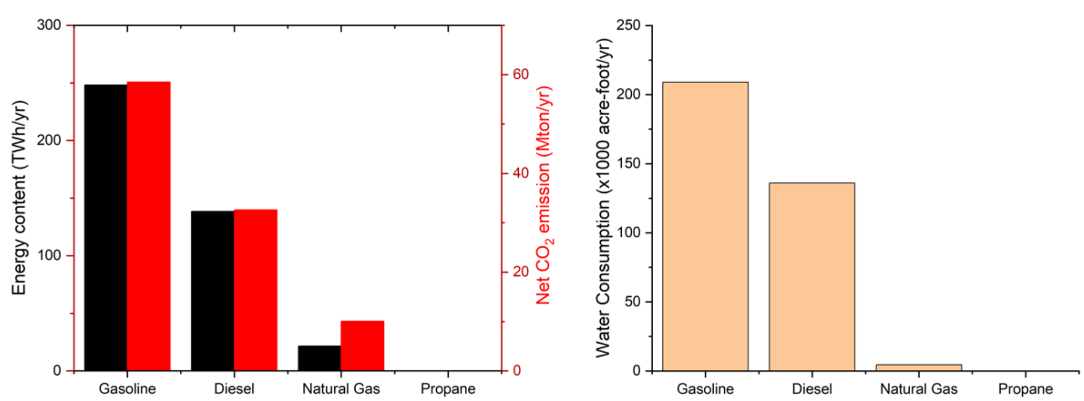

Figure 2: Left: Net energy content and CO_2 emission (right) net water usage for different hydrocarbon sources used for the transportation sector in the Intermountain West [1–3].

One pathway to reducing net CO_2 emissions in the transportation sector is with hydrogen fuel cells. The energy efficiency for an internal combustion engine using gasoline is 19%, diesel is 31%, and natural gas is 17% [4]; meanwhile, the H_2 fuel cell efficiency varies in the range of 40-60% [5]. Assuming an average efficiency of 50% for H_2 fuel cell vehicles, the net H_2 requirement to meet current transportation sector energy demand is 4.72 million ton/yr. The effects of transitioning from hydrocarbon fuel to hydrogen fuel cell are shown in Figure 3. In this calculation of replacing current transportation fuels with H_2, the following assumptions are applied: methane leakage of 3.5%, SMR energy consumption of 2.25 $kWh/m^3_{H2,STP}$, carbon capture efficiency of 85%, carbon capture energy requirement of 3000 J/g CO_2, and methane lifetime of 100 years and fuel cell efficiency of 50% [5] (Figure 3(a) and (b)). For the current regional scenario, replacing existing fuel sources with H_2 would reduce CO_2 emissions as follows: grey H_2, 19%; blue H_2, 55%, turquoise H_2, 67%, regional H_2, 82% and green H_2, 91%. In the cases of turquoise and renewable hydrogen, the electrolysis energy consumption of 50 kWh_e/kg_{H2} [6] was used in the calculations.

While applying turquoise and renewable hydrogen helps reduce the H_2 requirement significantly, it might be expensive due to the use of renewable energy. The other alternative is the use of regional blue H_2. Grey H_2 has the lowest water requirement (78k acre-foot/yr), as it requires water only for the SMR process and natural gas extraction. With blue H_2, the net water requirement increases threefold (210 acre-foot/yr) compared to grey H_2. This is due to high water requirements for carbon capture technologies. With turquoise H_2 the water requirement is 30% lower than blue H_2 and is maximum for regional blue H_2 (243k acre-foot/yr). Green H_2 has a net water requirement of 112k acre-foot/yr. In addition to the total water requirement, the water quality is also an important parameter. Electrolysis would require deionized water, while the SMR process would require potable-quality water. For mining and natural gas extraction we can use brackish water. (The water required for mining, natural gas extraction, and panel cooling are taken from [7–9]. Similarly, for cooling the system we can use produced water. This can help in significantly reducing the dependence on potable water sources; the net potable water required for blue H_2 is one-third of that for green H_2. Therefore, moving toward blue, turquoise, and regional blue H_2 with current state-of-art will help in reducing CO_2 emissions by 55-82%, with a marginal increase in potable water requirements.

The second scenario we have considered is an optimized SMR-H_2 production process with methane leakage decreased to 1% and improved energy efficiency of the SMR process unit operations. As discussed in the Appendix, the major contributor to NG fugitive methane emissions is compressor leakage. One way of reducing this is to place the compressor inside a box; the leaked NG can then be collected in the box and used as an energy source for compressor pumping.

Similarly, significant efforts are being made to reduce the fugitive emissions with advanced NG storage design and pipeline materials selection. For the base case discussed above, we have assumed SMR energy consumption of 2.25 kWh/m^{3}H$_{2,\ STP}$. With advanced process design and process intensification, the SMR energy requirement can be brought down to 0.5 kWh/m^{3}H$_{2,STP}$ [10]. Similarly, with advancements in carbon capture technologies, the capture efficiency can be increased to 97%. Additional process energy efficiency improvements are anticipated as technology matures, including H_2 fuel cell efficiency increasing to 60% [5] and the SMR reactor energy consumption decreasing to 25 kWh$_e$/kgH_2 [6]. Using the assumptions made in the advanced SMR-H_2 process, transition to grey, blue, turquoise, and green H_2 is calculated to further reduce the net CO_2 emission by 65%, 90%, 92%, 92% and 95%, respectively. Additionally, the net water requirement also improves (Figure 3(c) and (d)). Therefore, blue H_2 and regional blue H_2 could be critical in reducing net CO_2 emissions, provided technology advancements lead to reductions in methane leakage and SMR energy consumption.

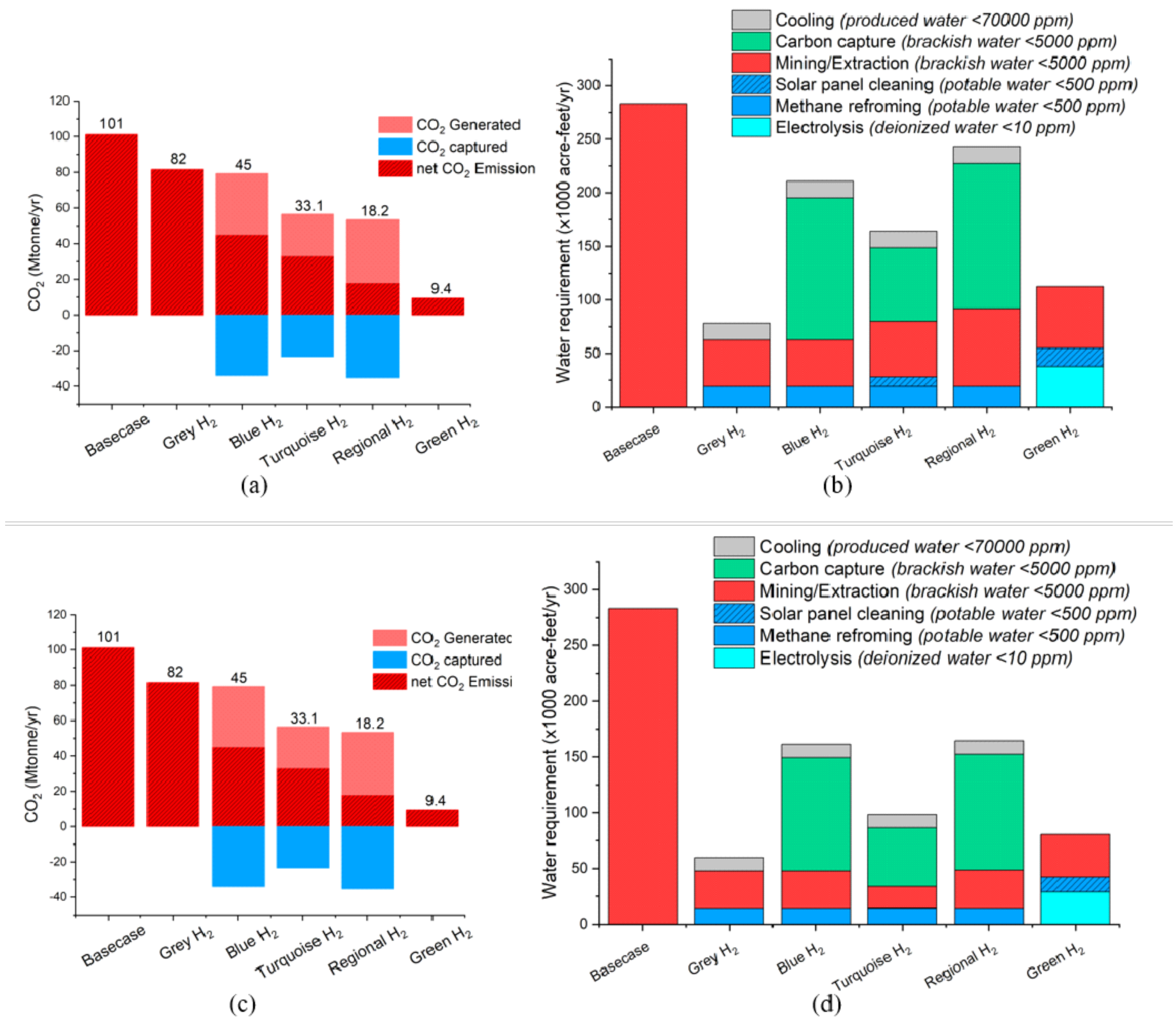

Figure 3: Role of blue, turquoise and regional H_2 in decarbonizing the transportation sector for the Intermountain West, and the impacts on the water footprint for (a, b) current scenario (methane leak 3.5%, energy 2.25 kWh/m^3, carbon capture efficiency and energy requirement of 85%, fuel cell efficiency of 50% and electrolysis energy requirement of 50 kWh$_e$/kg$_{H2}$), and (c, d) optimized SMR process (methane leak 1%, energy 0.5 kWh/m^3, carbon capture efficiency and energy requirement of 97%, fuel cell efficiency of 60% and electrolysis energy requirement of 25 kWh$_e$/kg$_{H2}$).

Electricity generation

Figure 4 (a) shows the net electricity profile for the Intermountain West, with an annual production of 307 TWh$_e$. Coal is the major contributor at 30.5%, natural gas power plants at 14.5%, natural gas combined cycle (NGCC) at 12.8%, wind energy at 11.1%, nuclear energy at 10.4%, hydro energy at 6.3%, solar energy at 4.4%, and a small contribution from petroleum, geothermal and biomass at 0.7% combined. The net annual CO_2 emissions from electricity production is 172 million tons/year. Due to the lower efficiency of coal power plants (33%), the net CO_2 emission is the highest at 67%.

Natural gas power cycle contributes to 19.2%, while natural gas combined cycle contributes to 11.8% of the total CO_2 emissions.

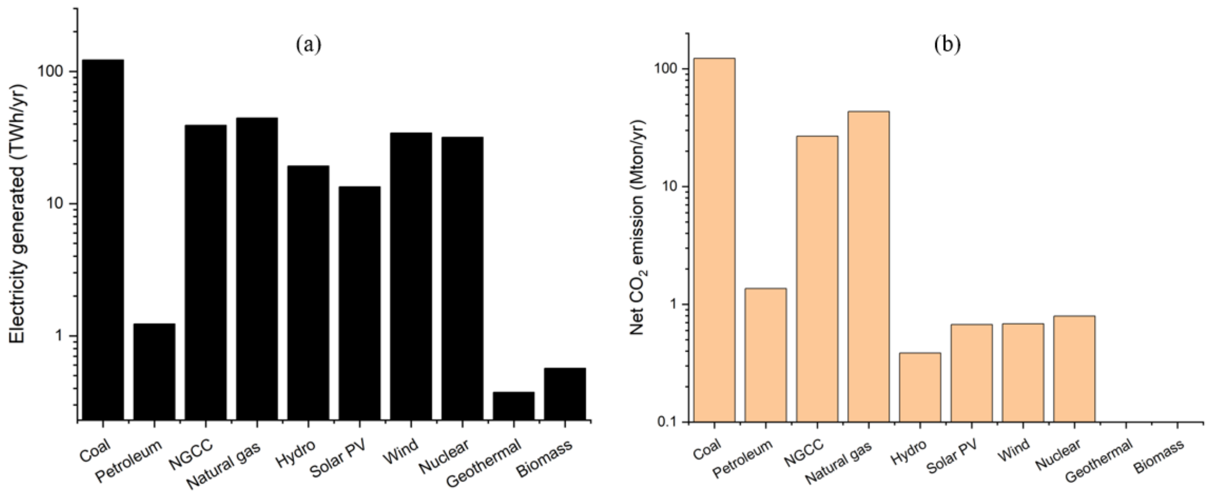

Figure 4: (a) Net electricity production (b) and net CO_2 emission for different energy sources in the Intermountain West.

Figure 5 (a) shows the possible approaches for reducing CO_2 emissions from electricity generation in the Intermountain West. The first possible approach considering the current scenario is replacing all coal power plants, natural gas power, and other hydrocarbon power with natural gas combined cycle (NGCC). Due to the higher energy efficiency of NGCC (60%), the net CO_2 emission can be reduced by 44% (with current average NG leakage of 3.5%), and by 52% (under only 1% methane leak). The other approach is blending the natural gas with 30% H_2 (by volume). Currently, NGCC operation is limited to 30% H_2, but with advanced turbine technology under development, it may be possible to operate with 100% H_2. By blending with 30% blue H_2, net CO_2 emissions reduce by 47%, while turquoise and regional blue H_2 blending results in a 50% reduction (for current scenario).

In the future, NGCC can be operated with 100% H_2, which will further help in reducing CO_2 emissions. Moreover, under a futuristic scenario, with reduced methane leakage and efficient SMR and carbon capture efficiency, the net CO_2 emissions could be reduced by 85%, 88.9% and 89.3% with blue, turquoise, and regional blue hydrogen, respectively.

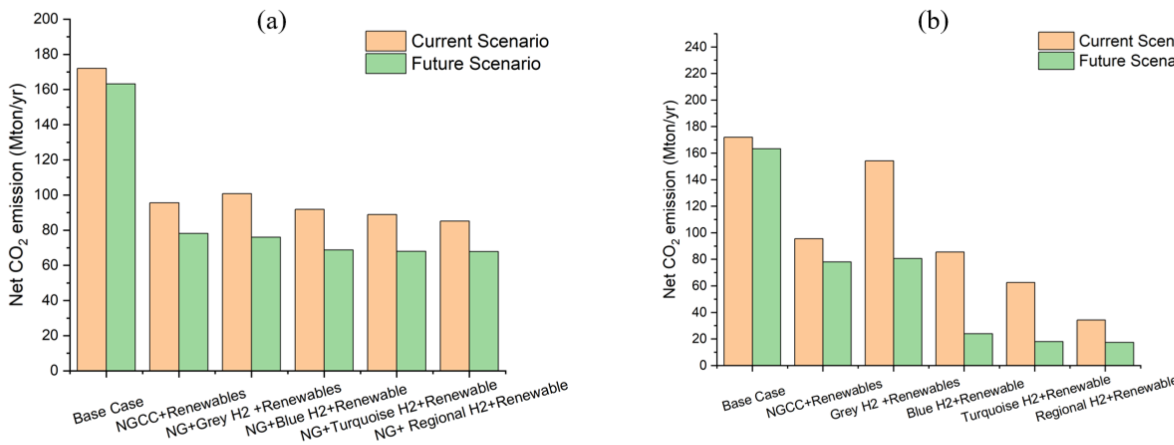

Figure 5: Role of blue, turquoise and regional H_2 in decarbonizing the electricity sector by blending, (a) 30% H_2 by volume and (b) 100% H_2 for NGCC operation. For current scenario (methane leak 3.5%, energy 2.25 kWh/m^3, and carbon capture efficiency of 85%), and future scenario (methane leak 1%, energy 0.5 kWh/m^3, and carbon capture efficiency of 97%).

Hydrogen as a replacement fuel for natural gas

Figure 6(a) shows the net NG production in the Intermountain West, which is about 5051 billion cu. feet/yr, [11]. New Mexico is the major contributor for NG production with 40% share, Colorado contributes 33%, followed by Wyoming 21%, Utah 5%, and Montana 1%. If all the NG produced annually is converted to H_2, the net grey H_2 will be 52 million ton/yr, net blue H_2 will be 22.5 million ton /yr, net turquoise H_2 will be 5.3 million ton /yr, and net regional H_2 will be 22.6 million ton/yr (Figure 6(b)). These calculations were carried out using a current SMR scenario of 3.5% methane leakage, 2.25 kWh/m^3 energy consumption, and carbon capture efficiency of 85%. However, for future scenarios (1% methane leak, 0.5 kWh/m^3 energy consumption and carbon capture efficiency of 97%) the net H_2 production from grey, blue, turquoise and regional H_2 will be 43, 41.3, 53.4 and 40.6 million ton /yr, respectively.

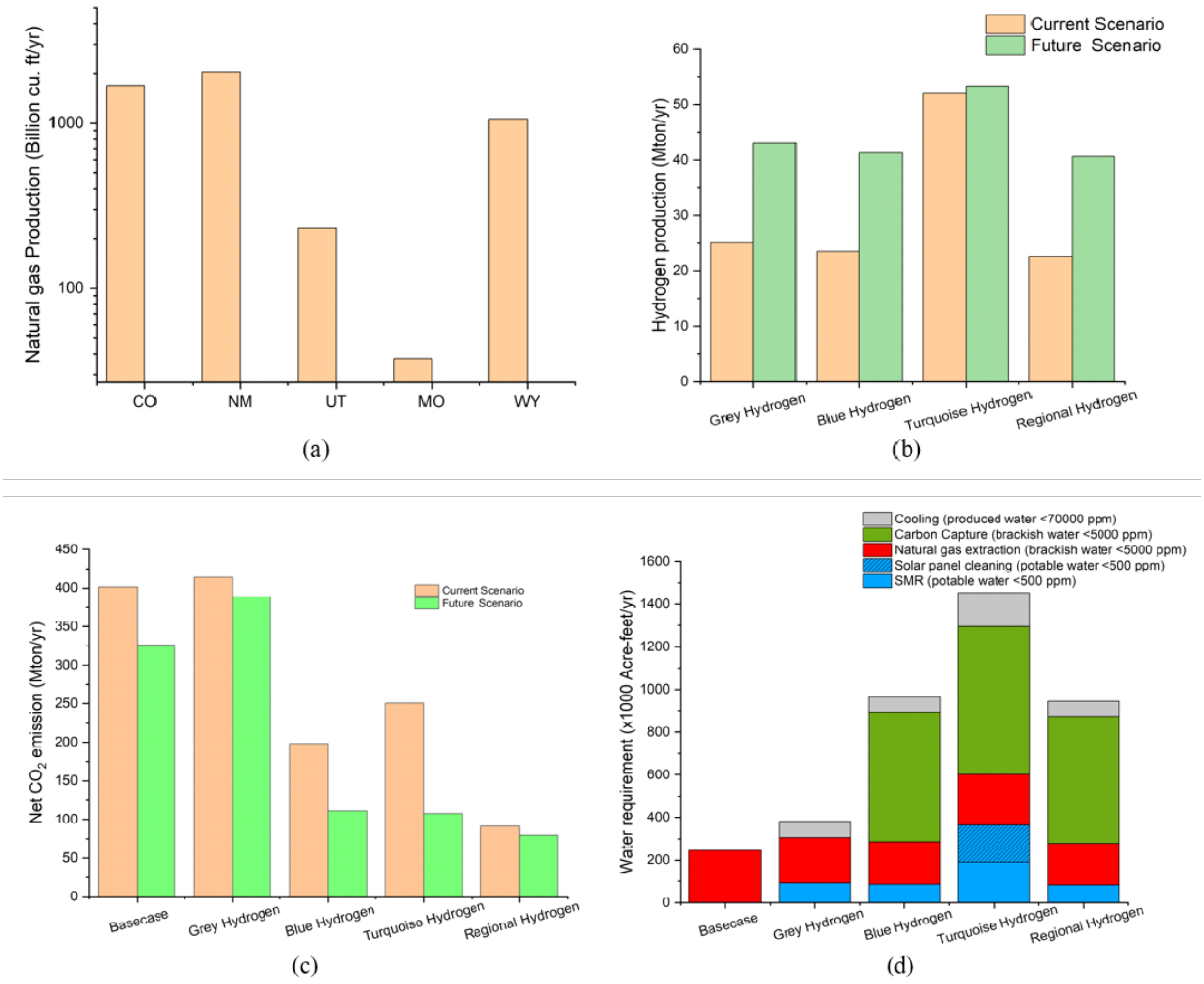

Figure 6: (a) Natural gas reserve and annual natural gas production, (b) potential hydrogen production by using annual natural gas production for current and future scenario, (c) effect on CO_2 emission while transitioning from natural gas to H_2 production for current and future scenario, and (d) net water demand to transition toward different H_2 production based on the current scenario.

Figure 6 (c, d) shows the net CO_2 generated and net water usage per year. For the base case of natural gas production with 3.5% methane leakage, the net CO_2 emissions are 401 million ton/yr. Transitioning toward grey H_2, the net CO_2 emissions increase by 3%, while blue, turquoise and regional H_2 can help reduce CO_2 emissions by 50%, 34% and 77%, respectively. Note, the net reduction in CO_2 emissions with turquoise H_2 is lower due to almost two times higher H_2 production compared to blue H_2. Figure 6 (d) shows the water demand for various scenarios, with a base case of 245k acre-feet. The net increase in total water demand compared to the base case is 55.7%, 293%, 493% and 285% for grey, blue, turquoise and regional H_2, respectively. The net increase in potable water demand is around 90k acre-feet for grey, blue and regional H_2, and 360k acre-feed for turquoise H_2.

Based on the transportation and electricity production analysis (with 30% blending with natural gas), an additional 6.4 million ton/yr of H_2 would need to be produced. This roughly translates to 1383 billion cu. ft/yr of natural gas, i.e., the current natural gas production from the Intermountain West needs to be increased by 27% to meet the increased blue H_2 demand for the electricity and transportation sectors. This would reduce net CO_2 emissions by 50%.

Conclusion

Hydrogen can play an important role in decarbonizing Intermountain West energy sectors. Numerous studies have been presented in literature comparing different types of H_2 production. Our study aimed to identify the key components contributing to the carbon footprint of H_2 production processes. While methane leakage is one of the most dominating factors, and could limit regional transition to H_2-based energy economies, another key component is the specific energy usages for H_2 production. With optimal energy integration and system design, the net energy consumption can be brought down to 0.5 kWh/m^3 (compared to 2.25 kWh/m^3 prevalent today). This would reduce net CO_2 emissions by 50%.

To show the applicability of H_2 in decarbonizing the energy sector, we considered replacing the transportation and electricity generation sectors with H_2 in the Intermountain West. We considered two scenarios: in the first, we assumed the existing trend, whereas in the second, we considered a more optimistic outlook. The Intermountain West contributes 101.2 million ton/yr of CO_2 and requires 283k acre-foot/yr of water. For the current scenario (3.5% leak and 2.25 kWh/m^3 energy requirement) the use of regional blue H_2 can reduce the CO_2 emissions by 55%, while in the future scenario (1% leak and 0.5 kWh/m^3), CO_2 emissions can be reduced by 90%. The net electricity generated in the region is 307 TWh$_e$/yr, which contributes to 182.9 million ton/yr of CO_2 per year and requires 1157k acre-foot/yr of water. Replacing all hydrocarbon power thermal power plants with NGCC can help reduce CO_2 emissions by 56%. For the current scenario (30% hydrogen blending with NG for NGCC power production process), use of regional H_2 can reduce the net CO_2 emissions by 65%, and in the future scenario (100% hydrogen), could result in 96% reduction in CO_2 emissions. Replacing the regional transportation sector and blending NGCC with 30% blue H_2 can reduce the CO_2 emissions by 50%. However, this needs an additional 27% increase in NG production.

Hydrogen production is a water-intensive process, especially considering potable water use. However, impaired water sources, including produced water (water produced during oil and gas extraction) and brackish water, can be treated and used in H_2 production. Future I-WEST assessments should include a detailed life cycle analysis and development adoption curve for the H_2 production technologies discussed in this report. Additionally, other H_2 production processes, including autothermal reforming, partial oxidation, biomass reforming, and electrolysis should be assessed in detail, along with industry-standard SMR processes.

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Appendix

In this study, we used a cradle-to-gate approach for life cycle assessment, with the following assumptions:

- Methane leakage base case: 3.5% [12]
- SMR energy requirement base case: 2.25 kWh_{th}/m^3 [12]
- CO_2 capture efficiency base case: 85% [12]
- Concentrating solar power CO_2 emission: 10 g/kWh_{th}[13]
- CH_4 global warming potential is 28 for 100 years and 84 for 20 years lifetime.
- NG consist of 100% CH_4.
- Calculation done for producing 1 MJ_{th} energy from hydrogen.

Figure A1 shows the net CO_2 emission breakdown for different H_2 production technologies. For a 20-year lifetime, methane leakage is the major contributor for net CO_2 emissions (45% for grey H_2, 65% for blue H_2, 58% for turquoise H_2 and 42% for direct methane burning). Due to the high contribution of methane leakage, the improvement in going from grey to blue H_2 is only 25%, and the net emission for blue H_2 and direct methane burning is the same. For blue H_2, SMR contributes to 40% of total emissions, fuel is 33%, carbon capture 11% and natural gas extraction process is 14%.

For a 100-year lifetime, the methane leak contribution to net CO_2 emissions significantly reduces (21% for grey H_2, 40% for blue H_2, 50% for turquoise H_2 and 25% for direct methane burning). In addition, blue H_2 reduces the net CO_2 emissions by 50% and 30% compared to grey H_2 and direct methane burning. Using renewable as an energy source (Turquoise hydrogen) helps reduce CO_2 emissions by 60% to direct methane burning, and by 30% compared to blue H_2 (>60% reduction in net CO_2 emissions). The other benefit of turquoise H_2 is up to 50% reduction in carbon capture compared to blue H_2.

Major contributors to net CO_2 emissions are methane leakage and fuel energy requirements. Here, we have studied the sensitivity of important parameters affecting the H_2 carbon footprint.

Methane leakage

Methane leakage is a function of extraction, compression, transportation, and storage [14–16]. Different values for methane leakage have been reported in literature. Here we have varied the methane leakage from 0-5%. For a 20-year lifetime, the methane leakage needs to lower than 3.5% for blue H_2 to be environmentally friendly compared to direct methane burning. For a 100-year lifetime, the blue H_2 gives superior performance to direct methane burning and is 28% lower than direct during of methane even at 5% methane leakage. Reducing the methane leakage from 3.5% to 1%, reduces the net CO_2 emissions for blue H_2 by 55% and 36% for 20-year and 100-year lifetimes, respectively (Figure A2 (a) and (b)). Therefore, the focus should be to minimize the methane leakage, especially for shorter methane lifetimes, as the penalty due to methane leak can be severe.

However, turquoise H_2 needs methane only for SMR, while direct methane burning needs methane as fuel; therefore, the improvement in net CO_2 emissions with turquoise H_2 remains constant at 50% and 63% as a function of methane leakage for a lifetime of 20 years and 100 years (Figure A2 (a) and (b)).

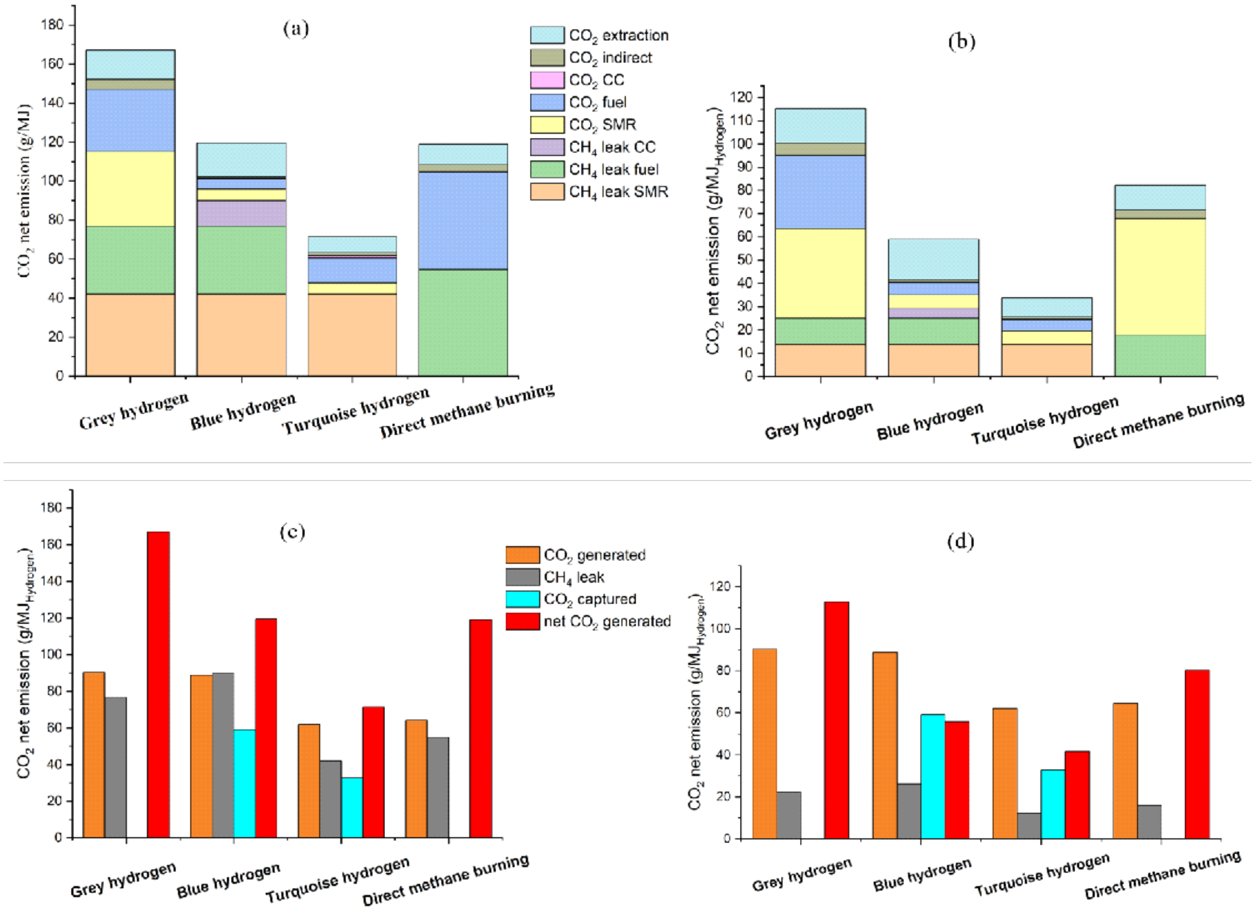

Figure A1: CO_2 net emission source breakdown as a function of methane lifetime (a) 20 years (b) 100 years. Plot of carbon emission and captured as a function of methane lifetime (c) 20 years and (d) 100 years. Methane leakage is fixed at 3.5%, SMR energy consumption of 2.25 kWh/m^3, carbon capture efficiency and energy consumption 85%.

SMR energy consumption

Steam methane reforming (SMR) is an energy-intensive process with energy consumption of 2.25 kWh/m$^3_{H2,STP}$[12]. Stoichiometric ratio of steam and methane is 2; however, to improve the reaction kinetics and conversion ratio, often the steam to methane ratio is varied between 3-4. This increases the heat requirement for the SMR process. Therefore, improving the energy efficiency of the system heat integration becomes essential, especially for feed pre-heating. The heat released from water gas shift reaction (exothermic reaction) and cooling of gas streams before it enters the PSA can also be used as a heat source for feed preheating. With optimal system design and process integration the SMR energy requirement can be brought down to 0.5 kWh/m$^3_{H2.STP}$ [10].

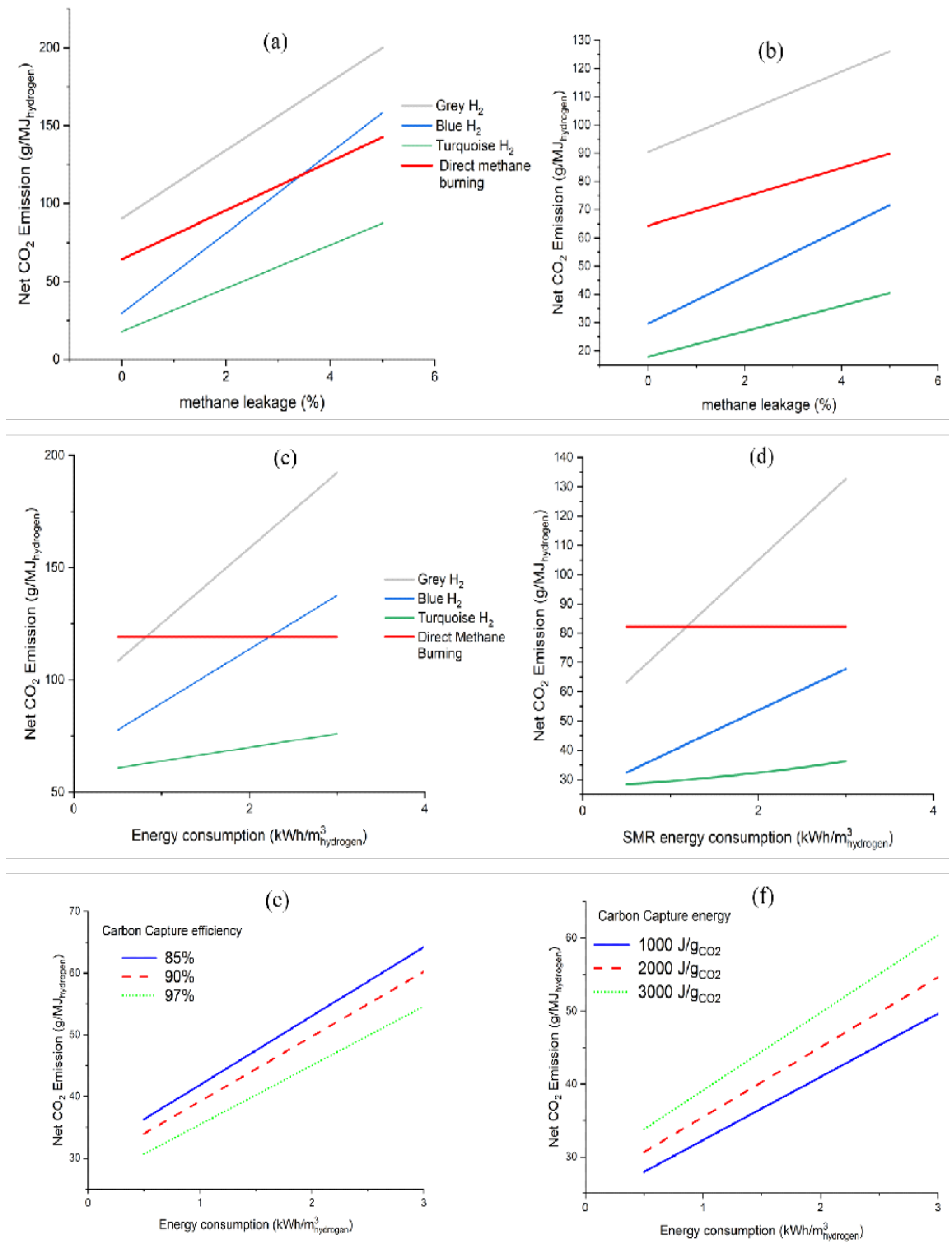

Figure A2: Net CO_2 emissions as a function of methane leakage for a lifetime of (a) 20 years (b) 100 years, while the SMR energy requirement, carbon capture efficiency and energy requirement are kept constant at 2.25 kWh/m^3, 85% and 2000 J/g_{CO2}. Net CO_2 emission as a function of SMR energy requirement for a lifetime of (c) 20 years (d) 100 years, while the methane leakage, carbon capture efficiency and energy requirement are kept constant at 3.5%, 85% and 2000 J/g_{CO2}. Net CO_2 emission as a function of SMR energy requirement and (e) carbon capture efficiency (f) carbon capture energy requirement, while the methane leakage, carbon capture energy requirement (e) and efficiency (f) are kept constant at 3.5%, 2000 J/g_{CO2} and 85%.

Reducing the SMR energy consumption from 2.25 to 0.5 $kWh/m^3_{H2,STP}$ can reduce the net CO_2 emission by 50% for blue H_2. Additionally, lower energy consumption of 0.5 $kWh/m^3_{H2,STP}$ lowers the net CO_2 emission by up to 50% compared to direct methane burning. While with turquoise H_2, reducing the SMR energy consumption from 2.25 to 0.5 $kWh/m^3_{H2,STP}$ gives a marginal improvement of 15% (Figure A2 (c) and (d)).

Carbon capture efficiency and energy consumption

Carbon capture efficiency and energy requirement can be critical in the advancement of the blue H_2 technology and is shown in Figure A2 (e) and (f). Recently, the Department of Energy issued a funding opportunity announcement that focused on increasing the carbon capture efficiency from 85% to 97%. This would result in a marginal improvement of 16%, similarly reducing the carbon capture energy consumption from 3000 J/g_{CO2} to 1000 J/g_{CO2} reduces the net CO_2 emission by 15%.

Based on a sensitivity analysis, it can be concluded that methane leakage and SMR energy consumption are major contributors to net CO_2 emission.

Use of various renewable energy sources as fuel for hydrogen

For turquoise H_2, different renewable energy sources can be used as a heat source, including solar photovoltaics (PV), wind energy, and concentrating solar thermal (CST). The renewable energy source is an intermittent source of energy and has a low annual capacity factor. Where capacity factor is defined as the ratio of actual annual generation to the amount generated had the plant operated at its nameplate capacity for the entire year [16]. Lower capacity factor will reduce the operation hour of the plant. To meet the SMR annual demand, energy storage for renewable energy is required. Since solar PV and wind produce electricity, we have used battery energy storage. Concentrating solar power typically uses molten storage tanks to increase its capacity factor to 60%. The remaining heat can be supplied by blue H_2.

Figure A3 shows the comparison between different energy sources for turquoise H_2 compared to blue H_2. It is interesting to note for turquoise H_2 powered by solar PV, the net CO_2 emissions are greater than blue H_2. This is due to lower capacity factor for solar PV systems, and use of battery storage for the remainder. Batteries for energy storage have a high carbon footprint and have an efficiency of 80%, which further increases the net input electricity required. The overall effect is a higher carbon footprint of turquoise H_2 compared to blue H_2. Since wind energy has lower carbon footprint than solar PV and higher capacity factor, using wind energy helps in reducing the CO_2 emission by 10-20% compared to blue H_2. CST has the lowest carbon footprint and use of thermal energy storage increases the net capacity factor. This results in significant improvement in the system performance compared to blue H_2 and can help in reducing the net CO_2 emission by 50%.

Table A1. Operating parameters for various renewable energy sources [13,17,18]

	Capacity factor	Emission (g/kWh)
Wind	50%	20
Solar photovoltaics	27%	50
Concentrating solar thermal	65%	10
Battery efficiency/emission	85%	100

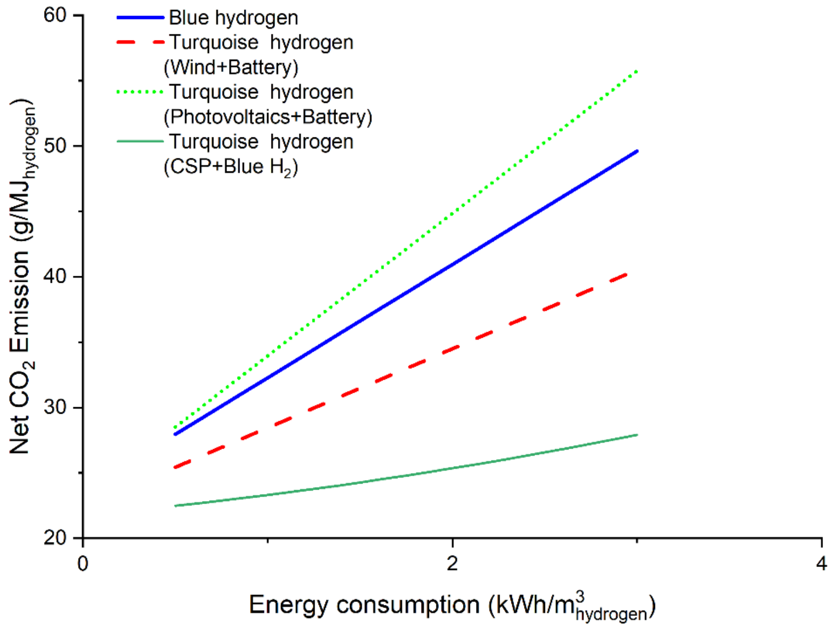

Figure A3: Comparison between the performance of blue H_2 and turquoise H_2 powered with different renewable energy sources, including solar photovoltaics, wind energy, and concentrating solar thermal. Methane leak and carbon capture efficiency and energy requirements are kept constant at 3.5% and 85% for a 100-year methane lifetime.

Regional Hydrogen

Figure A4 shows the breakdown for methane leakage. The major contributor is the gas compressor, where the gas leaks through the rod packing case for the reciprocating compressor and from wet seals for the centrifugal compressor. The methane needs to pressurize to 1000 psi for interstate transfer. Storage and pipeline methane leakage accounts for 27% of the methane leakage, which can be caused by gas diffusing out, value and pipe leakage. Drilling and extraction contribute to 28% emissions, which can be due to flaring of gases and does not meet the required standard and leakage from the pipelines [14,15].

Instead of compressing the methane and transporting it for H_2 production from SMR, the H_2 can be produced regionally by co-locating the SMR process close to the methane gas extraction location. It will also provide an easy opportunity for CO_2 sequestration. However, the energy density of H_2 is around 3 times lower compared to methane (11.5 $MJ_{H2,STP}/m^3$ and 35.5 $MJ_{CH4,STP}/m^3$). This increases the parasitic pumping energy requirement from 4% for methane to 15% for H_2. Additionally, with the H_2 being a much lighter fluid compared to methane, it will have higher leakage (in range of 1.5-3 times higher compared to methane). In this analysis, we assumed the H_2 leak rate to be 2.5 times that of methane. Also, H_2 has a global warming potential of 19 and 5 for 20-year and 100-year lifetimes [19].

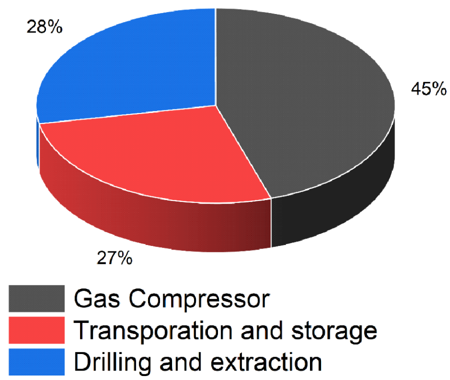

Figure A4: Methane leakage breakdown [14,15].

As shown in Figure A5, with regional H_2 production the net CO_2 emission from blue H_2 is 60% lower compared to direct methane burning. For a methane lifetime of 20 years, and for methane leakage >3.5%, even regional grey H_2 gives superior performance compared to direct methane burning. Therefore, co-locating the methane extraction process with the SMR process can significantly reduce CO_2 emissions. Turquoise H_2 can reduce net CO_2 emissions by 80% compared to direct methane burning.

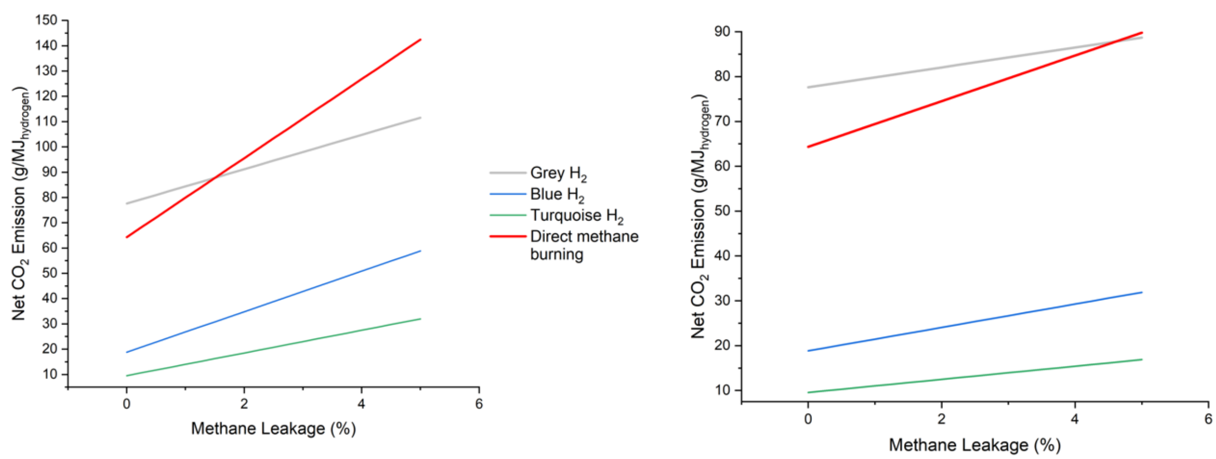

Figure A5: Net CO_2 emissions for regional H_2 as a function of methane leakage for a methane lifetime of (a) 20 years and (b) 100 years, while the SMR energy requirement, carbon capture efficiency and energy requirement are kept constant at 2.25 kWh/m^3, and 85%.

I-WEST

Phase One Final Report | Detailed Chapter

Hydrogen Demand

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About this chapter

The Intermountain West Energy Sustainability & Transitions (I-WEST) initiative is funded by the U.S. Department of Energy to develop a regional technology roadmap to transition six U.S. states to a carbon-neutral energy economy. I-WEST encompasses Arizona, Colorado, Montana, New Mexico, Utah, and Wyoming. Each state is represented in this initiative by a local college, university, or national laboratory. Additional partners from beyond the region were selected for their expertise in applicable fields. In the first phase of I-WEST, the team built the foundation for a regional roadmap that models various energy transition scenarios, including the intersections between technologies, climate, energy policy, economics, and energy, environmental, and social justice. This chapter presents work led by an I-WEST partner on one or more of these focus areas. A summary of the entire I-WEST phase one effort is published online at www.iwest.org.

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Table of Contents

Key Findings

- Hydrogen (H_2) has potential to be a viable and affordable transition fuel as the Intermountain West shifts from carbon-based energy sources to more sustainable options within a framework of a larger place-based energy transition for the region.
- 2019 Intermountain West Highway Transportation:
    - Approx. 18.4 million registered vehicles in the region
    - Requires approx. 1361 PJ of fuel: 8.3 billion gal gasoline and 2.1 billion gal diesel
    - Emits approx. 88.8 Mt CO_2
- Category-Specific Vehicle CO_2 Footprint
    - Categories: Motorcycles, Cars, Light Trucks (< 10,000 lbs.), Medium-Heavy Trucks (> 10,000 lbs.), and Buses
    - Med-Hvy Trucks emit more CO_2 per year per vehicle than other categories by far
        - 26.2 t CO_2 yr-1 veh-1
        - 4.8% of vehicles, consume 24.7% of fuel, emit 26.2% of CO_2
    - Med-Hvy Trucks are class to target for replacement first
- Requirements for replacement of all Internal Combustion Engine Vehicles (ICEVs) with Fuel Cell Electric Vehicles (FCEVs):
    - Requires between 2.6 and 6.1 Mt H_2 (depends on tank-to-wheels efficiencies of ICEVs replaced)
    - Water necessary:
        - If Blue H_2: Between 120.9 – 284.9 Mt H_2O
        - If Green H_2: Between 32.8 – 77.3 Mt H_2O
- Hydrogen Blending: Theoretically possible to reduce CO_2 emissions from combustion of natural gas
    - 12 blending pilot projects announced or in-process in U.S; only two in the Intermountain West
    - Gas utilities in the U.S. and Europe claim success at H_2 blend fractions of $y_{H2} \leq 0.2$
- CO_2 emissions reduction not linear with increase in H_2 blend fraction
    - H_2 has lowest energy density of any fuel (H_2-Natural Gas blend will have lower energy density than original natural gas stream)
    - Requires compensation by increasing blend consumption to avoid performance loss at appliances of end user
        - yH_2 = 0.20 à 16 vol% more gas required à Only 6.9% CO_2 reduction

Introduction

The transition to sustainable energy sources has already begun in much of the world. There is an overwhelming international scientific consensus that severe reductions in anthropogenic greenhouse gas (GHG) emissions are required in order to limit global warming to less than 1.5 °C relative to pre-industrial quantities—the threshold necessary to mitigate the effects of irreversible climate change [1]. To this end, the Biden administration has rejoined the Paris Agreement on Climate Change [2] and established a GHG reduction goal of 50% from 2005 levels for the U.S. by 2030 [3]. Additional U.S. goals include 100% carbon-free electricity by 2035 and a completely carbon-neutral U.S. economy by 2050 [3].

Hydrogen (H_2) is anticipated to be a significant carbon-free energy vector in the transition away from fossil energy systems, and may gain permanence as the principal chemical energy carrier once the transition is complete [4]. The most significant uses for hydrogen are in refinery operations and the production of ammonia and methanol [5]. However, hydrogen has tremendous potential as a carbon-free energy carrier as it can be sustainably produced from several energy sources including solar, wind, biomass, and decarbonized fossil fuels [6,7]. It produces zero carbon emissions when combusted and only water is emitted when hydrogen is used in a fuel cell to make electricity [6,8]. Hydrogen can also be blended and transported with natural gas to partially decarbonize natural gas consumption [9]. Furthermore, hydrogen has the largest energy density by mass of any common fuel [10].

The I-WEST initiative is developing a technology roadmap for sustainable energy transition for six states in the Intermountain West—Arizona, Colorado, Montana, New Mexico, Utah, and Wyoming—using a place-based approach that focuses heavily on engagement with relevant stakeholders and investment from local communities [11]. These states have environmental and geographic similarities that offer unique sustainable energy and GHG reduction possibilities. I-WEST is supported by the U.S. Department of Energy and led by Los Alamos National Laboratory in partnership with regional colleges and universities, other national laboratories, and a non-profit entity with expertise in energy-related policy.

Hydrogen employment is especially relevant for the Intermountain West as it is a practical transition technology that can supplement the current fossil-energy production portfolio of the region while drawing on the significant solar, wind, and geothermal resources that are locally available. Currently, hydrogen production is at or near zero within the region. However, hydrogen employment has the potential to become an affordable and abundant regional energy carrier as regional hydrogen production increases and relevant technologies improve and are adopted.

In this report, hydrogen utilization is considered via a "first-pass" analysis of (i) adoption of fuel cell electric vehicles (FCEVs) and (ii) blending of hydrogen with natural gas as potential CO_2 emissions reduction vectors within the Intermountain West. A base case and current state of GHG emissions is presented, followed by a discussion of relevant technology leading to hydrogen remediation of the base case. Some necessary infrastructure is mentioned with discourse regarding the amount of hydrogen possible under various constraints. The present work offers a partial overview of hydrogen utilization options for the realization of a regional hydrogen economy.

Fuel cell electric vehicles

Figure 1 shows a generic schematic of a hydrogen fuel cell (or proton exchange membrane fuel cell) and Figure 2 shows a diagram of a typical FCEV [12]. The fuel cell functions by converting hydrogen (fuel) and O_2 (from air) into electricity while emitting only water vapor. The electricity is used to turn an electric motor similar to battery electric vehicles (BEVs). As such, tailpipe CO_2 emissions are reduced to zero when an internal combustion engine vehicle (ICEV) is replaced with a FCEV.

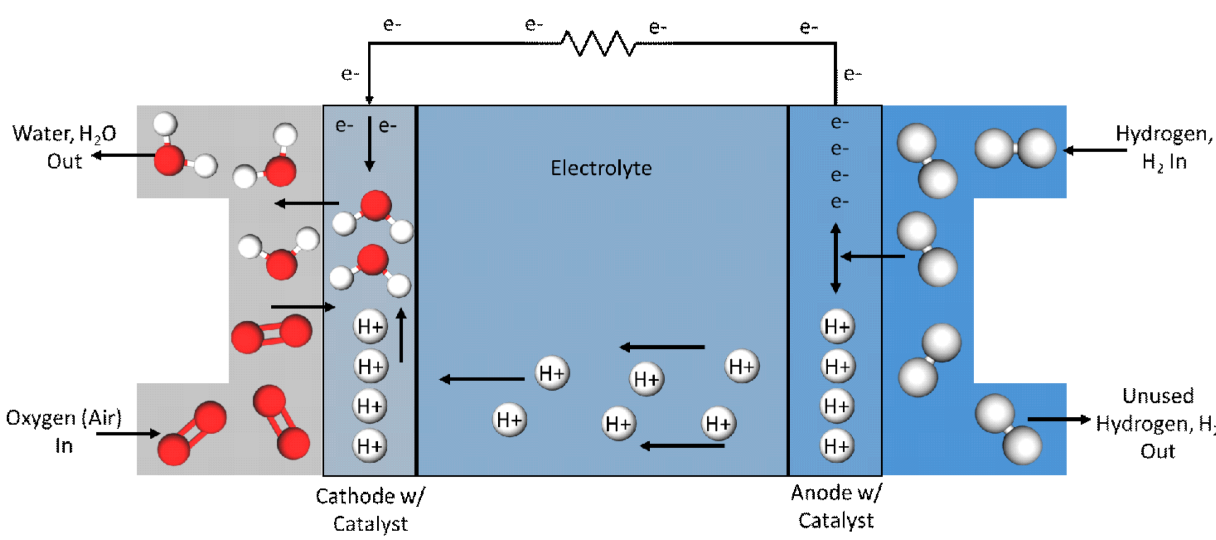

Figure 1. Schematic of a hydrogen fuel cell combining diatomic hydrogen with diatomic oxygen (O_2, from air) to produce electricity. Water is the only emission.

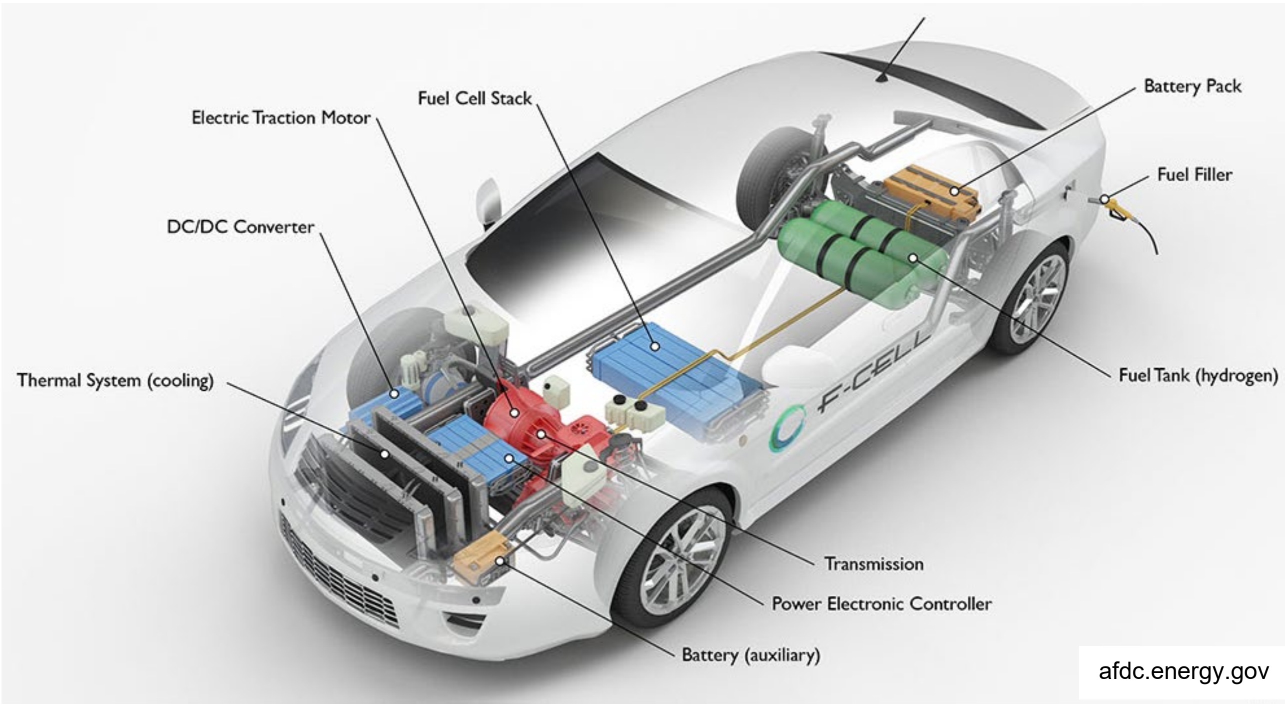

Figure 2. Diagram of a hydrogen fuel cell vehicle, showing major components [from 12].

Hydrogen fuel cell technology is well established and has existed for many decades [13,14]. While FCEVs are commercially available [15,16] adoption of FCEVs remains elusive due to FCEV cost relative to conventional ICEVs and lack of hydrogen infrastructure [17]. Though, more recently, FCEVs have been approaching cost parity with new vehicles due to the rising expense of the average new vehicle in the U.S. [15,18]. Currently, California leads the U.S. in employment of hydrogen fueling infrastructure and FCEV adoption with 58 fueling stations in operation and 11,800 FCEVs on the road [19,20]. This arises, in part, from the 168 laws and incentives related to alternative fuels and vehicles in CA. Specifically, the California Clean Vehicle Rebate Project provides fuel vouchers and rebates for FCEVs to encourage adoption [20]. In contrast, the entire Intermountain West region has only two *private* hydrogen filling stations (one each in AZ and CO) and zero FCEVs registered (see Figure 3) [20].

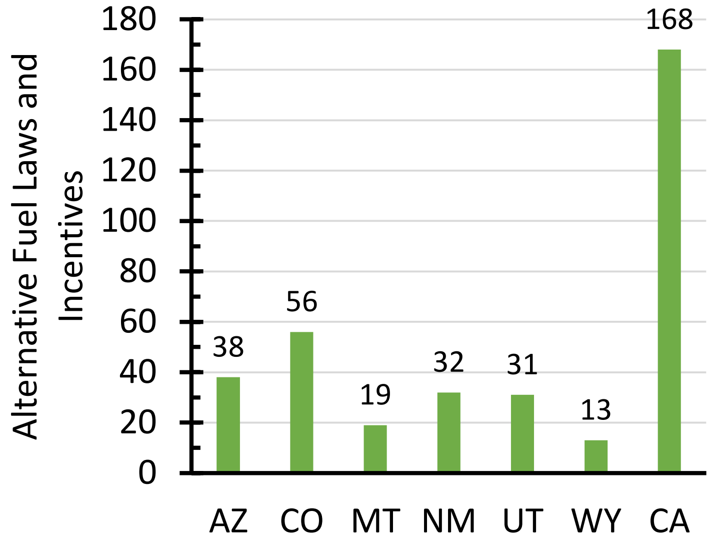

Figure 3. Laws and incentives as of 2022 in the Intermountain West region. CA leads the U.S. [20].

Both electricity (batteries) and hydrogen are energy carriers that possess similarities as well as unique opportunities and drawbacks in a carbon-neutral energy transition. Both FCEVs and BEVs produce zero tailpipe emissions, employ electric motors, and can be sustainably fueled or charged [6,21]. FCEVs are similar to conventional ICEVs as they have a range of over 300 miles and can be refueled in less than 20 minutes at a hydrogen fueling station [21]. This is especially important as vehicles within the Intermountain West spend more miles on rural roads relative to vehicles in the broader U.S., as shown in Table 1 [22]. Vehicles that drive more on rural systems, as shown for MT, NM, and WY, can expect to require a greater range between refueling. This is important as BEVs may require more downtime for recharging until high-power charging solutions become available. The greater range possessed by FCEVs is attributable to the larger energy density by mass of hydrogen relative to that for batteries. That is, FCEVs are lighter overall, which becomes increasingly important as the vehicle increases in size. For this reason, FCEVs are considered the lowest-cost choice for decarbonizing medium and heavy duty vehicles [23].

One of the primary obstacles to mass adoption of FCEVs relates to inefficiency of hydrogen storage. Hydrogen has the greatest energy density by mass, but it also has the lowest energy density by volume {7, 21]. This means that hydrogen requires significant compression to achieve efficient storage (700 atm in an FCEV) or liquefaction [21]. Furthermore, because hydrogen is the lightest (and simplest) gas, liquefying it requires approximately one-third of the energy stored in the hydrogen [6]. Proposed solutions to these problems have included using ammonia (NH_3) or dimethyl ether (DME) as hydrogen carriers because both molecules have greater hydrogen densities than hydrogen itself [24,25].

State	Rural (Million Miles yr^{-1})	Urban (Million Miles yr^{-1})	% Rural (--)	% Urban (--)
AZ	16,690	53,591	23.7%	76.3%
CO	16,216	38,418	29.7%	70.3%
MT	8,941	3,951	69.4%	30.6%
NM	16,423	11,349	59.1%	40.9%
UT	8,888	24,023	27.0%	73.0%
WY	7,190	3,018	70.4%	29.6%
I-WEST	74,347	134,349	35.6%	64.4%
U.S.	983,853	2,277,919	30.2%	69.8%

Table 1. 2019 Annual vehicle miles traveled by Intermountain West state compared to the broader U.S. [22].

Hydrogen blending with natural gas

Hydrogen blending may be an important transition step toward decarbonization, while minimizing energy disruptions for both producers and consumers [26]. Blends of hydrogen with natural gas (5-20 vol% H_2) are a potential opportunity to reduce combustion CO_2 emissions (i.e., residential or commercial appliances), though drawbacks may remain [27]. Hydrogen blending has been considered as a way to increase the output of renewable energy systems [9]. Employment of downstream separation operations has even been suggested as a way of supplying pure hydrogen via blending with natural gas [9].

Natural gas utilities in the U.S. have announced 26 pilot projects since 2020, 12 of which include hydrogen blending [28]. SoCalGas announced in 2021 that it has successfully blended 20% hydrogen in a closed-loop system [29]. Furthermore, German grid operator Avacon has successfully tested both 10% and 15% hydrogen blends, while 20% blends are planned in 2023 [30]. Of the 12 hydrogen blending projects announced, only two are located in the Intermountain West. A project in Colorado is performed by a collaboration between the U.S. Department of Energy and about 20 industry, academia, and public partners [28], and a project in Tempe, Arizona is conducted by a collaboration between Southwest Gas Holdings Co. and Arizona State University [28]. Both projects seek to evaluate optimal blend ratios, investigate impact on pipelines and infrastructure, and identify economic risks and opportunities [28].

Despite recent interest by natural gas utilities in hydrogen blending, potential drawbacks exist which may limit emissions reduction via blending. Hydrogen combustion in air can yield nitrogen oxides (NO_x) which can be a potent pollutant with a global warming potential 273 times that of CO_2 over 100 years [31,32]. Hydrogen has a global warming potential that is 5.8 times that of CO_2 over 100 years [33], and is more likely to leak in existing natural gas infrastructure due to the smaller size of hydrogen.

Methods

Highway transportation and fuel cell electric vehicles

The U.S. transportation sector generated 27% of total GHG emissions in 2020; the largest percentage of all economic sectors [34]. This principally arises from the burning of fossil fuels, and corresponding GHG emissions in transportation vehicles [34]. Conversion from conventional ICEVs to FCEVs presents an opportunity to reduce tailpipe GHG emissions to zero. Hydrogen FCEVs report a fuel efficiency (percentage of chemical energy converted into kinetic energy of the vehicle) of 42-64% [35-38], whereas conventional ICEVs can achieve a maximum efficiency of 42% [37,39,40].

The following analysis of highway CO_2 emissions is based on the number of registered vehicles reported N^{Fuel}_{Type} in 2019 for each Intermountain West state for the vehicle types of motorcycles, cars, light trucks, medium-heavy trucks, and buses [41-43]. Light trucks are those with a gross vehicle weight rating (GVWR) < 10,000 lbs. and include minivans and SUVs [44]. Medium-heavy trucks are those for which the GVWR > 10,000 lbs. (class 3-8 vehicles) [44,45]. The average fuel efficiencies for each vehicle type [$\varepsilon^{Fuel}_{Type}$, (miles gal^{-1})], type of fuel used (gasoline or diesel), and annual vehicle miles traveled [VMT_{Type} (miles yr^{-1} veh^{-1})] for each vehicle class are assumed to reflect the average efficiencies and VMT of the national vehicle stock [44, 46, 47]. Equation 1 provides the average annual fuel consumed [AFC^{Fuel}_{Type} (gal yr^{-1} veh^{-1})] for each vehicle type.

$$AFC^{Fuel}_{Type} = \frac{VMT_{Type}}{\varepsilon^{Fuel}_{Type}} \quad (1)$$

The product of the annual fuel consumed and number of registered vehicles produces the total annual fuel consumed [$TAFC^{Fuel}_{Type}$ (gal yr^{-1})] for each vehicle category according to Equation 2.

$$TAFC^{Fuel}_{Type} = AFC^{Fuel}_{Type} \times N^{Fuel}_{Type} \quad (2)$$

Mass of CO_2 emitted m^{Type}_{CO2} (kg) is simply the product of the total annual fuel consumed and the CO_2 literature coefficient k^{Fuel}_{CO2} (kg CO_2 gal^{-1} Fuel) provided by EIA as shown in Equation 3 [48].

$$m_{CO_2}^{Type} = TAFC_{Type}^{Fuel} \times k_{CO_2}^{Fuel} \quad (3)$$

Note, the present work does not consider the tailpipe emissions of out-of-region vehicles, that is, those vehicles registered in a state other than a state under assessment by I-WEST, unless the vehicle is also registered within one of the states.

Hydrogen blending with natural gas

The efficacy of hydrogen blending in natural gas streams is evaluated by calculating the reduction in CO_2 emissions obtained via blending at several hydrogen volume fractions between zero and one. As the volume fraction of hydrogen increases, the fraction of natural gas in the binary mixture decreases. Additionally, the absolute volume of the natural gas constituent also decreases even though the total volume of the stream increases to compensate for the reduced volumetric energy density of the hydrogen on the basis of lower heating value (LHV) [49]. Equation 4 shows the calculation of CO_2 emitted as a function of volume fraction hydrogen (y_{H2}).

$$m_{CO_2} = \frac{LHV_{NatGas}\rho_{NatGas}(y_{H_2} - 1)M_{CO_2}}{M_{CH_4}\left[LHV_{NatGas}\left(y_{H_2} - 1\right) - LHV_{H_2}y_{H_2}\right]} \quad (4)$$

Where m_{CO2} (kg) is the mass of CO_2 emitted, LHV_{NatGas} (MJ m^{-3}) is the lower heating value of natural gas, ρ_{NatGas} (kg m^{-3}) is the density of natural gas, M_{CO2} (kg $kmol^{-1}$) is the molar mass of CO_2, M_{CH4} (kg $kmol^{-1}$) is the molar mass of natural gas (assuming 100% of natural gas is CH_4), and LHV_{H2} (MJ m^{-3}) is the lower heating value of hydrogen [51,51].

Results and Discussion

Fuel cell electric vehicles

A summary of the registered vehicles, estimated fuel consumption, and CO_2 emissions for the Intermountain West are presented in Table 2. Figure 4(a) shows light-duty vehicle stock (cars and light trucks) in each state where light trucks are defined as all trucks with a GVWR < 10,000 lbs. including minivans and SUVs [45]. Figure 4(b) shows the medium-heavy vehicle stock (GVWR > 10,000 lbs.) in each state separated by fuel type. While cars and light trucks are predominantly gasoline ICEVs (not shown in Figure 4a), most medium-heavy vehicles use diesel. Figure 4 (c) shows the registered vehicles by vehicle type for the region. Light trucks (including minivans and SUVs) make up the largest share followed by cars. Buses total less than 50,000. The number of registered vehicles tracks closely with state population data (see Regional Overview chapter). There are over 18.4 million registered vehicles in the Intermountain West; in principle, each vehicle is a potential candidate for replacement with a FCEV.

Vehicle Type	No. of Registered Vehicles		2019 Fuel Consumed		Annual CO_2 Emissions	
	(No.)	(%)	(PJ yr^{-1})	(%)	(10^6 t CO_2)	(%)
Motorcycles	880,486	4.8%	4.9	0.5%	0.3	0.4%
Cars	6,345,959	34.5%	275.7	25.2%	17.6	19.8%
Light Trucks	10,259,920	55.7%	730.9	64.9%	46.7	52.6%
Med-Heavy Trucks	885,938	4.8%	336.8	9.2%	23.2	26.2%
Buses	43,241	0.2%	12.9	0.2%	0.9	1.0%
Total	18,415,544	100.0%	1361.2	100.0%	88.8	100.0%

Table 2. 2019 estimated fuel consumption and CO_2 emissions in the Intermountain West region by vehicle type. Light trucks are those where GVWR < 10,000 lbs. including minivans and SUVs. Med-Heavy trucks are those with GVWR > 10,000 lbs.

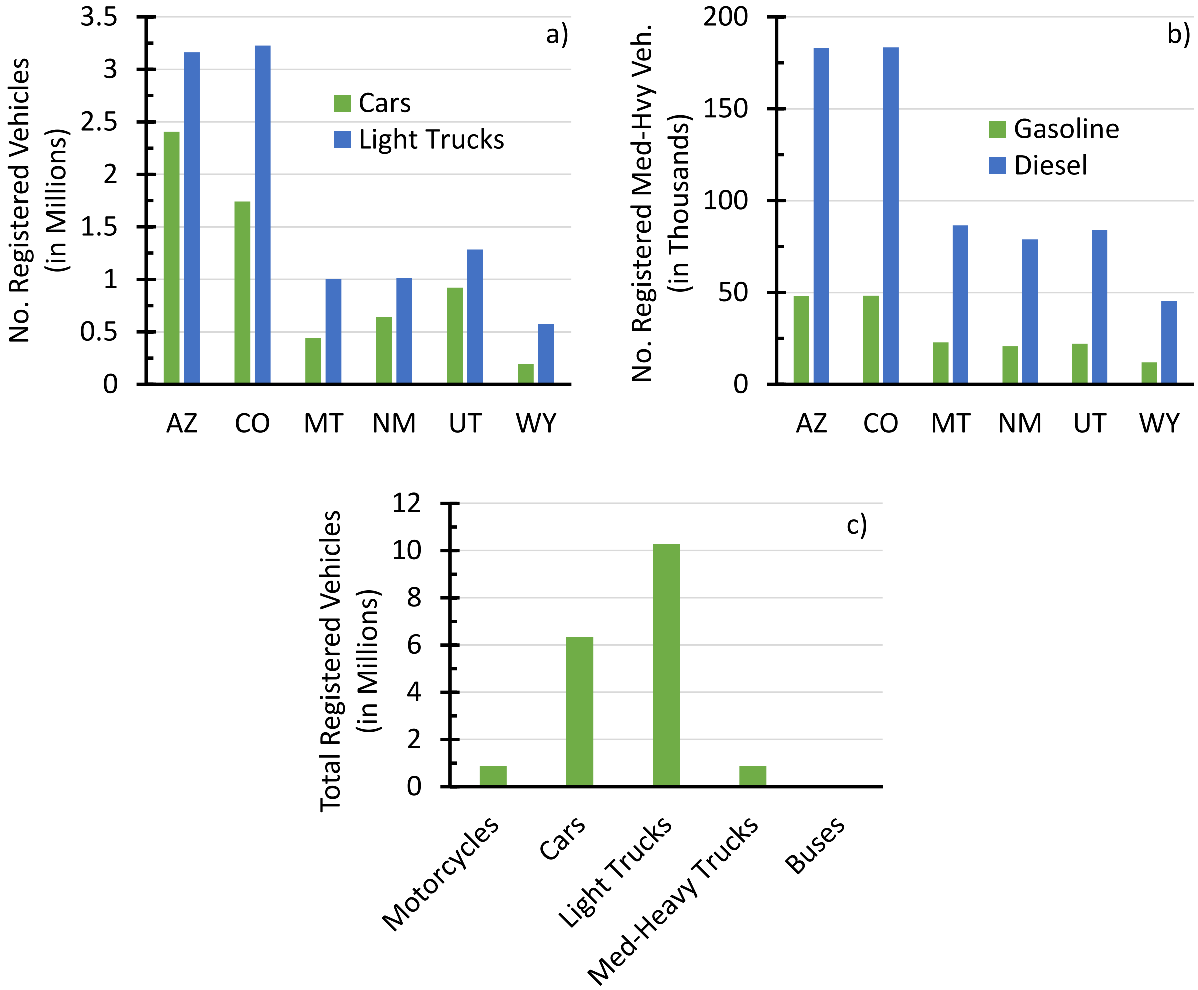

Figure 4. a) 2019 registered light-duty vehicles (cars and light trucks) in each state. b) 2019 registered medium and heavy trucks in each state. c) 2019 total registered vehicles in the entire region by vehicle type (see Table 2). Cars and light-duty trucks are Class 1 and 2 vehicles where the GVWR ≤ 10,000 lbs.; medium-heavy trucks are Class 3-8 vehicles where GVWR > 10,000 lbs. Categories with "truck" labels include vans and SUVs.

Figure 5 shows the amount of highway fossil fuel consumed in 2019 by a) state and fuel type in billion gallons yr^{-1}, b) state and fuel type in petajoules (PJ, 10^{15}) yr^{-1}, and c) vehicle type in PJ yr^{-1} for the whole region. Gasoline engines are clearly the majority of registered vehicles in each state. This is expected as gasoline engines are the primary contributor to the car and light truck segments. Gasoline ICEVs include E10 engines, as almost all finished gasoline in the U.S. contains 10% ethanol, as well as ethanol flex-fuel engines.

Fuel consumption of the states tracks closely with state population data (see the Regional Overview chapter). The total highway transportation fuel consumed in the Intermountain West in 2019 is approximately equal to 1,361 PJ. This represents the sum of about 8.3 billion gallons of gasoline and 2.1 billion gallons of diesel [52].

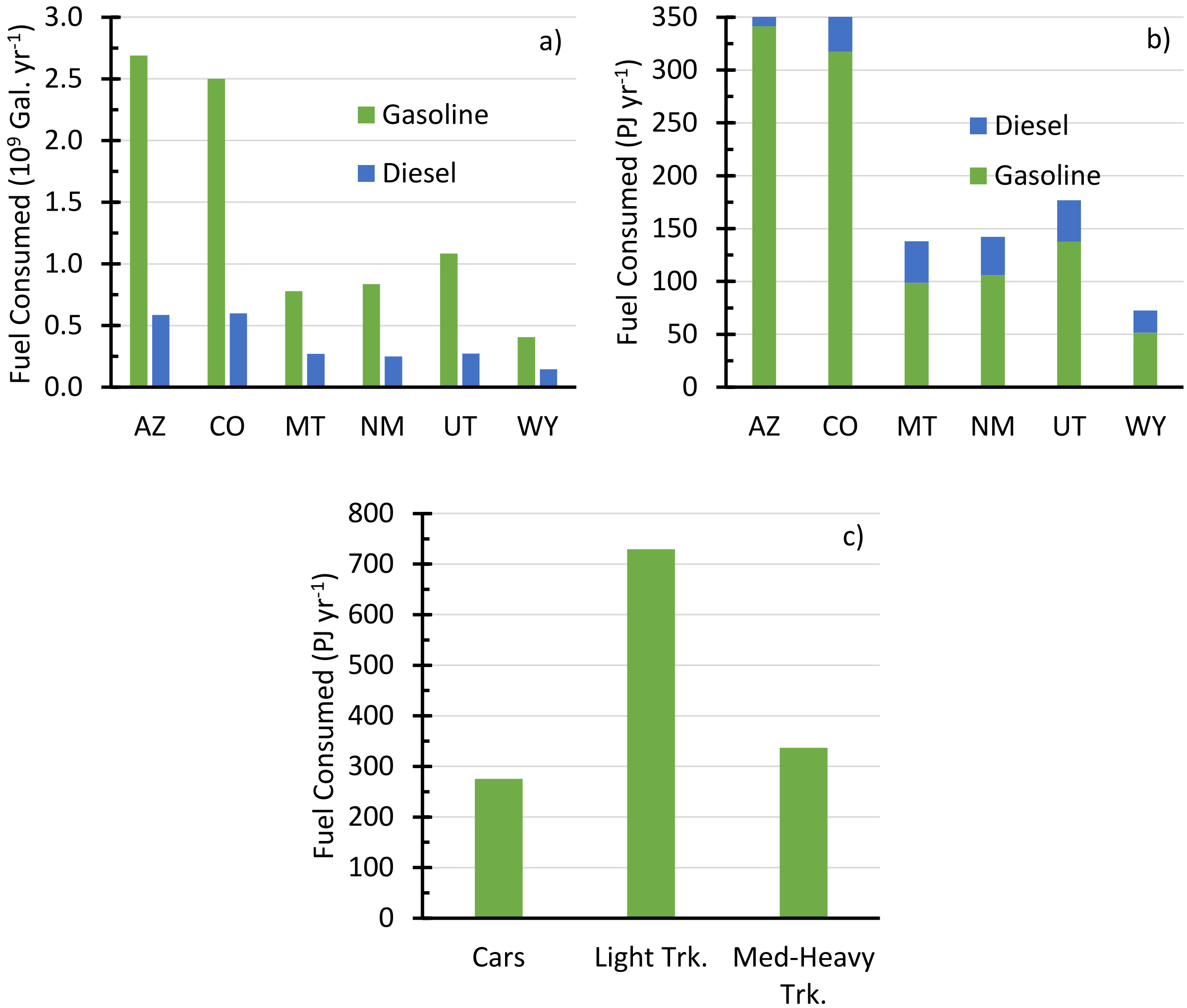

Figure 5. 2019 Intermountain West fuel consumption by a) state and fuel type in billion gallons yr-1, b) state and fuel type in PJ yr-1, and c) total highway fuel consumed in the region by vehicle type in PJ yr-1. Cars and light-duty trucks are class 1 and 2 vehicles where the GVWR ≤ 10,000 lbs.; medium-heavy trucks are class 3-8 vehicles where GVWR > 10,000 lbs. Categories with "truck" labels include vans and SUVs.

Figure 6 shows the vehicle-specific fuel consumed for each vehicle category in 2019 (except motorcycles, which were negligible). Comparing Figure 6 with Figure 4 and Figure 5, it is obvious that the cars and light trucks consume the most fuel as entire vehicle categories. However, medium-heavy trucks and buses consumed the most fuel, on average, *per vehicle*. Essentially there are significantly more vehicles classified as cars and light trucks (Table 2 and Figure 4) which, on average, spend less time each year in operation and consume less fuel per vehicle [22, 44, 46]. Conversely, vehicles classified as medium-heavy trucks and buses spend more time in operation consuming fuel [22, 44, 46].

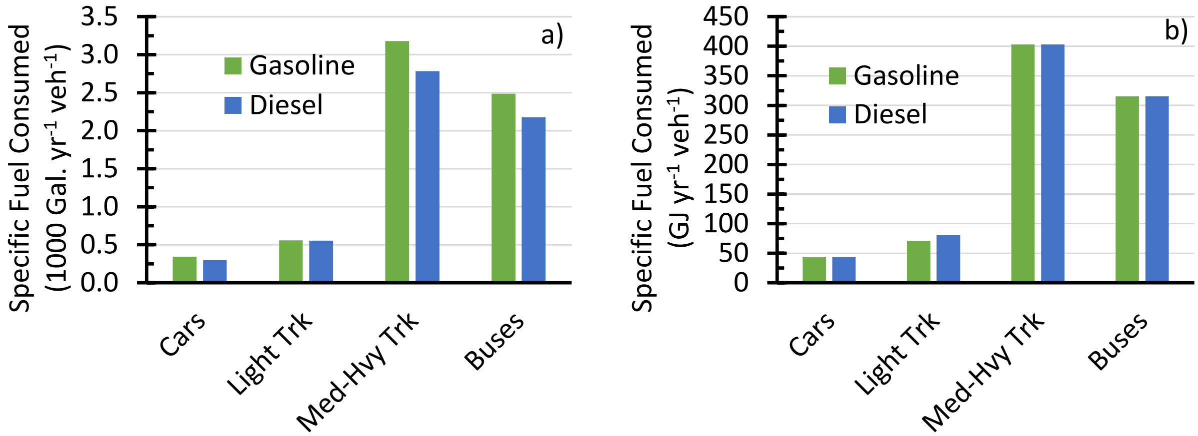

Figure 6. 2019 vehicle-specific fuel consumption for both gasoline and diesel ICEVs in a) fuel volume consumed and b) fuel energy consumed. Cars and light-duty trucks are class 1 and 2 vehicles where the GVWR ≤ 10,000 lbs.; medium-heavy trucks are class 3-8 vehicles where GVWR > 10,000 lbs. Categories with "truck" labels include vans and SUVs.

Figure 7 shows the estimated 2019 CO_2 tailpipe emissions for the Intermountain West, broken down by a) state and b) vehicle type (motorcycles and buses, not shown, produce 1% or less of CO_2, see Table 2). Tailpipe CO_2 emissions by state track closely with state fuel consumption trends (Figure 5), registered vehicles (Figure 4), and ultimately state population (see the Regional Overview chapter). Not surprisingly, the tailpipe CO_2 emissions by vehicle type also possess the same trends as fuel consumption by vehicle type (Figure 5c). That is, light trucks consume the most fuel and emit the most CO_2 as a category, followed by the medium-heavy truck segment, followed by cars. Furthermore, CO_2 emissions from gasoline ICEVs represent the majority share over diesel ICEV CO_2 emissions as a greater number of gasoline-fueled ICEVs are registered in each state, and more gasoline is consumed as well. By this estimation, tailpipe CO_2 emissions of registered vehicles in the region represent 88.8 10^6 t CO_2, or approximately 73.8% of all transportation CO_2 emissions for the Intermountain West [53].

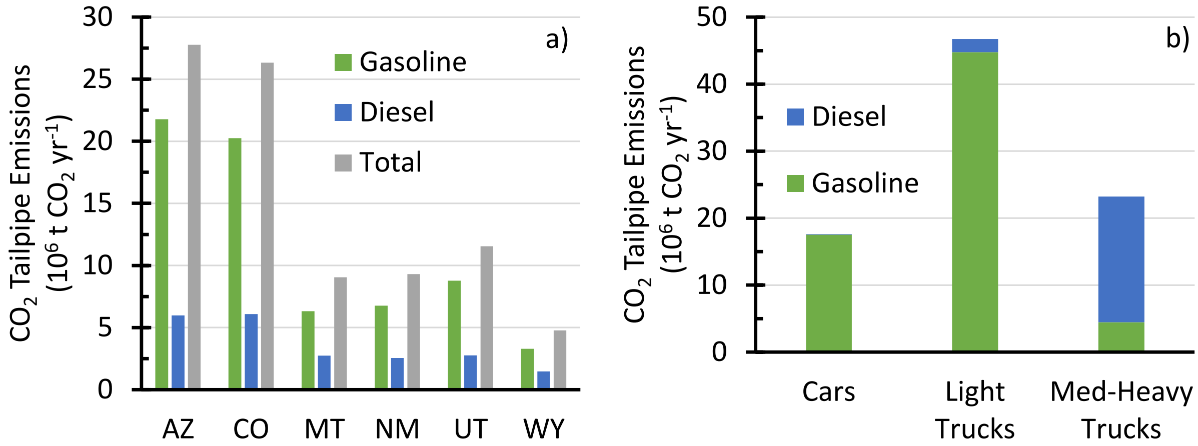

Figure 7. 2019 CO_2 tailpipe emissions by a) Intermountain West state and b) vehicle type. Cars and light-duty trucks are class 1 and 2 vehicles where the GVWR ≤ 10,000 lbs.; medium-heavy trucks are class 3-8 vehicles where GVWR > 10,000 lbs. Categories with "truck" labels include vans and SUVs.

Figure 8 represents the vehicle-specific, or average CO_2 emitted per vehicle, by a) fuel type and vehicle type, b) average value and vehicle type, c) fuel type and Intermountain West state, and d) average value and state. Comparing Figure 8 to Figure 6, it is clear that tailpipe CO_2 emissions are a function of fuel type and amount of fuel consumed in each vehicle class. Figure 8a shows that vehicle-specific CO_2 emissions generally increase with GVWR and that diesel ICEVs will emit more CO_2 than those using gasoline (diesel has a greater CO_2 emission coefficient than gasoline) [48]. Figure 8c-d show that (i) the average vehicle in each state emits similar amounts of CO_2, (ii) vehicles using diesel will emit a greater amount of CO_2 on average than those using gasoline, and (iii) average CO_2 emissions are governed primarily by gasoline ICEVs as the average values in Figure 8d are closer to parity with the gasoline values in Figure 8c (arising from the significantly greater number of gasoline-fueled ICEVs, see Figure 4).

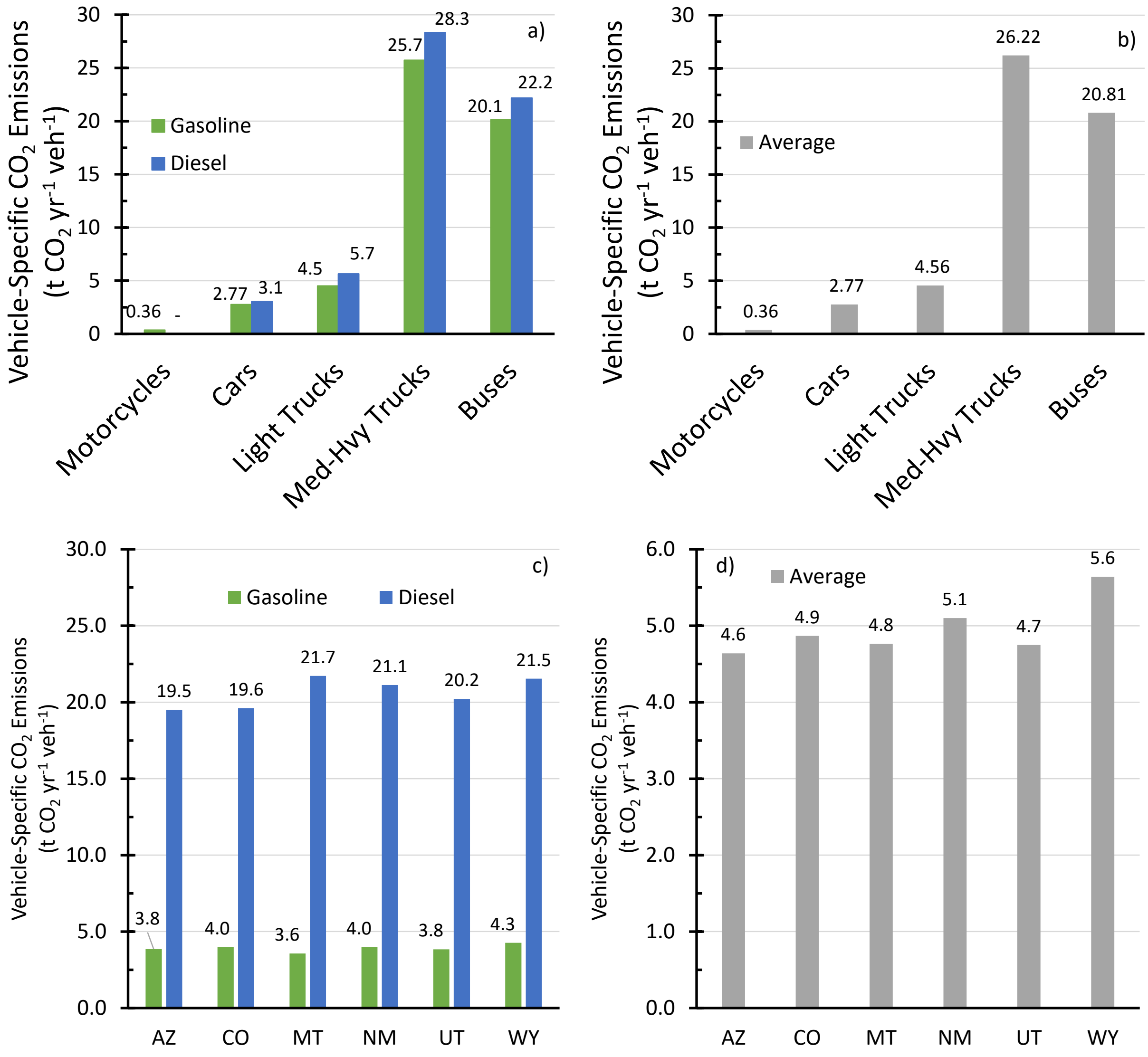

Figure 8. 2019 vehicle specific tailpipe CO_2 emissions by a) fuel type and vehicle type, b) average value and vehicle type, c) fuel type and state, and d) average value and state. Cars and light-duty trucks are class 1 and 2 vehicles where the GVWR ≤ 10,000 lbs.; medium-heavy trucks are class 3-8 vehicles where GVWR > 10,000 lbs. Categories with "truck" labels include vans and SUVs.

Perhaps most importantly, Figure 8a-b shows the average benefit that can be expected by replacing 1 ICEV with a FCEV in the region. That is, replacing an ICEV from one of the vehicle types shown in Figure 8b will yield an annual reduction in CO_2 emissions, on average, of the value shown for that vehicle type (i.e., 2.77 t CO_2 yr^{-1} veh^{-1} for cars). Knowing if the FCEV is replacing a diesel or gasoline ICEV will yield the corresponding value in Figure 8a.

As a group, light trucks represent the largest CO_2 emitter at 46.7 Mt CO_2 yr^{-1} or 52.6% of regional tailpipe CO_2 emissions in 2019. Yet, only 4.6 t CO_2 yr^{-1} veh^{-1}, on average, are saved when a light truck ICEV is replaced by a FCEV as “light trucks” are the largest vehicle category at 55.7% of vehicles in the Intermountain West region (compare Figure 8 with Figure 4 and Table 2). Conversely medium-heavy trucks emit 23.2 Mt CO_2 yr^{-1}, or 26.2% of regional tailpipe CO_2 emissions, but are only 4.8% of regional vehicles. Thus, replacing a medium-heavy truck ICEV with a FCEV will prevent 26.2 t CO_2 yr^{-1} veh^{-1}. This arises from very low diesel efficiency (approx. 8.8 avg. miles gal^{-1} diesel) [46], the greater annual vehicle miles traveled (approx. 24,465 avg. miles yr^{-1} veh^{-1}) [46], and the greater CO_2 emissions factor for diesel fuel (10.19 kg CO_2 gal^{-1} diesel vs. 8.10 kg CO_2 gal^{-1} gasoline) [46, 48]. This suggests that replacing diesel ICEVs with H_2 FCEVs is the highway transportation vector most likely to provide the best decarbonization efficiency; that is, the largest CO_2 reduction for the lowest cost or effort.

Figure 9 shows the sum of all transportation CO_2 emissions in the region, including the major contributors from the above tailpipe emissions analysis. The U.S. EIA states all transportation emissions for the region in 2019 summed to 120.3 Mt CO_2. After subtracting contributions from cars, light trucks, and medium-heavy trucks (87.5 Mt CO_2 in sum), 32.8 Mt CO_2 are absent from the current estimation. These remaining CO_2 emissions are from aviation (15.5 Mt CO_2) [54], out-of-region vehicles (vehicles not registered in an Intermountain West state) as the Intermountain West possesses two major freight corridors [52, 54-56], and other sources which include motorcycles, buses, recreational vehicles, as well as rail and marine sources [57].

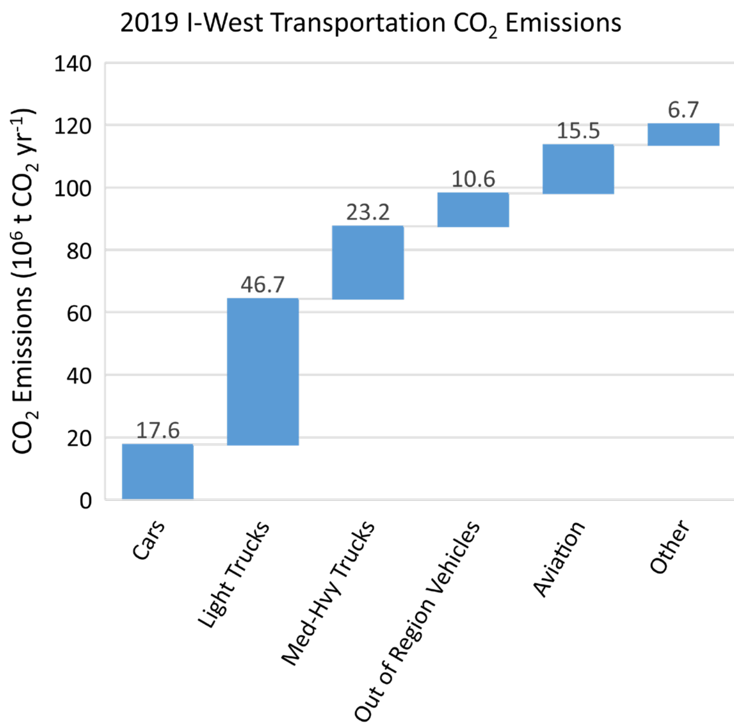

Figure 9. 2019 Transportation CO_2 Emissions in the Intermountain West region totaling 120.3 Mt CO_2. "Other" includes CO_2 emissions from motorcycles, buses, RVs, rail, and marine sources. Cars and light-duty trucks are class 1 and 2 vehicles where the GVWR ≤ 10,000 lbs.; medium-heavy trucks are class 3-8 vehicles where GVWR > 10,000 lbs. Categories with "truck" labels include vans and SUVs.

Table 3 and Figure 10 show the maximum and minimum required hydrogen and H_2O for ICEV replacement with a FCEV as a function of vehicle class. The minimum and maximum requirements are based on the maximum and minimum engine efficiencies, η_{Fuel}, for ICEVs ($0.14 \leq \eta_{Gas} \leq 0.40$, $0.28 \leq \eta_{Diesel} \leq 0.42$, and $\eta_{FCEV} = 0.64$) [38, 58, 59]. The maximum and minimum H_2O requirements are a function of the corresponding hydrogen requirement and a conversion for both blue and green hydrogen processes (see the Hydrogen Supply chapter).

Vehicle Type	H_2 Required		H_2O Required (Blue H_2)		H_2O Required (Green H_2)	
	Min Mt H_2 yr^{-1}	Max Mt H_2 yr^{-1}	Min Mt H_2O yr^{-1}	Max Mt H_2O yr^{-1}	Min Mt H_2O yr^{-1}	Max Mt H_2O yr^{-1}
Motorcycles	0.008	0.022	0.358	1.022	0.097	0.277
Cars	0.43	1.22	20.07	57.11	5.44	15.49
Light Trucks	1.18	3.24	54.89	151.39	14.89	41.06
Med-Heavy Trucks	0.94	1.55	43.75	72.53	11.87	19.67
Buses	0.04	0.06	1.79	2.79	0.49	0.76
Total	2.59	6.10	120.86	284.85	32.78	77.26

Table 3. 2019 Hydrogen and H_2O required for ICEV replacement with FCEV. Minimum and maximum values are based on minimum and maximum ICE efficiencies.

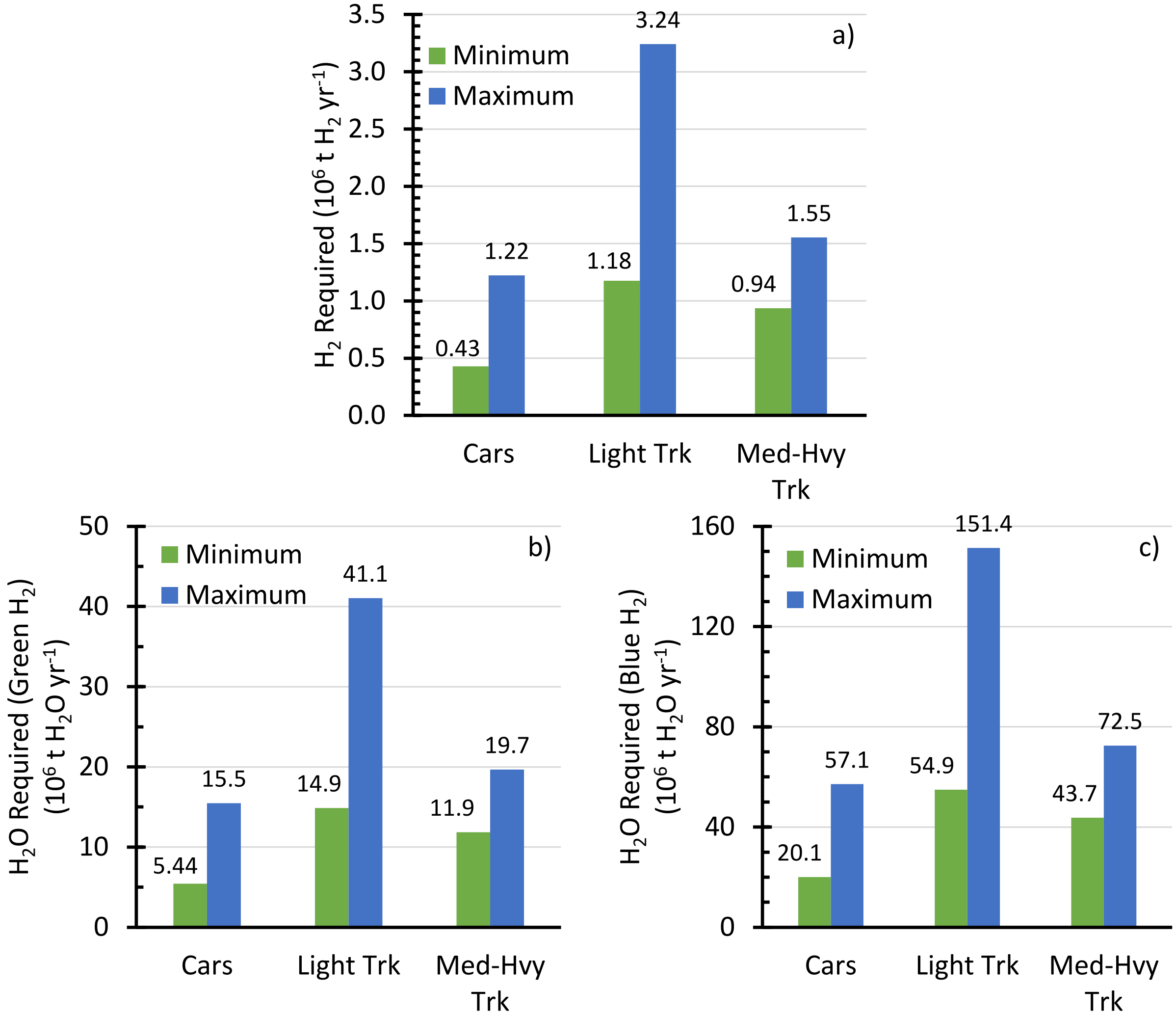

Figure 10. 2019 maximum and minimum requirements by vehicle class (depending on ICE efficiencies) for a) hydrogen, b) H_2O for green hydrogen, and c) H_2O for blue hydrogen.

Replacing all 18.4 million ICEVs registered in the Intermountain West with H_2 FCEVs will require between 2.6 and 6.1 Mt H_2 yr^{-1}. Current hydrogen production capacity in the U.S. is only approximately 10 Mt H_2 yr^{-1}, while global hydrogen production in 2021 was 94.2 Mt H_2 [60-62]. As such, replacing all regional ICEVs with FCEVs would require approximately 26-61% of all hydrogen currently produced in the U.S. or 2.7-6.5% of hydrogen globally. While this is highly improbable in the near- to medium-term, there is unprecedented momentum for hydrogen as a pivotal carbon-neutral energy carrier as the world transitions away from fossil energy [60, 63].

As previously discussed (see Figure 8), targeting the medium-heavy trucks category makes sense as an initial attempt to stimulate adoption of FCEVs as this reduces tailpipe CO_2 emissions by approximately 26.2 t CO_2 yr^{-1} veh^{-1}. Furthermore, this can be accomplished with a hydrogen requirement of about 25-36% of the hydrogen necessary to switch out all ICEVs in the Intermountain West.

Figure 11 shows the maximum and minimum hydrogen and H_2O required as a function of Intermountain West state rather than vehicle class. FCEVs and BEVs are complementary technologies. FCEVs excel in cases of heavier vehicles (as discussed above) and in cases where rural miles are driven significantly more than urban miles. As mentioned previously (see Table 1), the region has three states (MT, NM, and WY) where the annual vehicle miles traveled (VMT) were more rural than urban. While BEVs have a higher energy density than a FCEV, the hydrogen fuel has a greater energy density by mass than batteries. This makes a FCEV more suitable for heavier vehicles and longer trips [6]. Where the BEV has less of a range and may require significant down time to recharge, the FCEV can refuel in less than 20 min (similar to an ICEV) [6]. Furthermore, Figure 11a shows that the rural states MT, NM, and WY are also the states which would require the least amount of hydrogen to enable ICEV replacement by FCEVs.

Cars and light-duty trucks may provide additional opportunities for highway transportation decarbonization in the Intermountain West as each comprise over 34.5% and 55.7% of the region's vehicles respectively. In Table 2 cars are estimated to consume 20.3% of fuel and emit 19.8% of CO_2 emissions while light-duty trucks are estimated to consume 53.7% of fuel and emit 52.6% of CO_2 emissions. Currently, battery electric vehicles (BEVs) have achieved more adoption in the light-duty market, both regionally as well as nationally [17, 20, 64], and their implementation reduces GHG emissions by 45, 56, and 74 t CO_2e for sedans, sport utility vehicles, and pickup trucks, respectively, relative to ICEVs on a life cycle basis [65]. This analysis becomes more complicated once local electricity sources are considered for BEVs; however, BEVs successfully reduce CO_2 emissions relative to ICEVs in over 98% of U.S. counties [65]. It may be possible that FCEVs can compete with BEVs in the light-duty market and can improve upon BEV implementation if the hydrogen is produced using carbon capture or completely renewably such as blue or green hydrogen as discussed in previous sections.

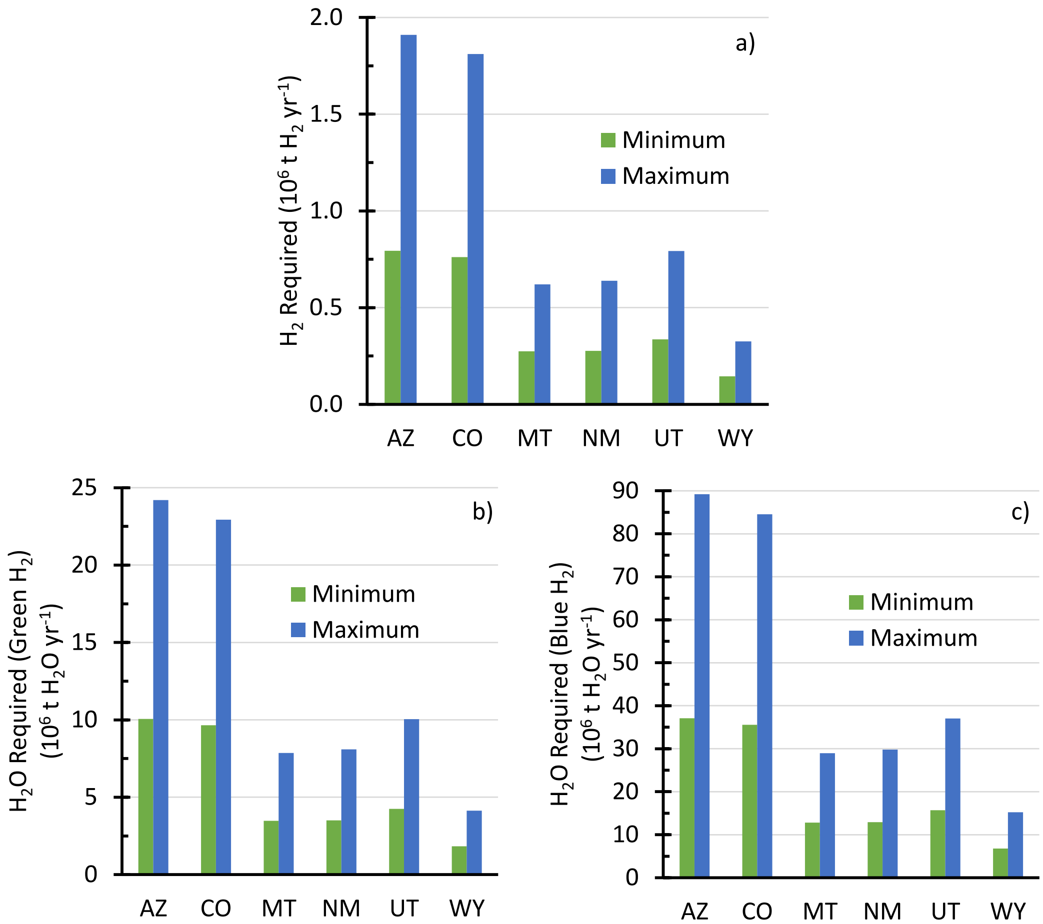

Figure 11. 2019 maximum and minimum requirements by Intermountain West state (depending on ICE efficiencies) for a) hydrogen, b) H_2O for green hydrogen, and c) H_2O for blue hydrogen.

Hydrogen blending with natural gas

Hydrogen has the potential to perform as a transition fuel that can supplement the current fossil-energy portfolio of the Intermountain West while drawing on the region's considerable solar, wind and geothermal resources. Research from some natural gas utilities suggests that low hydrogen blend fractions ($y_{H2} \leq 0.2$) are possible without requiring significant upgrading to the infrastructure [27-30]. However, larger hydrogen blend fractions ($y_{H2} > 0.2$) will likely require upgrading and modification of infrastructure [9]. Furthermore, correct hydrogen blend fractions are expected to be highly infrastructure-dependent and should be comprehensively evaluated on the basis of each system [9].

Based on Equation 4, Figure 12 shows the theoretical reduction of CO_2 results from natural gas combustion as $0 \leq y_{H2} \leq 1$. Although hydrogen has the largest energy density by mass of any fuel, it unfortunately has the lowest energy density by volume [7, 21]. Thus, when hydrogen is blended into natural gas at constant volume (meaning, to add hydrogen an equal volume of natural gas is removed), the resulting stream has a lower energy density than the natural gas alone. To compensate, the end user will need to consume a greater volume of the gas stream in order to receive the same amount of energy from the utility. The result is the half-parabolic shape shown in Figure 12 where an increase in the H_2 blend fraction, y_{H2}, does reduce CO_2 emissions upon combustion but not linearly.

The first five data points from Figure 12 are shown in Table 4 to further illustrate this phenomenon. Presently, gas utilities in the U.S. and Europe claim to have successfully tested hydrogen blend fractions as high as 15-20% [29, 30]. The results from Table 4 and Figure 12 show that as the hydrogen blend fraction increases, the total volume of the gas stream must also increase in order to compensate for the reduction in energy density. Thus, theoretical hydrogen blends of 15% and 20% require corresponding increases in volume of 12% and 16%, respectively, and the CO_2 reduction potential is limited to 5% and 6.9% respectively.

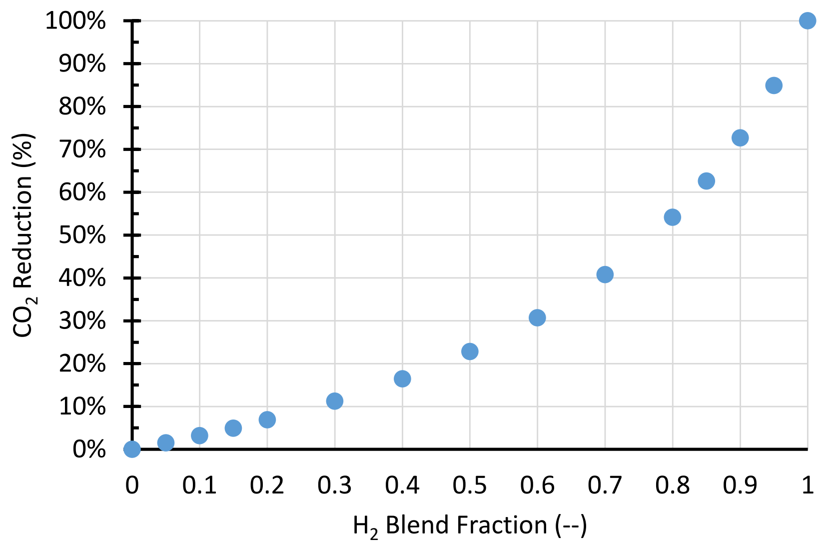

Figure 12. Results from Equation 4 verifying theoretical CO_2 reduction possible when blending hydrogen between $0 \le y_{H2} \le 1$ in natural gas distribution systems.

y_{H2} (--)	y_{NatGas} (--)	LHV (MJ m^{-3})	V_{Total} (m^3 hr^{-1})	V_{H2} (m^3 hr^{-1})	V_{NatGas} (m^3 hr^{-1})	y_{CO2} (--)	CO_2 Reduction (%)
0.00	1.00	36.63	1.00	0.00	1.00	1.000	0.0%
0.05	0.95	35.34	1.04	0.05	0.98	0.985	1.5%
0.10	0.90	34.05	1.08	0.11	0.97	0.968	3.2%
0.15	0.85	32.76	1.12	0.17	0.95	0.950	5.0%
0.20	0.80	31.47	1.16	0.23	0.93	0.931	6.9%

Table 4. The first five results from Equation 4 corresponding to hydrogen blends at $0 \le y_{H2} \le 0.2$. See Figure 12. LHV represents the Lower Heating Value of the gas stream [49-51].

Issues relating to the costs of hydrogen blending remain unsettled. At present, renewable (green) hydrogen costs 4-5 times more than natural gas [27]. The present natural gas distribution system in the Intermountain West was not designed for hydrogen. Thus, there may be issues with hydrogen embrittlement of the pipeline infrastructure if the hydrogen blend fraction increases above a critical concentration and the storage and transport systems are lacking integrity [66]. Additionally, hydrogen is expected to have a greater leak rate than natural gas within the existing natural gas infrastructure due to the small size of hydrogen. The extra gas flow required to maintain the energy density of the original stream results in additional costs. The customer may increase the gas flow (if possible) to maintain the same performance from their appliances or the utility may compensate for this further upstream.

Hydrogen blending, using green hydrogen, has the potential to reduce CO_2 emissions in the Intermountain West and provide a transition fuel as the region shifts from fossil-energy sources. As the costs and technical barriers associated with blending remain unsettled, cooperation and transparency between producers and consumers will be required.

Conclusion

Presently, there is no hydrogen production in the Intermountain West, though some projects are under development. Hydrogen has tremendous potential to be a viable and affordable transition fuel as the region shifts from fossil-based energy sources. A "first-pass" analysis was used to consider the possibilities of FCEV technology and hydrogen blending of natural gas as part of a place-based transition to sustainability within the region.

Replacing ICEVs with FCEVs presents a tremendous opportunity to decarbonize the transportation sector of the region. The literature was used to estimate that there are approximately 18.4 million registered ICEVs in the Intermountain West. These vehicles consume approximately 1361 PJ of fossil fuel annually while producing about 89 Mt CO_2 in tailpipe emissions alone. This accounts for roughly 73.8% of transportation CO_2 emissions in the region.

Cars and light trucks combine for over 90% of registered vehicles. Light trucks as a class consume the most fuel and emit the most CO_2 annually. After light trucks, medium-heavy duty trucks consume the most fuel and emit the most CO_2. This is interesting as cars make up 34.5% of the regional vehicle stock, while medium-heavy trucks comprise only 4.8%. The disparity between percentage of vehicle stock and CO_2 emitted suggests that targeting the medium-heavy vehicle class for transition to FCEVs is likely the transportation vector with the best decarbonization efficiency.

An average vehicle-specific CO_2 footprint was used to further settle on medium-heavy trucks (average of 26.2 t CO_2 yr^{-1} veh^{-1}) as the vehicle class to target for ICEV replacement with FCEVs to provide the most CO_2 mitigation efficacy.

Future work regarding FCEVs in the Intermountain West will require a much more granular look at vehicle data within the region to more clearly identify CO_2 emissions coming from other transportation sources while also evaluating risks from NO_x, particulate matter, SO_x and other pollutants with GWP. Additionally, the economic and policy conditions necessary to begin and accelerate adoption of FCEVs within the region will be evaluated to identify a realistic strategy and timeline for the technology to have a measurable carbon emission impact.

Hydrogen blending into natural gas streams, at hydrogen blend fractions of $y_{H2} \leq 0.2$, appears to be viable based on research primarily performed by natural gas utilities outside of the region. However, the addition of hydrogen into a natural gas stream reduces the energy density of the mixture by a nontrivial percentage. To compensate, the end user will need to consume more of the gas mixture to maintain appliance performance than otherwise would have been necessary. While much remains uncertain, or even controversial, even fairly low hydrogen blend fractions can have a measurable reduction in natural gas combustion CO_2 emissions. Transparency and cooperation will be required between all stakeholders if such a hydrogen transition is to be implemented.

Further work regarding hydrogen blending in natural gas streams will more clearly evaluate the integrity of the natural gas infrastructure within the Intermountain West as it was not designed for hydrogen blending. An in-depth exploration of all issues relating to cost is already in process, including considerations of non-CO_2 emissions (i.e., NO_x) as well as equity-related issues that may accompany shifting industrial technology or strategies.

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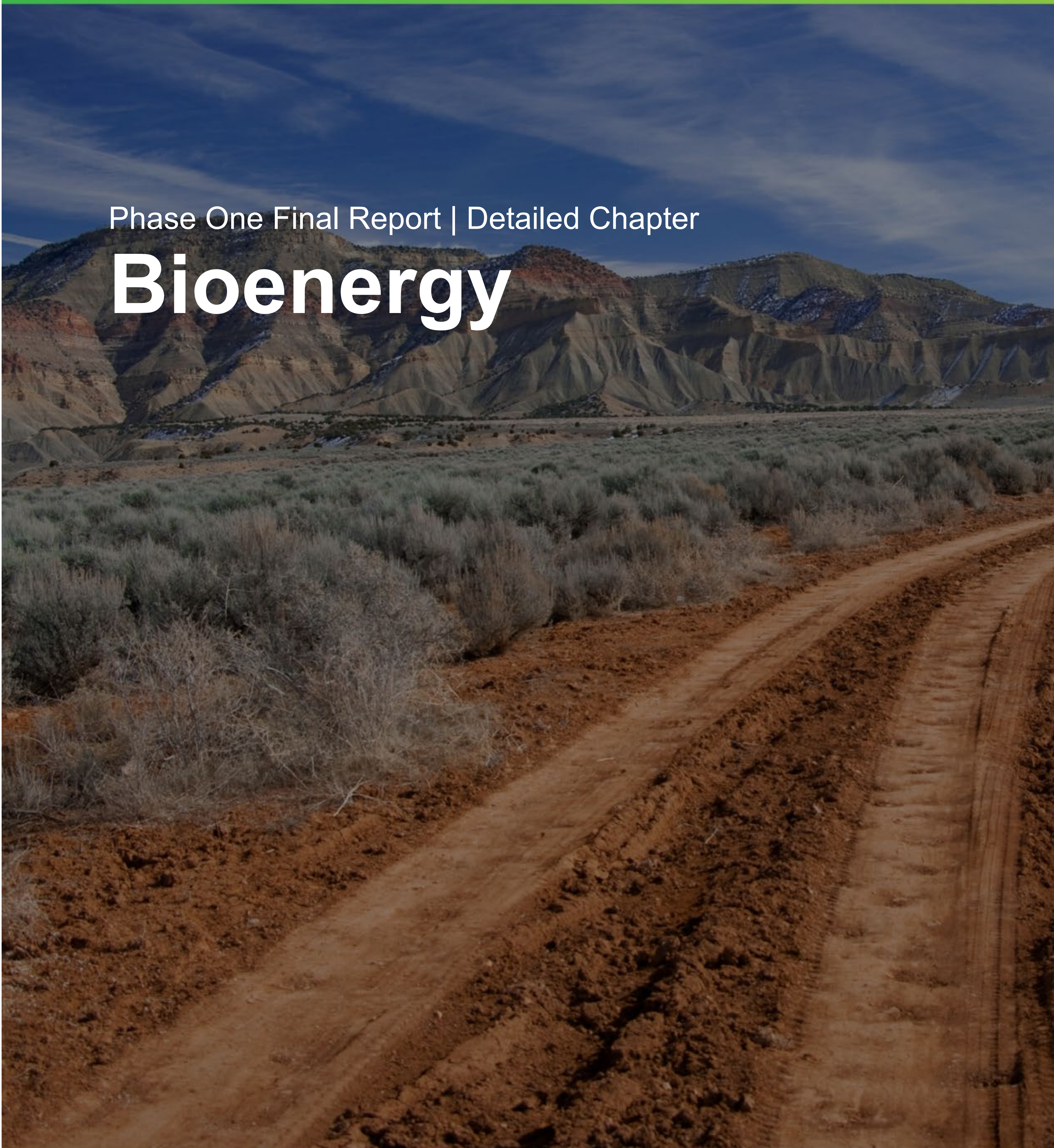
Phase One Final Report | Detailed Chapter

Bioenergy



About this chapter

The Intermountain West Energy Sustainability & Transitions (I-WEST) initiative is funded by the U.S. Department of Energy to develop a regional technology roadmap to transition six U.S. states to a carbon-neutral energy economy. I-WEST encompasses Arizona, Colorado, Montana, New Mexico, Utah, and Wyoming. Each state is represented in this initiative by a local college, university, or national laboratory. Additional partners from beyond the region were selected for their expertise in applicable fields. In the first phase of I-WEST, the team built the foundation for a regional roadmap that models various energy transition scenarios, including the intersections between technologies, climate, energy policy, economics, and energy, environmental, and social justice. This chapter presents work led by an I-WEST partner on one or more of these focus areas. A summary of the entire I-WEST phase one effort is published online at www.iwest.org.

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Table of Contents

Summary

Bioenergy—biofuels or biopower generated from biomass or using biotechnology—is an emerging economic sector in the U.S., including the Intermountain West. While the bioenergy sector has synergies with other energy sectors in the region, it is also distinguished by its close association with the economic sectors of forestry and agriculture. The Intermountain West has an abundance of biomass resources with the potential to increase the regional bioenergy economy, and I-WEST examined several technologies that can be used to convert these resources to energy. Our assessment investigated the potential benefits—including reduction of CO_2 emissions—that could be achieved by growing the bioenergy sector, as well as the challenges, such as water scarcity and the projected impact of climate change on the availability of biomass resources in the region.

Key messages

- Multiple bioenergy-related technologies are currently being deployed in the Intermountain West region. These technologies include modular, portable, and stand-alone technologies as well as integrated, circular systems to convert a variety of biomass feedstocks and organic wastes to biogas or other bioenergy intermediate products.
- The type of applicable technologies in the region will primarily depend on the feedstock, with forest residues, crops and crop residues, wastewater of various types, and livestock wastes being primary choices.
- CO_2 emissions reductions can result from using bio-feedstocks and waste carbon feedstocks in place of conventional fossil feedstocks for electricity generation and bio-ethanol production.
- Given the close ties between bioenergy and bioeconomy-related technologies with other important regional economic sectors (e.g., agriculture, forestry, etc.), it is important to ensure that there is minimal competition for natural resources such as fresh water and land use. Synergies with agriculture and forestry industries are also opportunities to grow bioenergy-related technologies in the region.
- Some of the technologies that could be deployed in the region are not yet commercially available, and some require further R&D, pilot-scale demonstrations, and technology transfer to industry in order to integrate these technologies. Trends in technology development that could advance bioenergy deployment are described in this report.
- Promoting a distributed model of smaller-scale technologies, empowering local communities, and deploying projects (including pilot-scale projects) that engage local

communities can help accelerate deployment and growth of bioenergy-related industries in the region.

- Providing technical assistance to local bioenergy project developers, as well as actively developing an agile workforce through vocational training that addresses the range of new energy technologies, are some of the critical steps that need to be taken.

Introduction

The bioenergy sector has symbiotic and synergistic relationships with other economies that can bring the Intermountain West to carbon neutrality: biomass and other organic wastes can be converted to electricity; bioenergy production from plants, plant products, and other photosynthetic organisms capture and utilize CO_2 to grow; and hydrogen can be produced by the gasification of biomass, or by microbial synthesis. The bioenergy sector is also synergistic with other economic sectors that are prevalent in the region, specifically forestry and agriculture, both livestock and plant-based crops. This synergy between the bioenergy economy and the agriculture and forestry economies distinguishes bioenergy from the other pathways addressed by I-WEST, but also introduces other factors. For example, growth of the bioenergy economy may compete for natural resources like clean water or land use. On the other hand, utilization of waste plant or forest material may benefit communities by adding value to their crops or reducing the risk of wildfires. Therefore, growing the bioenergy economy in the Intermountain West needs to be done in such a way that local communities and their existing economic interests are considered. Finally, with a large indigenous population in the region, cultural and traditional values may influence the response of the local community to growing the bioenergy economy.

In addition to synergies with electricity, hydrogen, and CO_2 economies, the bioenergy economy is closely linked to agriculture and forestry; for example, food crops, livestock, forests, or algae cultivation (Figure 1).

The production of power and fuels from biomass or waste carbon sources can play an important role as a low carbon source for our energy needs. Biomass or biogas can directly replace fossil feedstocks as a source of liquid transportation fuel or electricity. Biofuels produce 60% lower GHG emissions from light duty vehicles than fossil fuels, while cutting 99% of the most harmful pollutants [1]. Production of electricity from biomass or biogas can also reduce the carbon footprint of electricity production compared to the use of fossil feedstocks. Likewise, the use of biomass or waste carbon feedstocks in production of chemicals or materials can help to lower the carbon footprint of industry and building sectors, respectively. Finally, the agriculture sector can be made

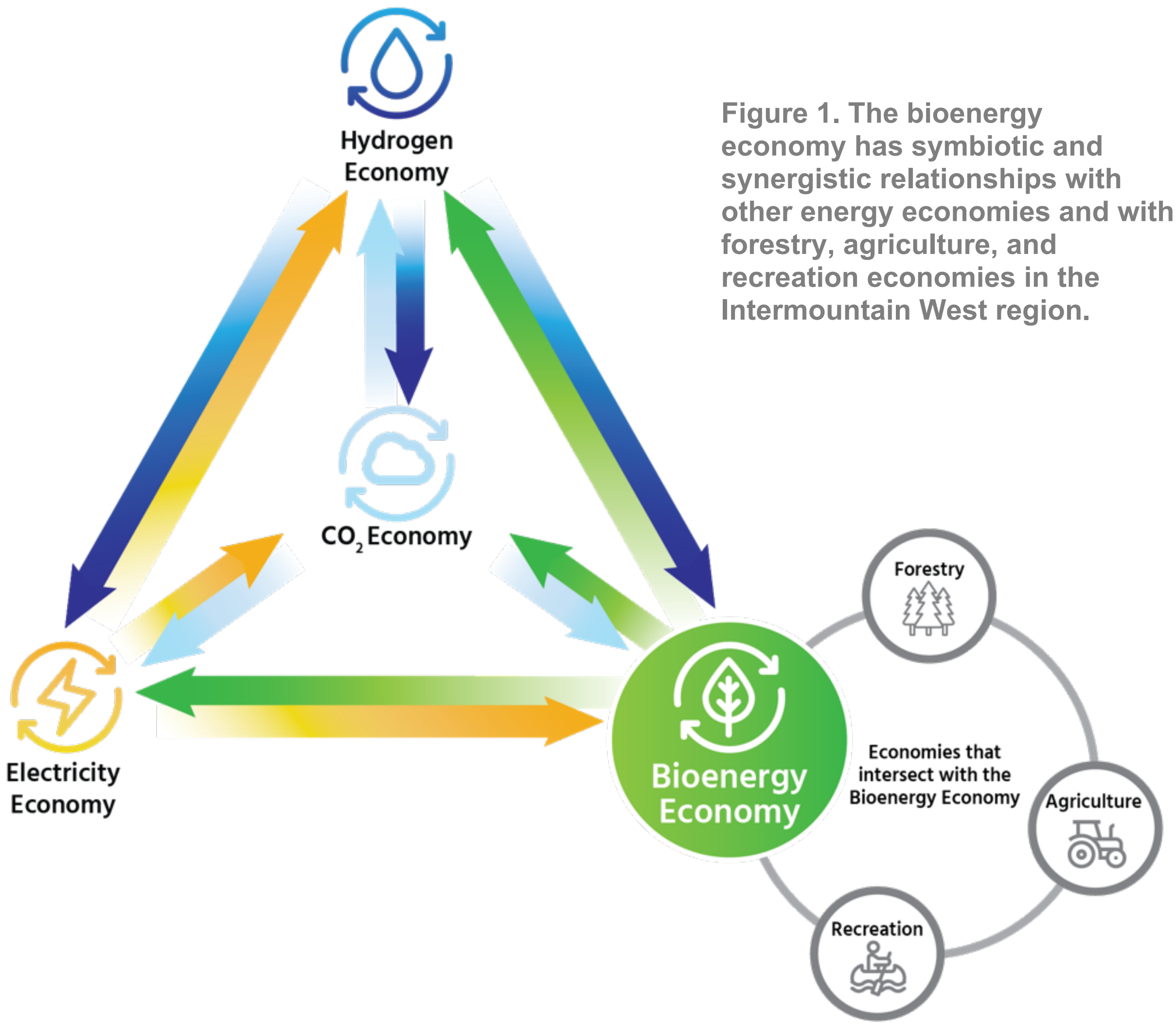

Figure 1. The bioenergy economy has symbiotic and synergistic relationships with other energy economies and with forestry, agriculture, and recreation economies in the Intermountain West region.

less carbon intensive, for example, by capturing and reutilizing biowastes for energy production or applying to soil to restore and sequester carbon.

Bioenergy feedstocks

There is a wide range of options for feedstocks used for bioenergy: First-generation feedstocks, such as corn, are food crops and directly compete with food production for natural resources, including fresh water. Second-generation feedstocks are crop residues (corn stover), forest residues, mill residues, municipal solid waste, or other waste biomass or carbon sources that can be converted into energy. Third-generation feedstocks are microalgae. Fourth-generation feedstocks are other microorganisms, or genetically modified organisms (Figure 2).

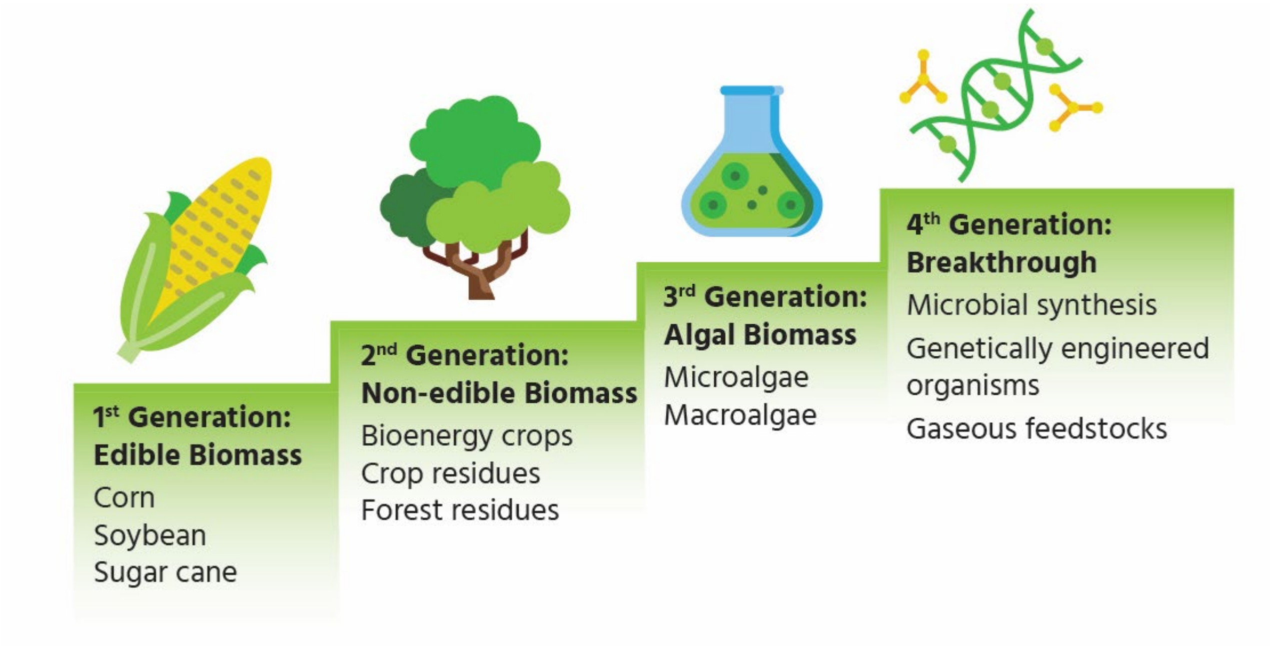

Figure 2. First, second, third, and fourth generation bio-feedstocks used for bioenergy production.

Bio-based energy can be utilized in many economic sectors where it can substitute for fossil-based energy sources and/or can help reduce greenhouse gas emissions in that sector. In transportation, biofuels can directly substitute for fossil fuels in internal combustion engines as drop-in replacements, or as blends with fossil fuels such as bioethanol blended with gasoline. In the electricity sector, renewable natural gas can be produced from organic wastes, such as biogas from manure, and blended with conventional natural gas. Bio-based fuels or biogas can also be used as a heat source for industry processes or for heating or energizing residential or commercial buildings. Finally, byproducts of bioenergy production such as biochar can be important sources of carbon to regenerate soils for agriculture. Our I-WEST analyses focused mainly on bioenergy for the electricity and transportation sectors.

The Intermountain West has high solar irradiance, which is essential for production of natural biomass resources. The region also has an abundance of unused land, including land that has been degraded by mining or oil and gas extraction or is otherwise non-arable. These unused lands may provide opportunities for growth of the bioenergy economy. For example, algae ponds or greenhouses could be built on such lands, and bioenergy byproducts such as carbon biochar or anaerobic digester solids could be used to restore soils for agriculture.

Existing bioenergy economy

Commercial production of bioenergy, biofuels, and related bio-waste or carbon-waste producing industries in the Intermountain West are shown in Figure 3 and listed in Table 1.

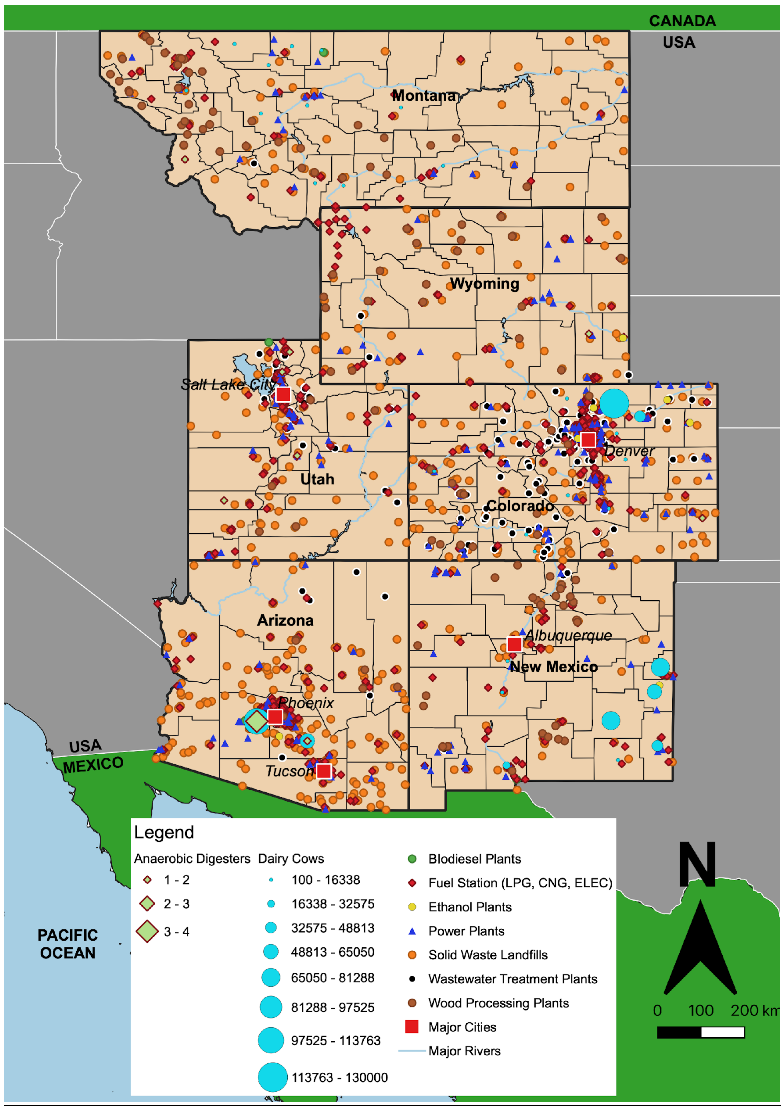

Figure 3: Industry locations in the region relevant to bioenergy and biofuels. Dairy cow and anaerobic digester data come from the U.S. Department of Agriculture [2] and the U.S. Environmental Protection Agency AgSTAR database [3], respectively. All other data are from the U.S. Department of Homeland Security Homeland Infrastructure-Level Data (HIFLD) database [4]. Data are listed in Table 1.

Table 1: Data from Figure 3 tabulated by state and by industry								
State	**Anaerobic Digester Facilities**	**Dairy Cows**	**Ethanol Plants**	**Bio-diesel Plants**	**Alternative Fuel Stations (CNG, LPG, Electric)**	**Power Plants**	**Solid Waste Landfills**	**Wastewater Treatment Plants**
Arizona	5	194000	1	4	509	42	235	7
Colorado	1	202000	4	0	344	82	168	129
Montana	1	11000	0	1	59	24	66	2
New Mexico	0	292000	1	2	98	30	48	7
Utah	4	0	0	2	184	30	101	43
Wyoming	1	0	1	0	55	25	54	3

Regional biomass resources

Energy crop yield

For most of the region, the total energy crop yields are projected to increase when viewed at the county scale. At the state scale, when viewed as individual crops, the yields of grain crops appear to be slightly increased over time, whereas hay yields appear to decrease slightly over time. Figures 4-7 show crops and crop residue yields from the 2016 Billion Ton Report [5], projected for 2022, 2027, 2032, 2037 in map form for the Intermountain West. These data represent baseline scenario estimates, where the energy crops represented within each county are the same crops shown for state-level estimates in the bar graphs that follow in Figures 8-13.

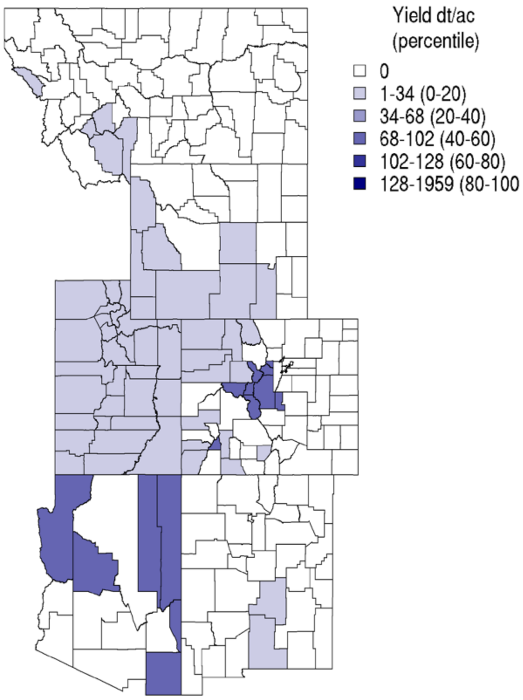

Figure 4. Total energy crop yield in 2022.

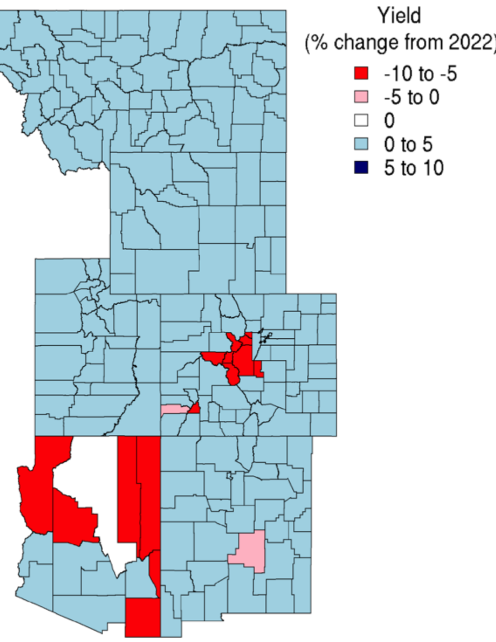

Figure 5. Total energy crop yield in the region projected in 2027.

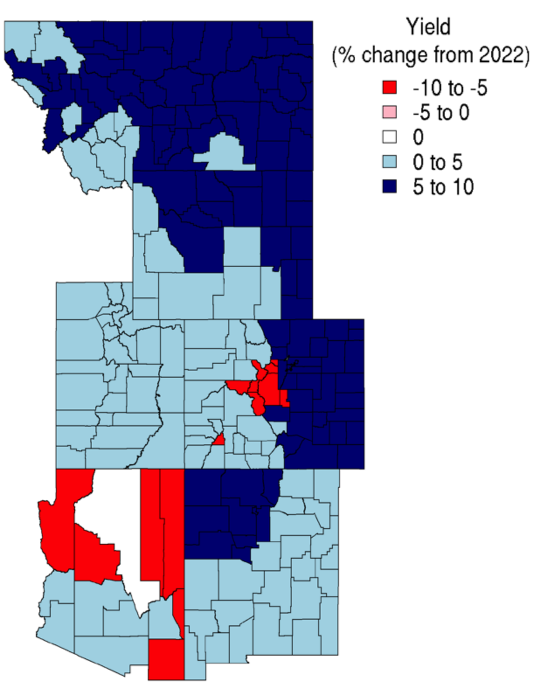

Figure 6. Total energy crop yield in the region projected in 2032.

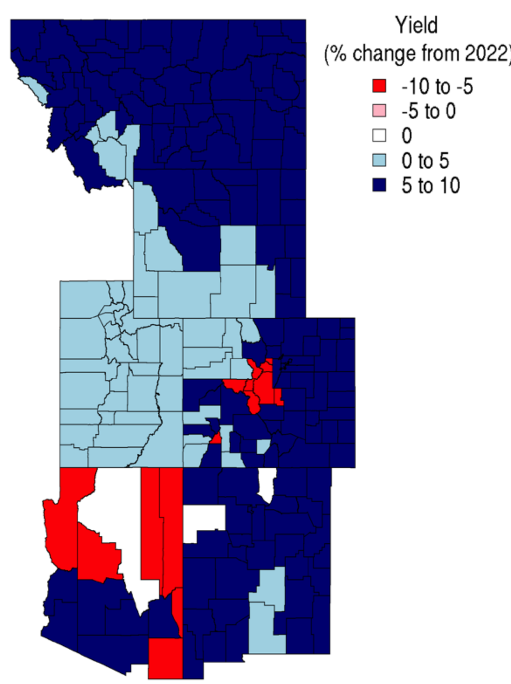

Figure 7. Total energy crop yield in the region projected in 2037.

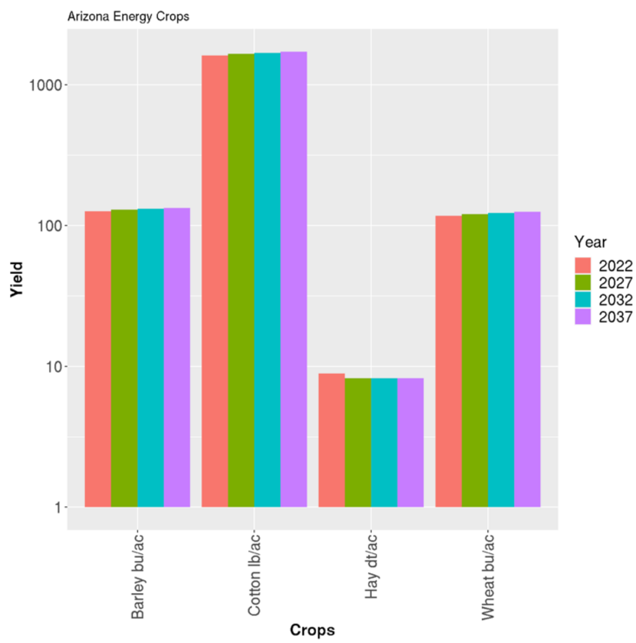

Figure 8. Energy crop yields in Arizona by type and by year.

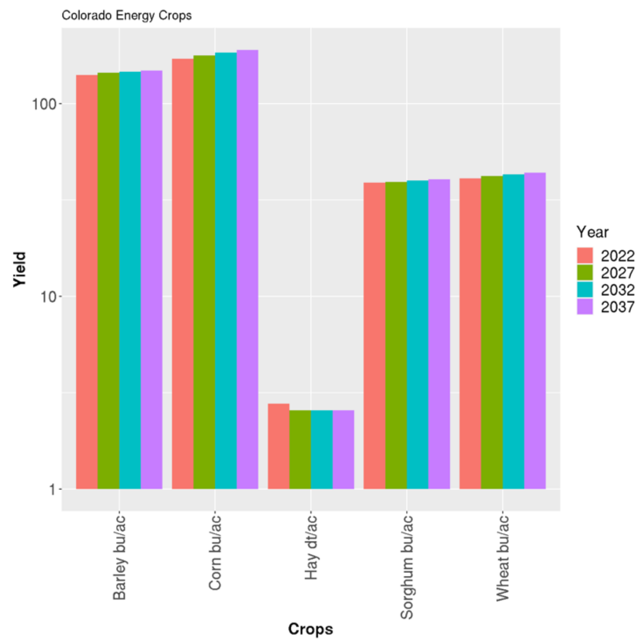

Figure 9. Energy crop yields in Colorado by type and by year.

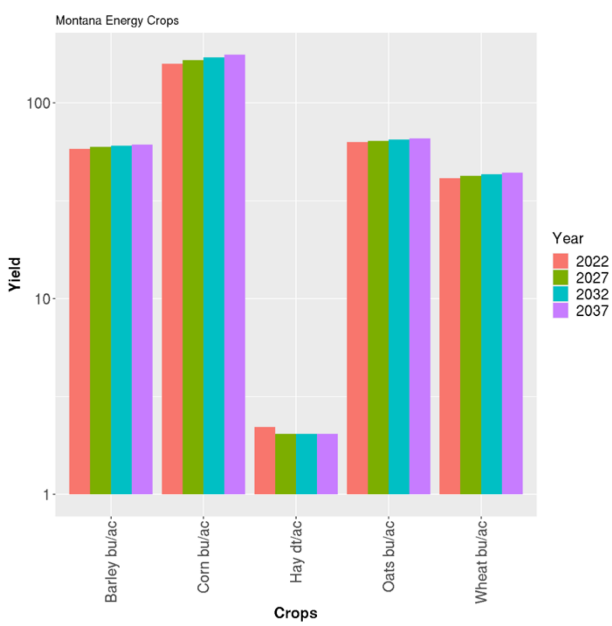

Figure 10. Energy crop yields in Montana by type and by year.

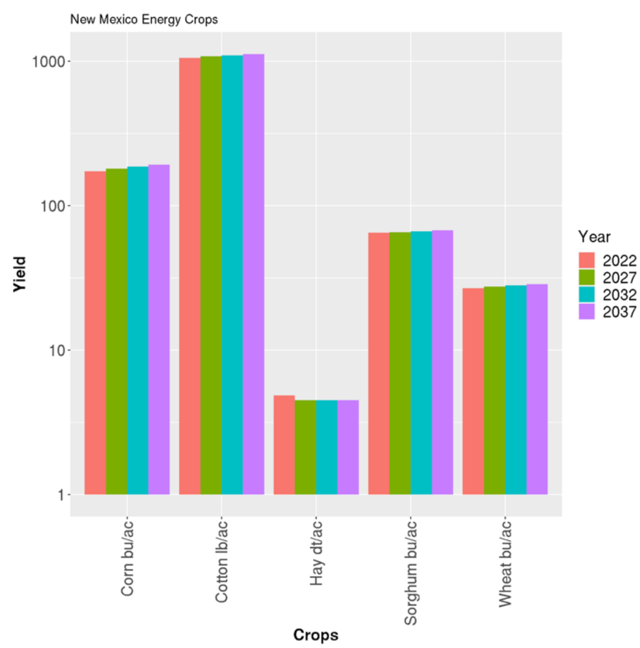

Figure 11. Energy crop yields in New Mexico by type and by year.

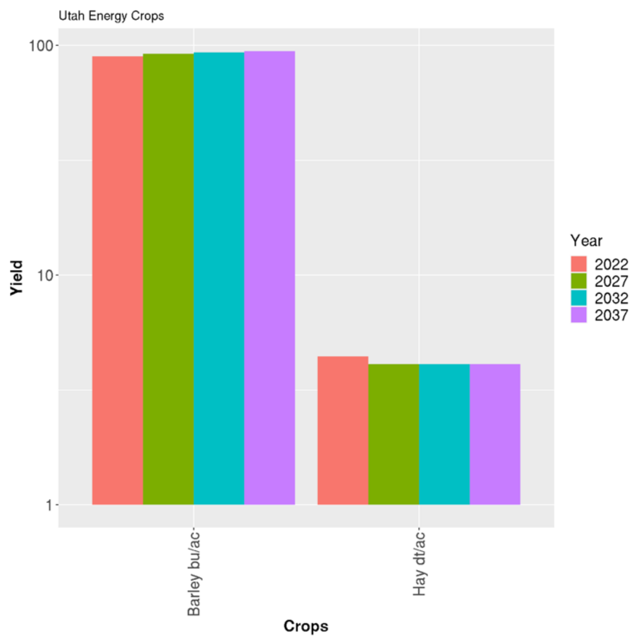

Figure 12. Energy crop yields in Utah by type and by year.

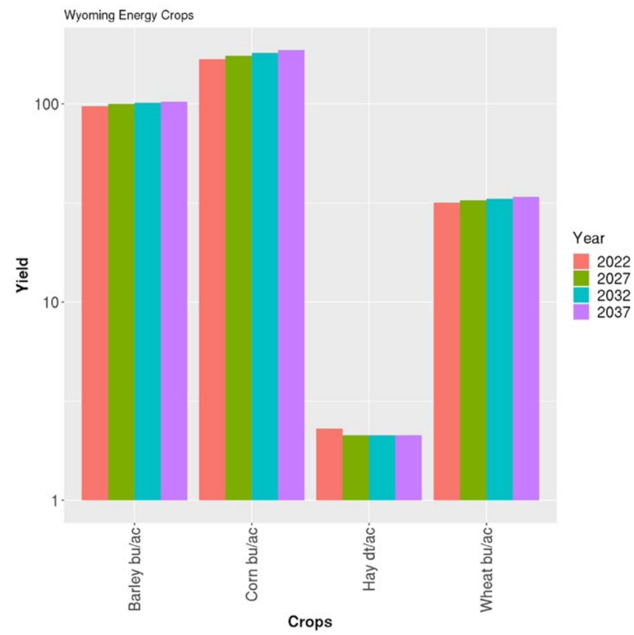

Figure 13. Energy crop yields in Wyoming by type and by year.

Forest Productivity

Forest residues, when viewed at the county or state level, appear to have variable production potential over time. Some areas in the Intermountain West are projected to have stable or slight net increases; other regions are projected to have decreased production potential over time. Figures 14-17 show forest residues from the 2016 Billion Ton Report [5], projected for 2022, 2027, 2032, 2037. These data represent “medium housing, medium energy demand” scenario estimates that assume a biomass price of $30. The forest resources represented within each county are the same resources shown for state-level estimates in the bar graph plots that follow in Figures 18-23.

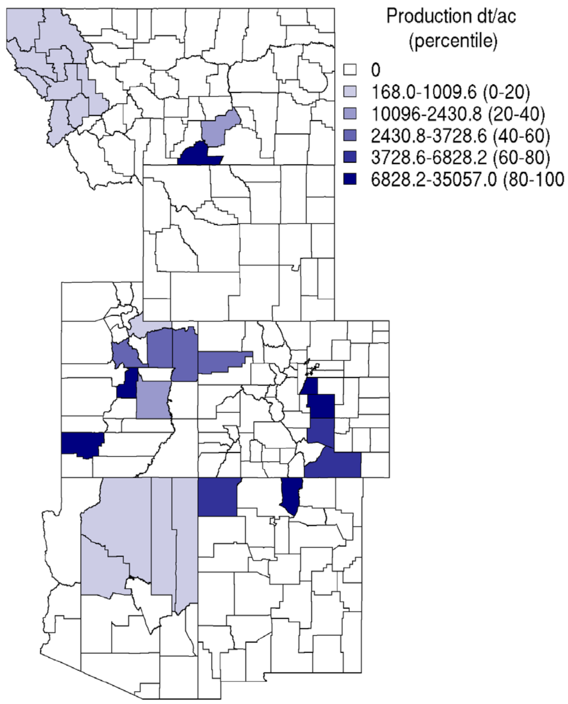

Figure 14. Total forest productivity in the region, by county, in 2022.

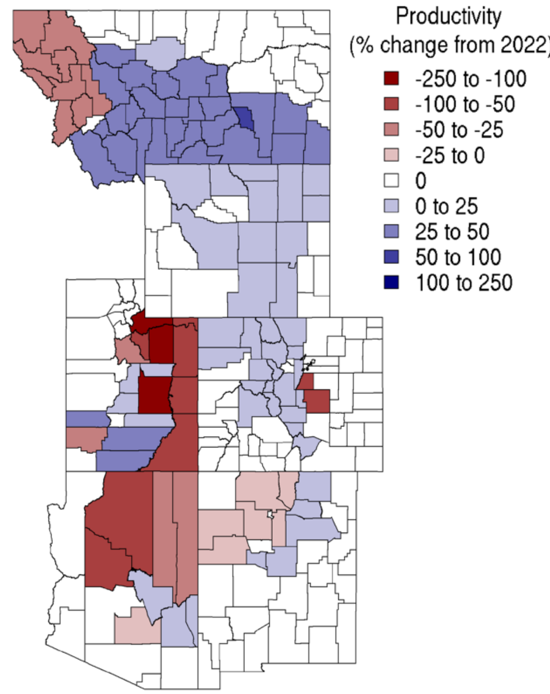

Figure 15. Total projected forest productivity in the region, by county, in 2027.

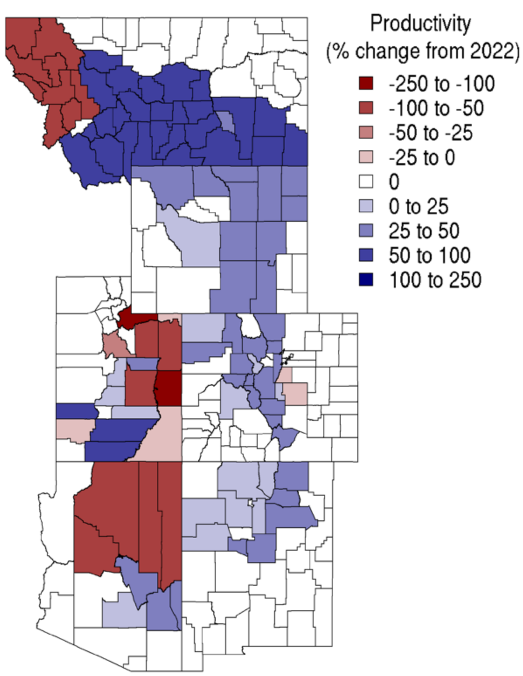

Figure 16. Total projected forest productivity in the region, by county, in 2032.

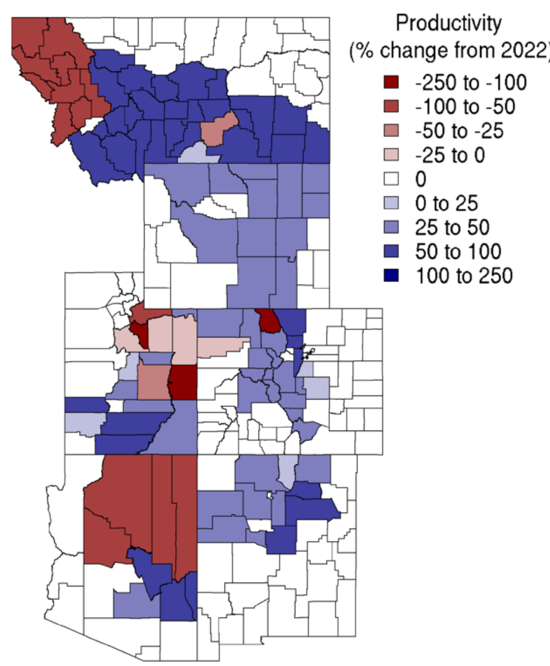

Figure 17. Total projected forest productivity in the region, by county, in 2037.

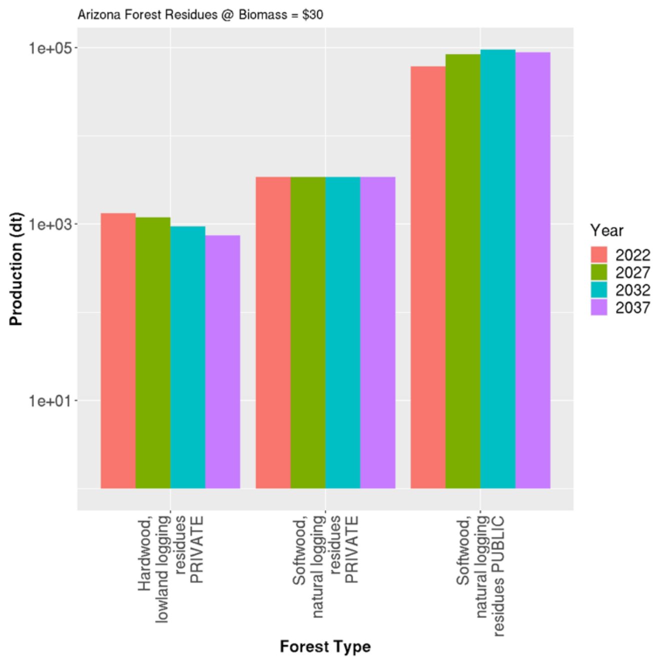

Figure 18. Total projected forest productivity in Arizona, by type and by year.

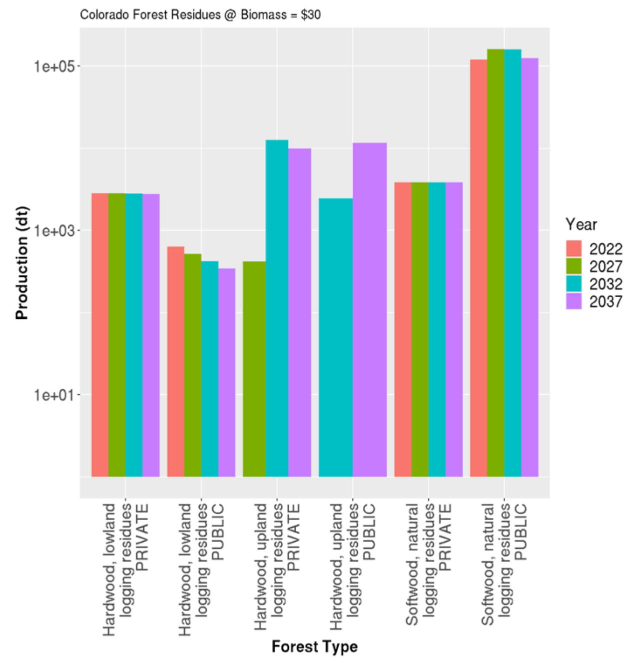

Figure 19. Total projected forest productivity in Colorado, by type and by year.

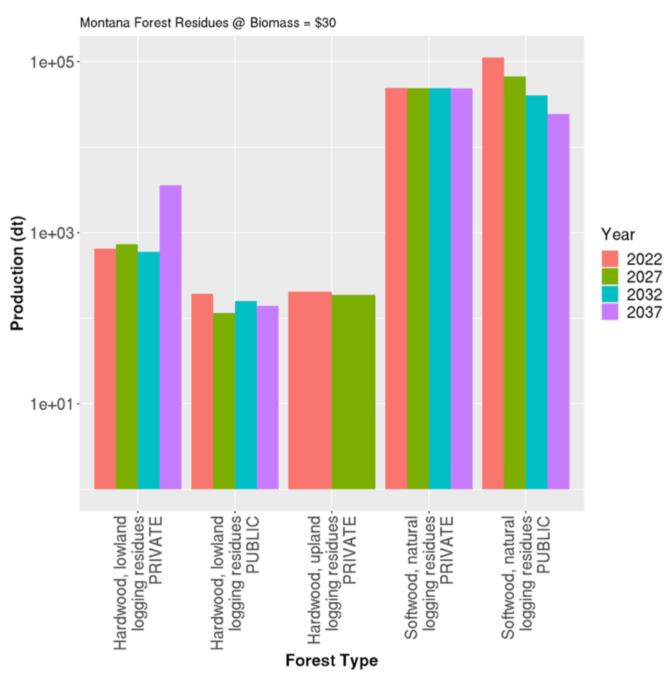

Figure 20. Total projected forest productivity in Montana, by type and by year.

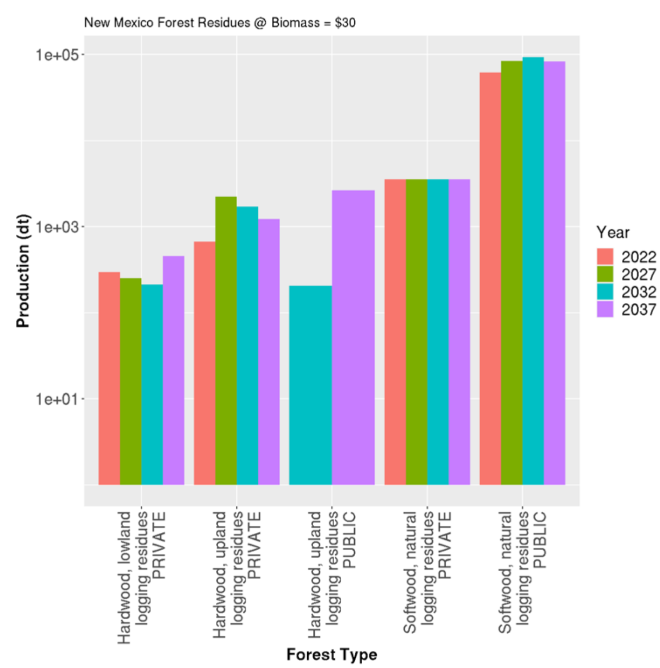

Figure 21. Total projected forest productivity in New Mexico, by type and by year.

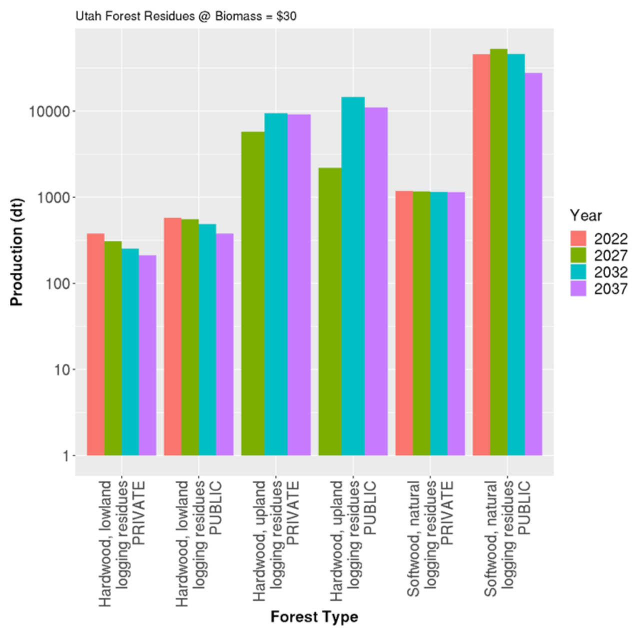

Figure 22. Total projected forest productivity in Utah, by type and by year.

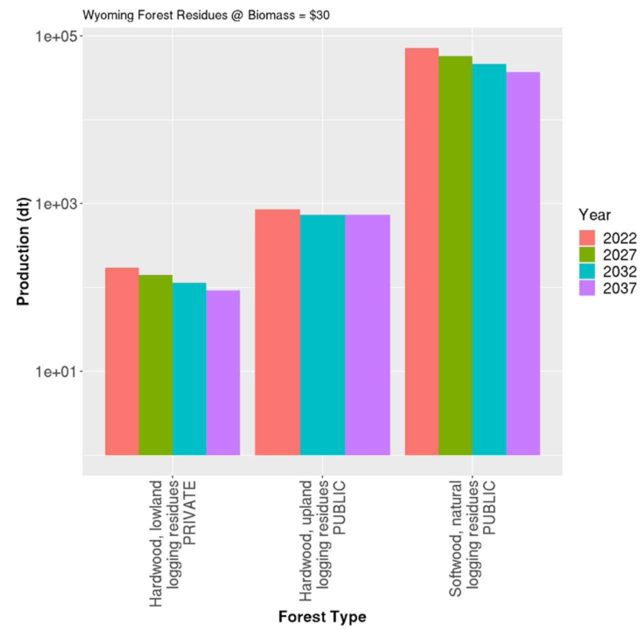

Figure 23. Total projected forest productivity in Wyoming, by type and by year.

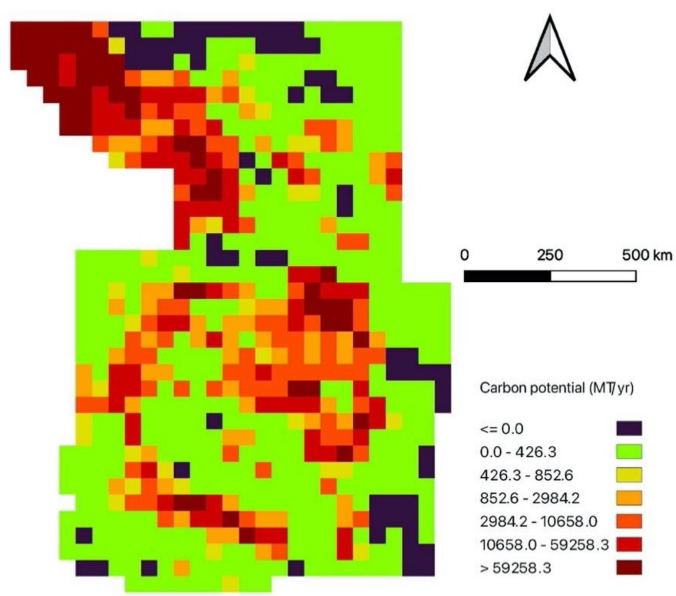

Figure 24. Distribution of forest residue (carbon potential) from all types of disturbances and forest management in the region.

Taking a closer look at forest residues available for bioenergy production across the Intermountain West, we would only want to consider the forest materials that are already disturbed (e.g., dead trees from natural events or from harvesting for land development or industry) rather than harvesting old, healthy growth.

Carbon potential from different types of disturbances is estimated based on data from 2000-2014 remote-sensing-based canopy cover loss [6]. We attributed disturbances to four categories (anthropogenic, fire, drought, and other) by combining multiple datasets from different sources and of various native spatial resolutions [7]. The drought and fire categories mainly refer to potential carbon availability from standing dead trees.

For the anthropogenic category, the carbon availability could result from either selective harvesting, land use change, or forest management (e.g., thinning). The carbon potential is estimated based on the aboveground biomass for canopy trees. Using the attributed carbon potential, we clipped the national map to the Intermountain West region and estimated the carbon potential for energy use. The map shows a high potential for the northwest and central region with high forest carbon stocks. Figure 25 shows the distribution of the forest carbon potential by type of disturbance. Standing timber dead from fire has the highest carbon potential. If we assume only the zone with 100-meter radius accessible from roads, 35% of these disturbance forest carbon sources are accessible. The total potential accessible carbon for energy use from disturbed forest biomass is about 60 million tons per year for the region.

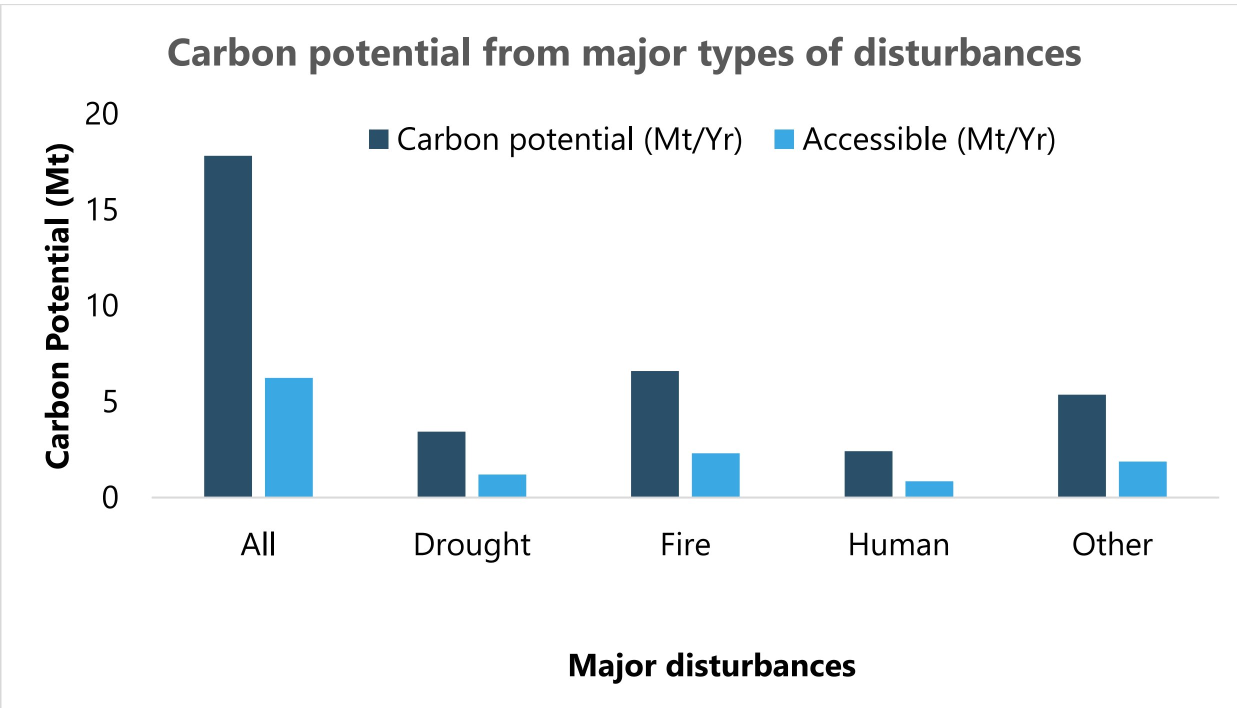

Figure 25. Summary of carbon potential (Mt/Yr) from different types of disturbances and forest management sources in the Intermountain West and the accessible potential (Mt/Yr) assuming a 100-meter radius accessible from roads.

Analysis of electricity potential and CO_2 emissions reduction potential from biomass

The Intermountain West has untapped potential for energy production based on biomass. We conducted an analysis on the potential for energy production (electricity production from biogas [8,9]) and CO_2 emissions reduction using actual observations—our results offer a projection of energy consumption and CO_2 emissions in 2030 and 2050. We did not take into account the effects of climate change on the availability of biomass. We also did not account for the efficiency of scale and GHG emissions of the transformation technologies utilized to convert the feedstocks to electricity, which varies by technology. For this analysis, we assumed that there is only one technology for each transformation pathway, and the yield is scale independent.

Biomass and bio-derived feedstocks considered in the analysis

Crop Residues. This includes harvested crop residues from corn, wheat, soybeans, cotton, sorghum, barley, oats, rice, rye, canola, dry edible beans, peanuts, safflower, sunflower, sugarcane, and flaxseed by county. The crop residues were estimated using total crop production, crop to residue ratio, and moisture content. It is assumed that only 35% of the total residue could be collected as biomass. The remaining portion is to be left on the field to maintain ecological and agricultural functions.

Urban Wood. Urban wood waste by county - wood material from municipal solid waste (MSW, wood chips and pallets), utility tree trimming and/or private tree companies, and construction and demolition sites. Data used is in dry metric tons/year.

Primary Mill. This field contains data on primary mill residues by county. Primary mill residues include wood materials (coarse and fine) and bark generated at manufacturing plants (primary wood-using mills) when round wood products are processed into primary wood products, such as slabs, edgings, trimmings, sawdust, veneer clippings and cores, and pulp screenings. This data illustrates the total amount of primary mill residues (used and unused) by county. Note that most of this resource is currently utilized. Data used is in dry metric tons/year.

Secondary Mill. Data for secondary mill residues by county (wood scraps and sawdust from woodworking shops — furniture factories, wood container and pallet mills, and wholesale lumber yards). Data used is in dry metric tons/year.

Forest Residues. This category includes logging residues and other removable material left after carrying out silviculture operations and site conversions, as well as harvesting timber for industrial products and domestic fuelwood. Logging residue consists of unused portions of trees, cut or killed by logging and left in the woods. Other removables are the unutilized wood volume of trees cut or otherwise killed by cultural operations (e.g. pre-commercial thinning) or land-clearing to non-forest uses. This data illustrates 65% of logging residues and 50% of other removals could be collected as biomass. The remaining portion is to be left on the field to maintain ecological functions. Data used is in dry metric tons/year.

Data sources used were from USDA census, 2012[10] and USDA Forest Service, 2012 [11].

Sources of biogas data used in the analysis

Methane generation potential from industrial, institutional, and commercial organic waste (in metric tons/year). This analysis estimates the methane generation potential from food manufacturing and wholesalers (e.g., fruit and vegetable canneries, dairy creameries, meat packing and processors, etc.), as well as institutional facilities such as hospitals, nursing homes, educational and correctional facilities. Data sources were the U.S. Census Bureau's County Business Patterns 2012 [12], and the Homeland Security Infrastructure Program (HSIP) 2012 [13], which is further processed to estimate the amount of these resources by county that were used.

Methane generation potential from animal manure (in metric tons/year). The following animal types were included in this analysis: dairy cows, hogs, and chickens (broilers). The methane generation potential was calculated by animal type and manure management system at the county level using data from the USDA, National Agricultural Statistics Service 2007 Census [10].

Methane generation potential from wastewater treatment (in metric tons/year). This analysis estimates the methane generation potential of wastewater treatment plants using methodology from the EPA's Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2011 [14], and data from the EPA Clean Watersheds Needs Survey (2008) [15].

Methane emissions from landfills (in metric tons/year). Methane emissions are estimated at each landfill considering total waste in place, status (open or closed), and waste acceptance rate using data from the EPA's EMOP database (as of April 2013) [16], and then aggregated to the county level. Note: this analysis includes "candidate" landfills only. EPA's Landfill Methane Outreach Program (LMOP) defines a candidate landfill as one that is accepting waste or has been closed for five years or less, has at least one million tons of waste, and does not have an operational or under-construction project; candidate landfills are also designated based on actual interest or planning.

Table 2: Total energy potential in the Intermountain West by state
(Biomass comprises crop, forest, mills, and urban landscaping residues.
Biogas is derived from manure, industrial/organic waste, wastewater, and landfills)

State	total MWh	MWh from biomass	MWh from biogas
AZ	198.00	174.24	23.75
CO	358.85	349.36	9.49
MT	419.09	415.02	4.07
NM	71.33	53.82	17.51
UT	80.66	74.04	6.62
WY	42.62	40.62	2.00

Figures 26-34 below show the total electricity production potential from all types of biomass and biogas sources used in this analysis; followed by individual biomass and biogas sources, by county. Bio-feedstocks are crop residues, forest residues, urban wood, mills residues, and landscaping residues, as well as manure, industrial waste, wastewater, and landfill methane.

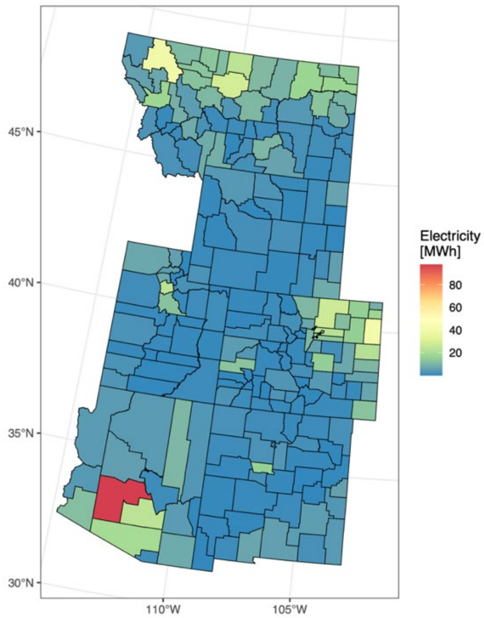

Figure 26. Electricity production potential from all types of biomass and biogas sources described above.

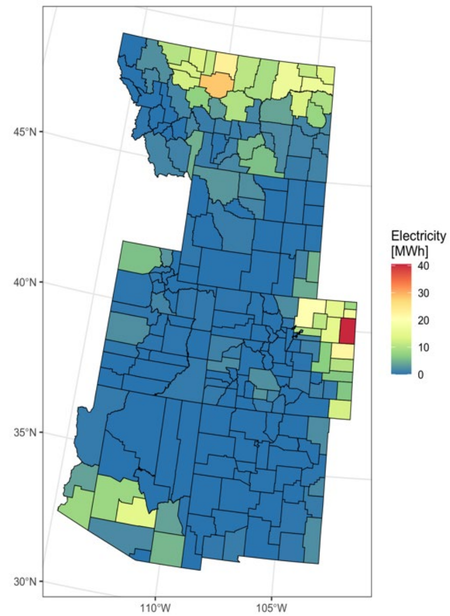

Figure 27. Electricity production potential from crop residues.

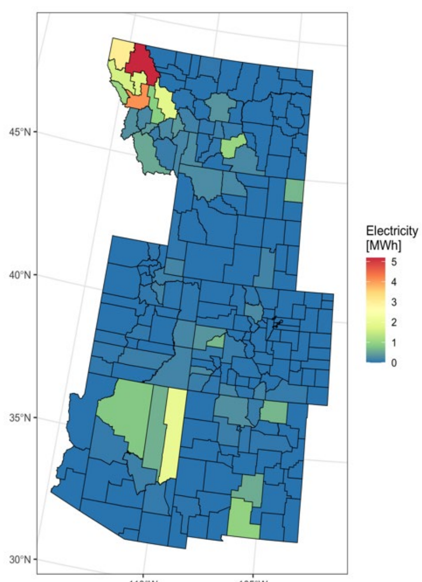

Figure 28. Electricity production potential from forest residues.

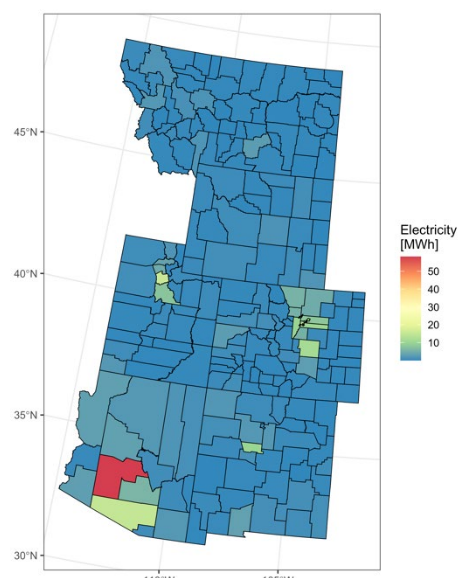

Figure 29. Electricity production potential from urban wood residues.

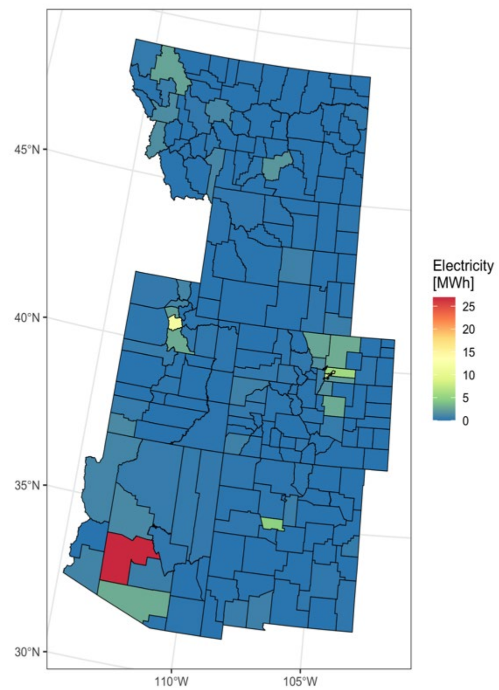

Figure 30. Electricity production potential from primary and secondary mills residues.

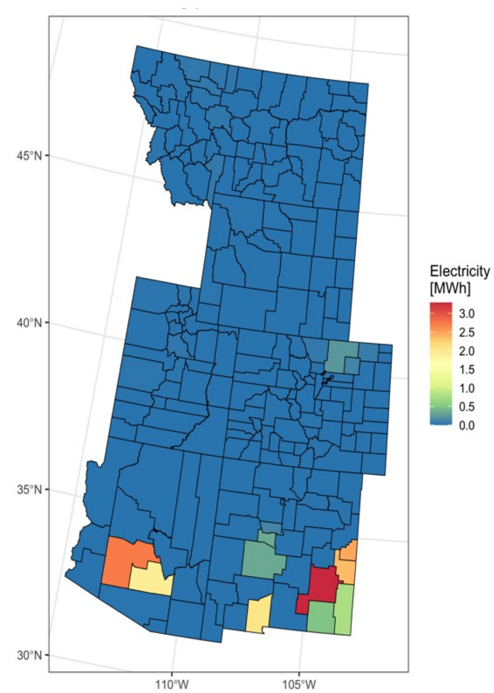

Figure 31. Electricity production potential from biogas sourced from manure.

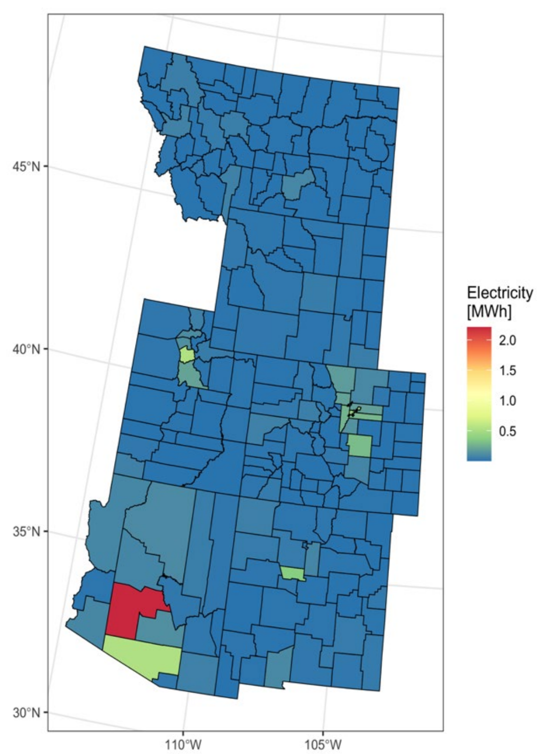

Figure 32. Electricity production potential from biogas sourced from industrial organic waste.

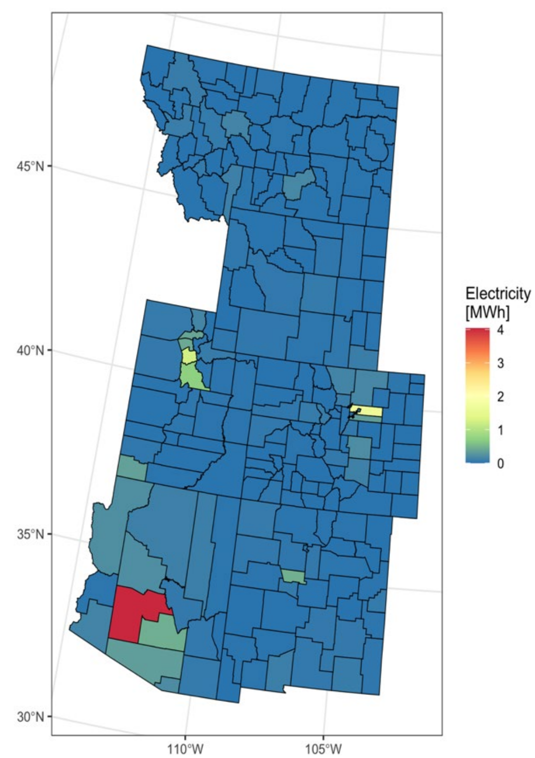

Figure 33. Electricity production potential from biogas sourced from wastewater treatment plants.

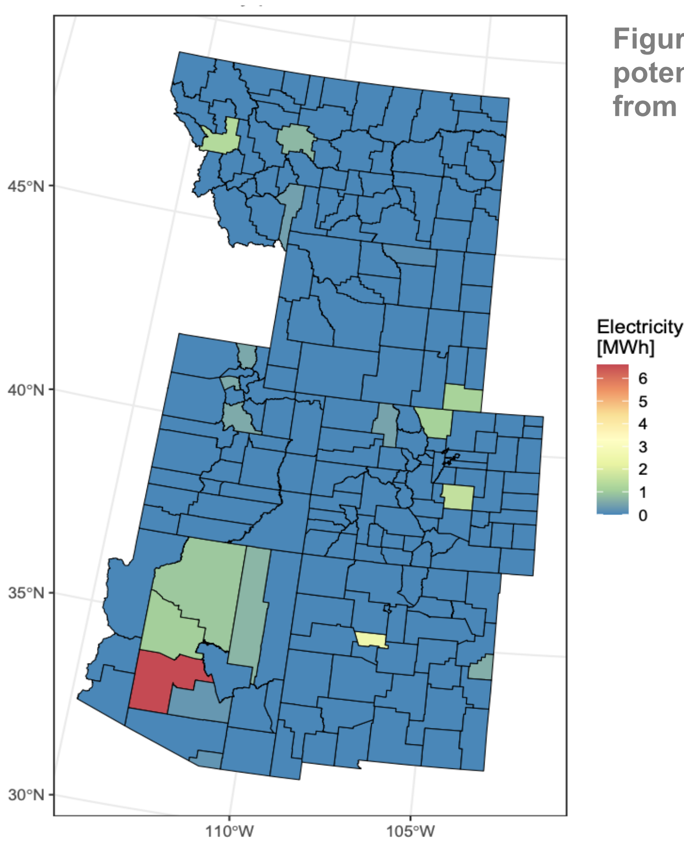

Figure 34. Electricity production potential from biogas sourced from landfills.

Table 3. State-level availability of the most abundant bio feedstocks (forest residues of all types, and crop residues), in dry tons per year					
State	**Crop residues**	**Urban wood residues**	**Mills residues**	**Forest residues**	**Forest disturbances residues**
Arizona	362,771	773,045	210,675	29,127	390,565
Colorado	1,745,954	731,841	260,815	19,557	876,606
Montana	2,301,657	156,792	626,644	191,386	536,442
New Mexico	69,595	253,233	80,136	21,971	397,981
Utah	123,447	333,687	118,522	8885	216,832
Wyoming	149,327	90,721	68,582	12,028	284,202

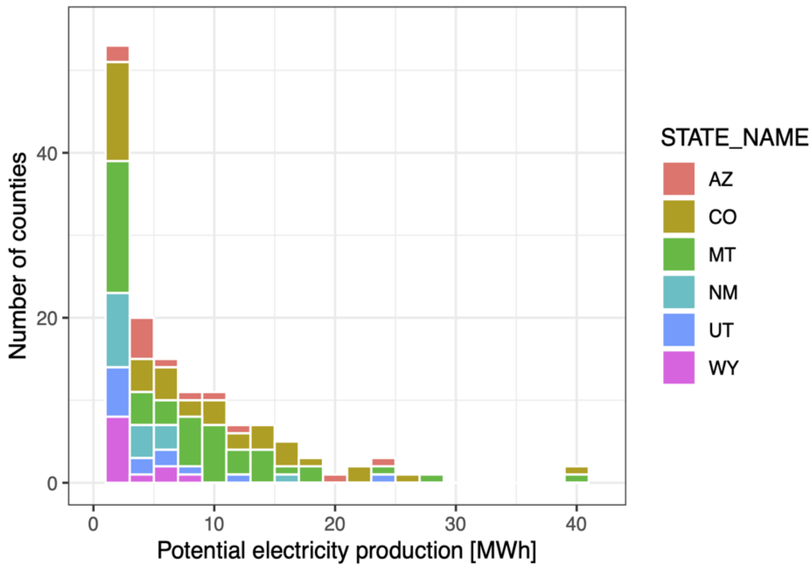

Figure 35: Bio-feedstock energy production potential by county. Maricopa county, Arizona, is not included in the plot for readability (97.6 MWh of energy production potential from bio-feedstocks).

Microalgae for energy production Outdoor cultivation of microalgae is a viable process in parts of the Intermountain West, particularly in the southern parts of Arizona and New Mexico where the growing season can be longer [17]. A number of studies have analyzed the potential supply of algae biomass and biofuel in different geographic regions of the U.S., with particular focus on water availability [18-20] as well as suitable terrain [5].

Microalgae produce lipids, which can be converted to a “drop-in” biofuel (fuel that is chemically similar to fossil-based fuel). In addition, certain species of algae or cyanobacteria can be very robust in outdoor cultivation systems. They can utilize saline or brackish water, thereby reducing or eliminating freshwater use in cultivation. They also can be grown using point source or direct air captured (DAC) CO_2 as a carbon source. Analysis of co-location potential of stationary CO_2 sources with algae cultivation—ethanol plants, coal electric generating units (EGUs), and natural gas EGU sites in proximity to CO_2 distribution pipelines [21]—were addressed in the 2016 Billion-Ton Report [5] and other studies [22]. Based on temperature and length of growing season alone, southern Arizona and southern New Mexico are the most suitable locations for commercial algae cultivation using open ponds. However, at this time there are only a handful of commercial algae production sites in those states. The theoretical potential for algae cultivation in the region is high: Figure 36 illustrates this untapped potential using currently accepted open outdoor cultivation ponds and marine strains of algae.

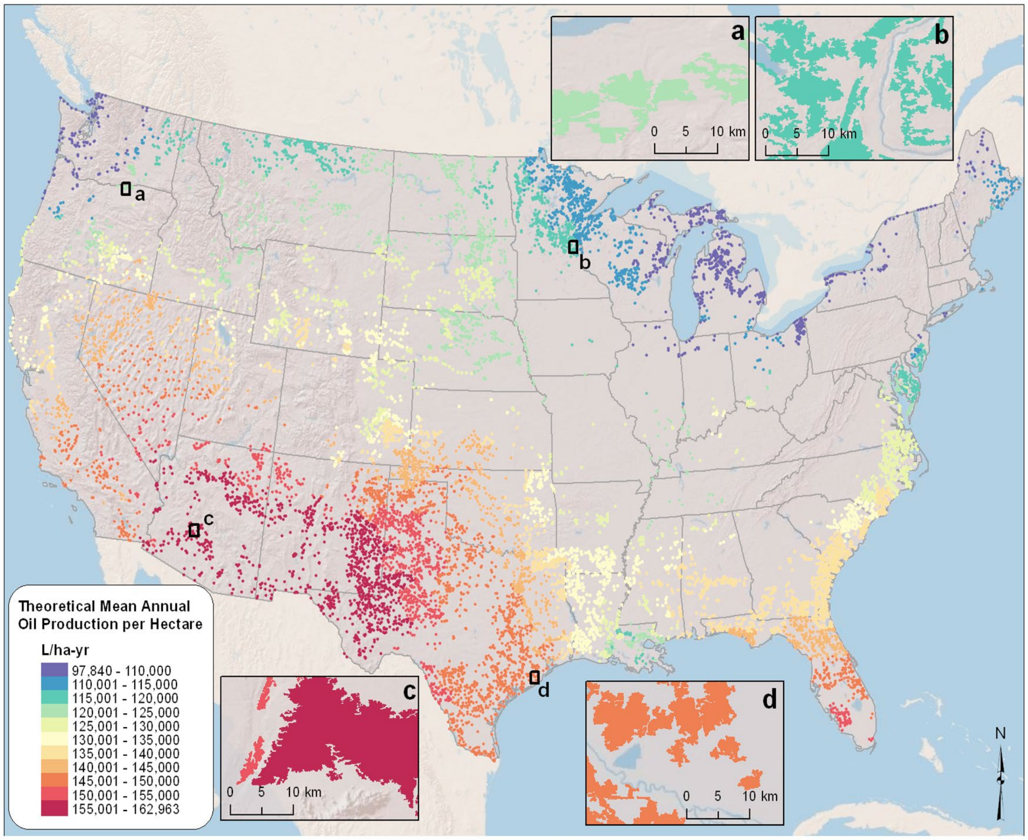

Figure 36. Mean annual theoretical maximum biofuel production (L ha−1 yr−1) plotted at the centroid of each pond facility. Insets illustrate underlying detail at the pond facility (490 ha) scale [18].

Microalgae can also be grown in indoor systems, greenhouses, and specialized photobioreactors that can be temperature and light controlled, much like industrial fermentation systems. The ability to grow algae in indoor reactors allows for algae cultivation systems to be deployed more widely. Attached or biofilm-based [23] growth systems are also possible and are used to efficiently filter water in wastewater treatment facilities. The company Clearas in Montana uses microalgae as a "filter" to treat municipal wastewater. The algae biomass can be harvested periodically and sold to companies that process the biomass for use in materials such as polymers.

Analysis of reducing CO_2 emissions from bioenergy production with biomass and biogas

This section presents the analysis that was conducted to project the potential reduction in CO_2 emissions in the Intermountain West from biomass and biogas utilization for bioenergy production: electricity or bioethanol production. Biomass comprises forest, residues, crop residues, urban, and mill residues. Sources of biogas are animal manure, organic waste, wastewater treatment, and landfills.

CO_2 emission reduction by use of biofeedstocks for electricity production

Figures 37-39 show the CO_2 emissions reductions at the county level for 2015, 2030, and 2050 when bio-feedstocks are used for electricity production. Table 4 lists the state-level EPA estimates of CO_2 equivalent emissions for electricity production.

Table 4. State level EPA estimates of CO_2 equivalent emissions in lbs/MWh for electricity production

State	CO_2 2015	CO_2 2030	CO_2 2050
Arizona	734.20	903.07	1074.40
Colorado	1212.20	1508.62	1952.90
Montana	905.70	1014.04	1308.30
New Mexico	1252.80	1366.98	1494.03
Utah	1554.90	2028.70	2945.58
Wyoming	1975.60	2039.41	2244.57

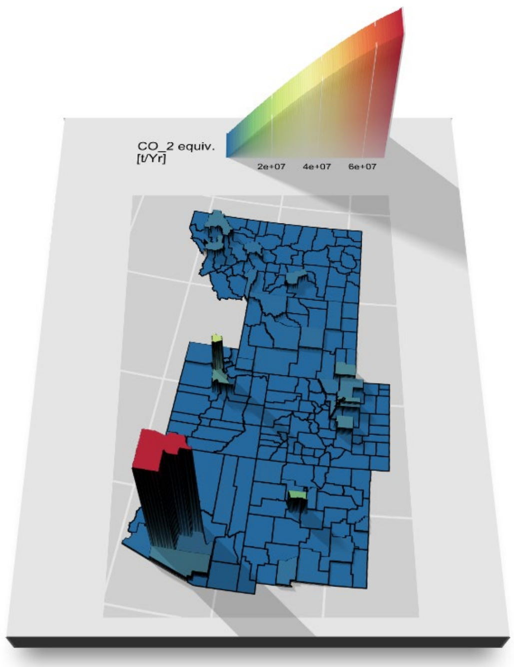

Figure 37. Electricity production. County-level potential CO_2 reduction from the use of biomass and biogas, using 2015 electricity consumption levels.

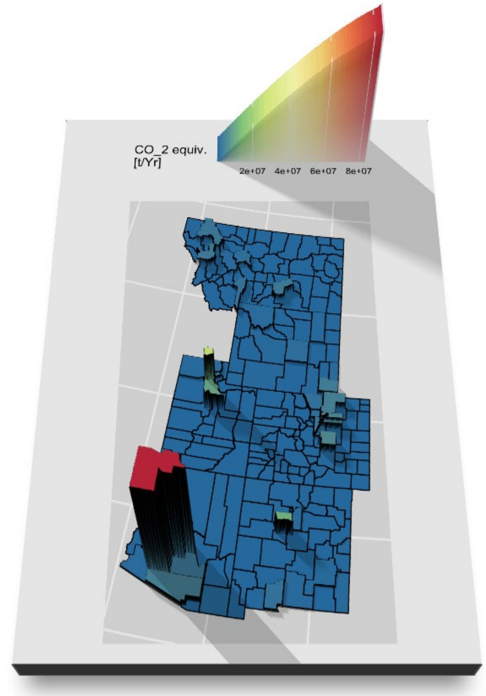

Figure 38. Electricity production. County-level potential CO_2 emissions reduction from the use of biomass and biogas, using 2030 electricity consumption levels.

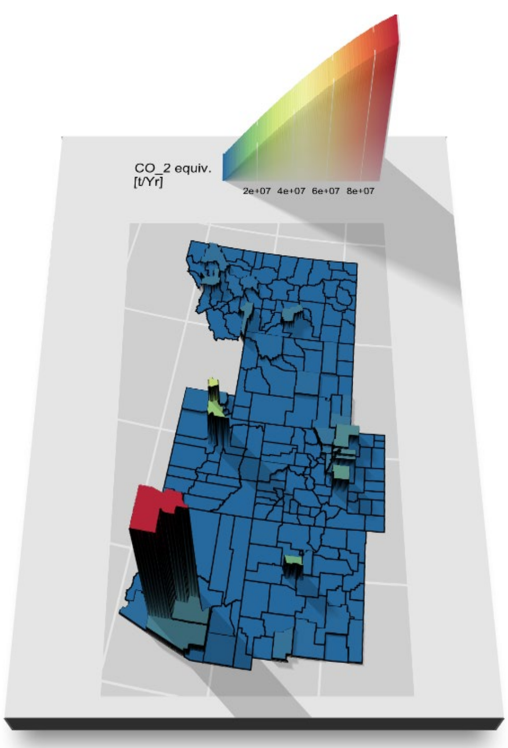

Figure 39. Electricity production. County-level potential CO_2 reduction from the use of biomass and biogas, using projected 2050 electricity consumption levels.

Table 5 shows the top 20 counties in the region with the highest potential for CO_2 reduction by using biofeedstocks for electricity production. The growth potential represents the increase of CO_2 reduction in 2050 relative to 2015. A positive growth value indicates a likely higher return on the investment. Table 5 lists the CO_2 equivalent reduction from offsetting electricity produced using fossil fuel with electricity produced from biomass and biogas.

Table 5. I-WEST counties with highest potential for CO_2 reduction from biofeedstock use in electricity production

County	State	Reduction growth	CO_2 Reduction relative to 2015
1 Maricopa	AZ	0.31	15883219.36
2 Salt Lake	UT	0.34	5016676.17
3 Bernalillo	NM	0.20	2361439.42
4 Utah	UT	2.47	1341675.47
5 Laramie	WY	-0.34	904949.08
6 Adams	CO	0.42	900272.08
7 Denver	CO	0.11	843157.08
8 El Paso	CO	1.38	827050.57
9 Pima	AZ	0.41	771329.40
10 Arapahoe	CO	0.63	688987.20
11 Flathead	MT	-0.43	677968.40
12 Missoula	MT	0.22	630611.06
13 Weld	CO	1.31	615262.35
14 Yellowstone	MT	0.60	517068.32
15 Jefferson	CO	0.14	483802.61
16 Davis	UT	0.63	450605.71
17 Pinal	AZ	2.29	369951.74
18 Doña Ana	NM	0.52	311068.33
19 Cascade	MT	-0.18	281017.71
20 Larimer	CO	0.84	279932.66

Table 6: CO_2 equivalent reduction from offsetting electricity produced using fossil fuel with electricity produced from biomass and biogas

State	CO_2 2015 [t/Yr]	CO_2 2030 [t/Yr]	CO_2 2050 [t/Yr]
Arizona	75936897	92112367	103315691
Colorado	22842477	29169142	38370793
Montana	12211033	13519026	15994909
New Mexico	14521818	16581623	18132568
Utah	32520079	42064782	57664288
Wyoming	8282999	8236355	8264697
IWEST Total	160 MillionMT/y		

Cumulative: 2022-2050= 6000 MT (6GMT)

Figures 40 and 41 suggest that an average reduction of CO_2 of 214MMT per year can be achieved. This corresponds to 55% reduction of the total 2022 Intermountain West CO_2 emissions of 387 MMT.

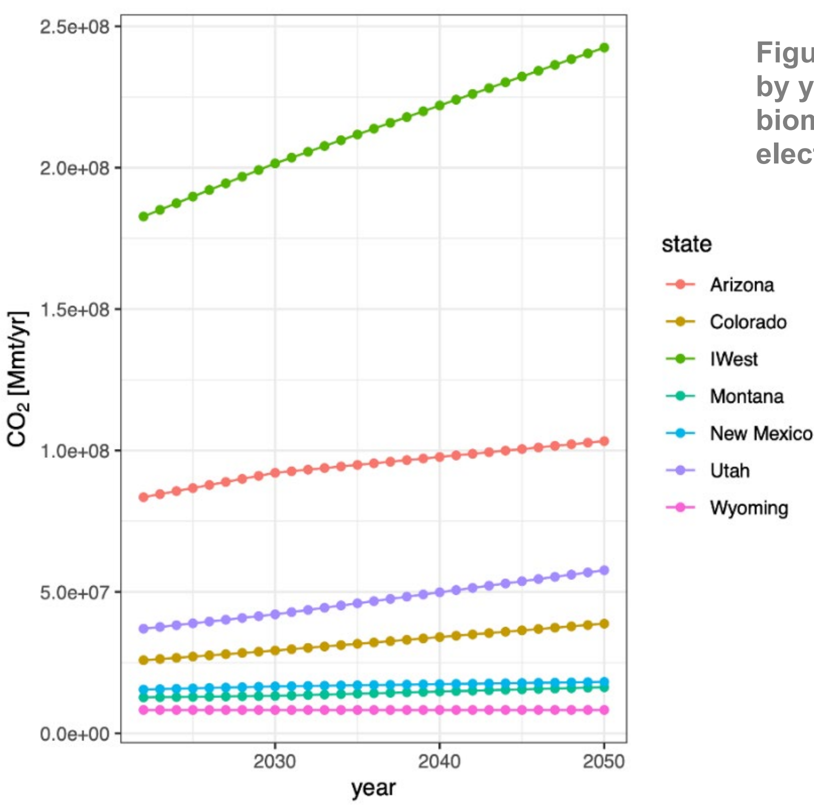

Figure 40. Potential CO_2 reductions by year and state from using biomass and biogas to produce electricity (t/yr).

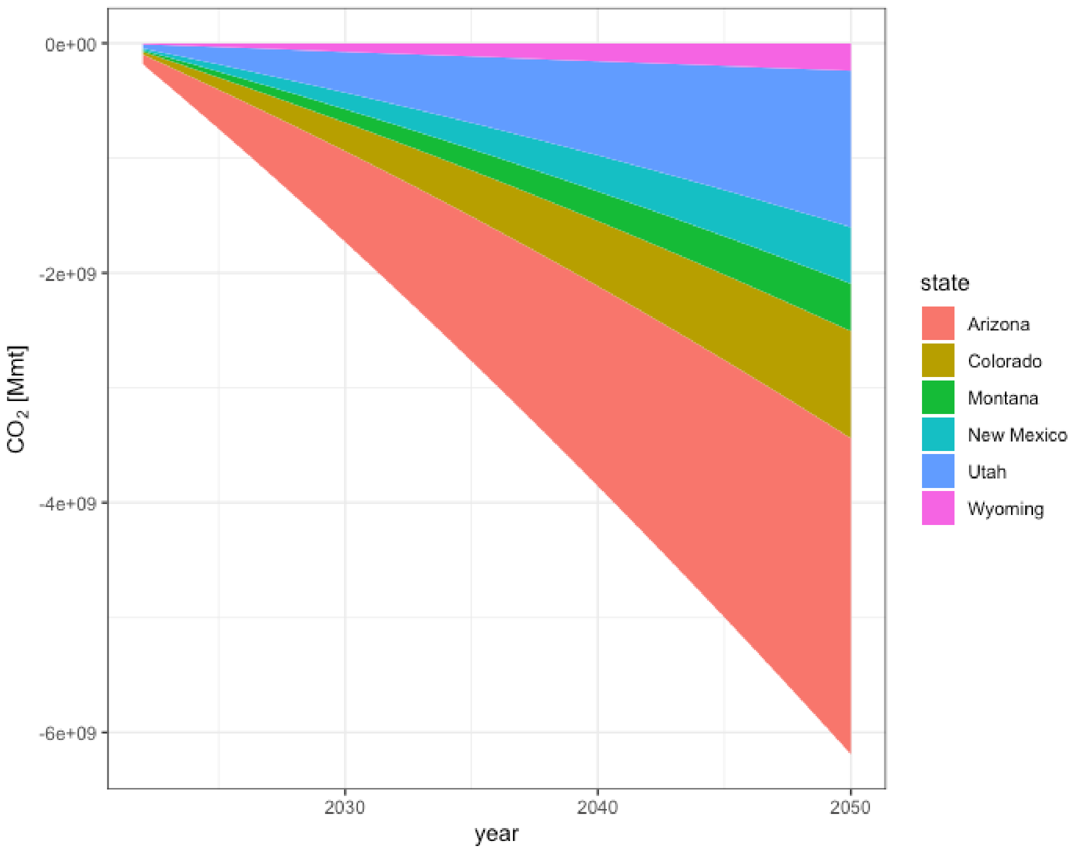

Figure 41. Cumulative potential for CO_2 reductions by year and state from using biomass and biogas to produce electricity (million metric tons).

CO_2 emission reduction by bioethanol in the transportation sector

In this analysis (Figures 42-45), biofeedstocks from agriculture, forestry, and mill residues are converted to ethanol. Methane produced from manure, water treatment sludge, landfills, and industrial production is also converted to ethanol. Ethanol is blended with gasoline and used in the transportation sector. Total CO_2 saving was computed by summing the emissions corresponding to the number of liters of gasoline displaced by ethanol. The conversion yields are derived from the literature and are validated, where possible, using the Argonne GREET database [24]. EIA long-term predictions of U.S. gasoline consumption for the transportation sector are almost constant.

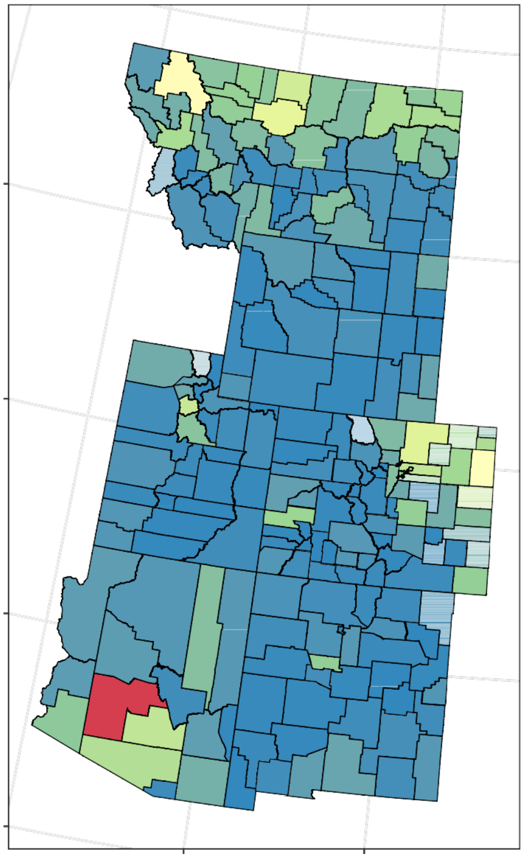

Figure 42. Potential ethanol production from biofeedstocks by county in the Intermountain West.

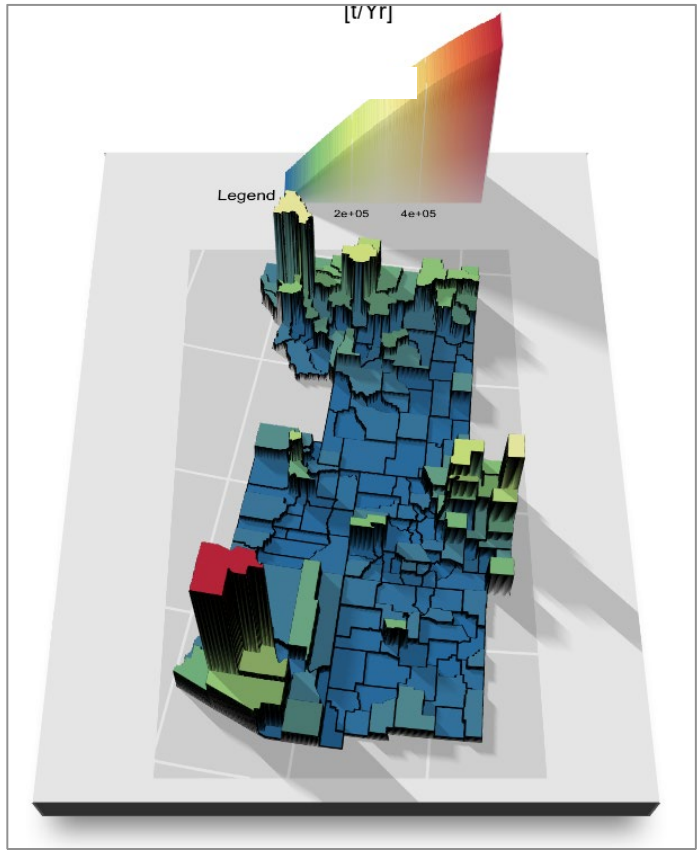

Figure 43. Potential CO_2 reduction from bioethanol used in transportation by county (t/yr).

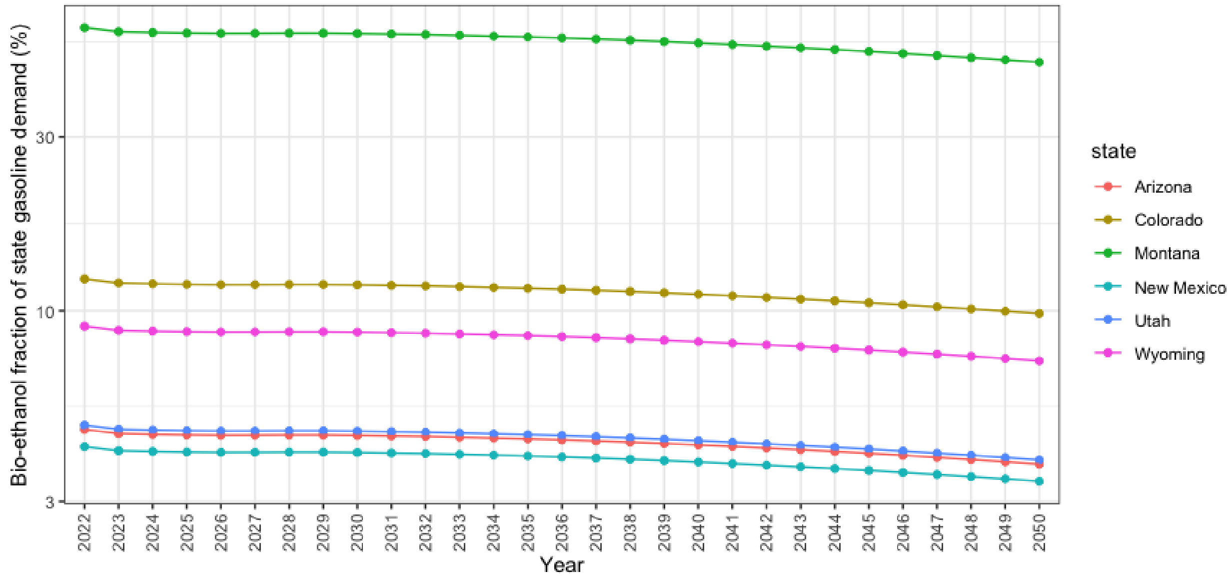

Figure 44. Fraction of state-level gasoline projected demand by year for transportation that can be potentially offset by locally produced bioethanol. Gasoline demand is based on EIA long-term national consumption projections applied to 2021 state-level gasoline consumption data.

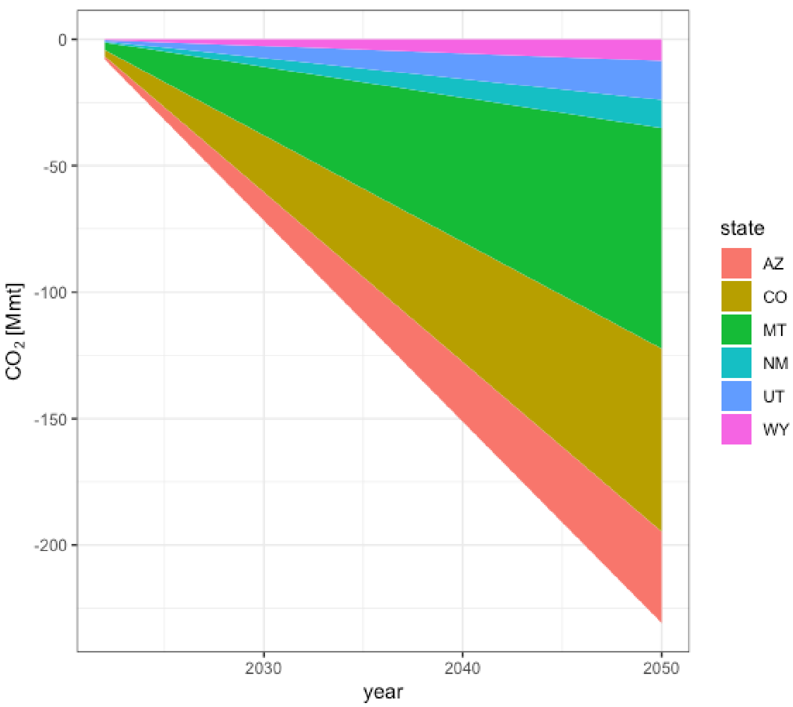

Figure 45. Potential cumulated CO_2 reduction from bio-ethanol– a ton of CO_2 equivalent. Bioethanol is produced by biomass and biogas transformation. CO_2 savings are computed as gasoline emissions displaced by bioethanol.

These analyses (Figures 42-45) indicate that CO_2 emissions can be reduced by 225+ MMt by 2050 through bio-ethanol usage. The yearly saving is almost 8 Mmt of CO_2. The reduction in CO_2 emissions from use of bio-derived feedstocks to produce electricity is substantially higher than the potential for reduced CO_2 emissions from the transportation sector, using bioethanol.

Bioenergy processing pathways

Conversion technologies/emerging trends and technologies

Just as there are a variety of bio-feedstocks, and bio-derived waste carbon sources that can be converted into bioenergy products or chemicals and materials that would replace fossil-based products, there is a range of technologies and pathways for converting these feedstocks into a product (Figure 46).

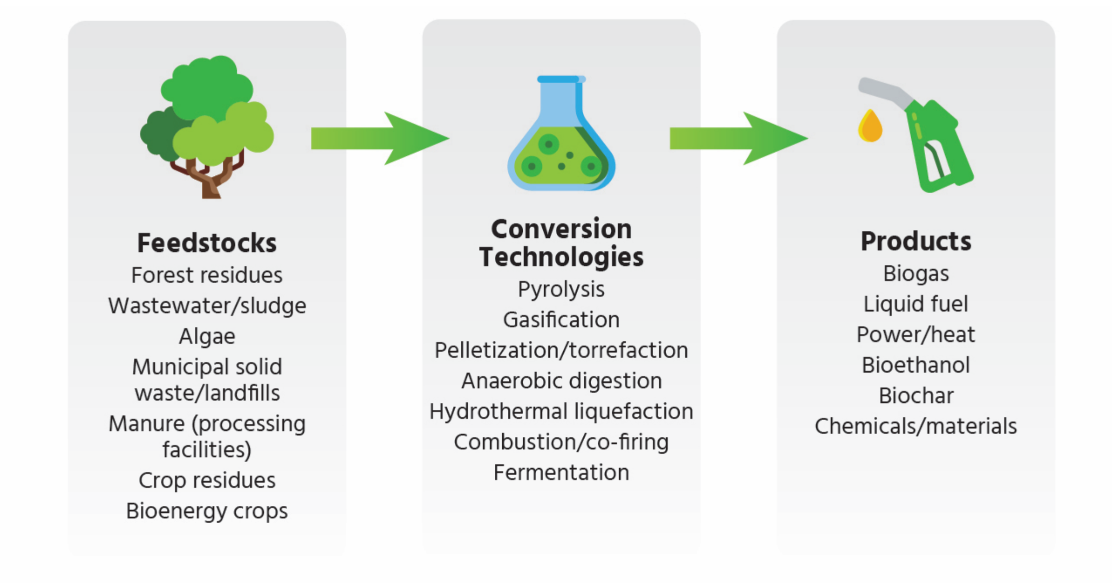

Figure 46. Feedstocks (left) are biomass or bio-derived, and alternative biofeedstocks as considered in this report are highlighted [25]. Some feedstocks may need pretreatment or preprocessing before being converted to improve efficiency; pretreatment or preprocessing technologies are not shown here. Conversion technologies (center) convert the feedstock to a gas, a liquid, or a solid and the composition varies depending on the feedstock. Generally speaking, each conversion route can apply to more than one type of feedstock. The efficiency of conversion and the products will vary. Finally, there are a range of products (right) from the conversion technologies and multiple products (co-products or by-products) can also be obtained from a single feedstock and conversion technology pathway.

Primary conversion technologies

Pyrolysis

In pyrolysis, low-moisture, bulky, lignocellulosic biomass such as forest or crop residues, purpose-grown bioenergy crops, or municipal solid waste are converted at high temperatures and high heating rate in the absence of oxygen to a bio-oil, which can be used as a liquid fuel; or a clean syngas, which can be used for electricity generation or renewable natural gas. A co-product of the conversion is biochar, which can be applied as a soil amendment or as an adsorbent for water filtration. The conversion in the reactor can be optimized by adjusting the processing conditions and by the addition of suitable catalysts. These modifications will also determine the percentage of product (bio-oil, gas, or char) obtained. In pyrolysis, one challenge is the variability in the form and composition of the feedstock. This can be partly solved through pretreatments that partially deconstruct the biomass before sending it to the pyrolyzer [26].

Gasification

Biomass gasification is a mature technology pathway that uses a controlled process involving high heat (>700°C), steam, and oxygen to convert biomass to hydrogen and other products without combustion [26].

Pelletization/torrefaction

Woody biomass can be thermally treated to densify it for use as a replacement for coal. The densification process can also be a pretreatment for the lignocellulosic biomass to make the pyrolysis or gasification process more efficient [27].

Hydrothermal liquefaction

Hydrothermal liquefaction converts wet/high moisture biomass into liquid fuels through a thermochemical process in a hot, pressurized water environment, which breaks down and depolymerizes solid components into liquid components. Hydrothermal liquefaction is still in pre-demonstration scale; but has shown promise for processing of microalgae to biocrude [28]; and for conversion of municipal wastewater sludge [29] and food waste to biofuel intermediates [30].

Biochemical conversion (anaerobic digestion)

Anaerobic digestion (AD) is a technology that is widely used in food processing, wastewater treatment, and on livestock farms. AD technology is based on the natural process by which microorganisms, in a closed system without oxygen, break down organic wastes to produce a gas. Recovered biogas can be an energy source for electricity, heating, or transportation fuel. The compressed biogas can be pumped into existing gas pipelines, from where it can be sold and distributed. The AD process also generates solid and liquid coproducts such as natural fertilizer, compost, and animal bedding. AD technology is mature, but there are still opportunities to improve the efficiency of the technology [31, 32].

Biochemical Conversion (Fermentation)

Bioethanol is produced from biomass through a process involving pretreatment (initial breakdown), then enzymatic hydrolysis (to convert polysaccharides to monomer sugars), followed by fermentation by different microorganisms to convert the sugars into ethanol. Other alcohols like isobutanol can also be generated from biomass. In a different biochemical conversion process, Alder Fuels in Colorado uses microbes to convert food and farm wastes to short hydrocarbons called Volatile Fatty Acids (VFA). The VFAs are then processed further by chemical catalysis to longer hydrocarbons, and selectively separated to become sustainable jet fuel [33].

Future opportunities

Use of produced water to minimize fresh water consumption in bioenergy production

The Intermountain West supports an abundance of oil, gas, and coal resources—water that is co-extracted with these fossil-based resources has the potential to replace some fresh water use in the drought-prone region. In New Mexico, water from oil production is produced in a 10:1 ratio (Figure 47). This “produced water” can be treated or, in some cases, used directly for bioenergy applications such as cultivation of algae for biofuel production [34, 35]. Produced water (PW) reuse has also been suggested for some crop irrigation purposes, but there are some conflicting reports on how safe this would be. Two recent greenhouse studies suggest that plant immune response to pathogens may be suppressed when PW is used for irrigation, along with decreased soil health, wheat yields, and (soil) microbial diversity [36, 37]. However, in California, a panel found no evidence of elevated threat to human or crop safety from use of oil field PW to irrigate crops [38], and this has been supported by field studies using low-saline PW [39]. Whereas the use of PW for irrigation of food crops may continue to be controversial for some time, its use for production of biofuel and bioenergy crops may be less controversial, provided combustion of such feedstocks does not increase toxic emissions and, in the case of bioenergy crops like oil seed crops or switchgrass, there are no adverse effects on soil health or crop yield.

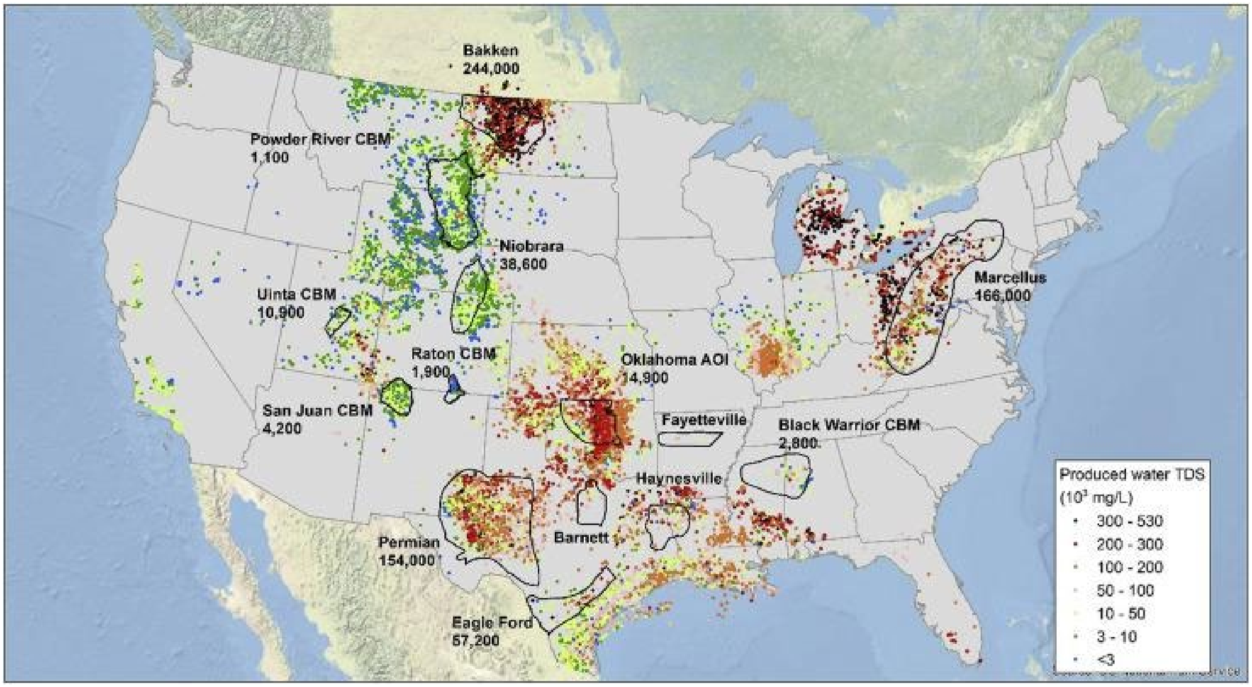

Figure 47: Total dissolved solids (TDS) of produced water from the USGS Produced Waters database (version 2.3) with supplemental data for the New Mexico region of the Permian Basin provided by the New Mexico Institute of Mining and Technology (NMIMT) Petroleum Research and Recovery Center (PRRC) and data from the USGS in the Eagle Ford Play. 2020 [40].

Smaller modular technologies

Small, modular, process-intensification technologies would make bioenergy and bioproduct production accessible to both rural and urban communities for more modest investments than construction of large-scale, central biorefineries. For example, the Trio Renewable Gas (a California based company) fast pyrolysis platform is modular and mobile, meaning operable on a semi-truck. The ability to bring a small portable unit to the site of harvesting to process biomass would be a game-changer in utilizing alternative biomass feedstocks for conversion into syngas. Likewise, hydrothermal liquefaction systems and anaerobic digesters, if made smaller in scale, could be used on location to process or pre-process biomass into fuel or energy intermediate products.

Use of ML/AI to accelerate process optimization

Several reports have been published recently on the use of machine learning and artificial intelligence (ML/AI) to optimize bioenergy processes. For example, ML/AI tools have been applied to optimize biomass gasification processes [41, 42], hydrothermal liquefaction of biomass [43], and algae cultivation productivity for biofuel production [44]. Application of ML/AI tools could help to accelerate the pace of innovation and new energy technology deployment in the Intermountain West to achieve the needed reduction in GHG emissions in the next decade and beyond. ML/AI tools can be applied to optimize operational practices and can also help equipment manufacturers improve equipment and equipment component design (e.g., catalyst and membrane materials selection).

Synergies of bioenergy with agriculture

Agriculture (livestock, agricultural soils, and food crop production) contributes to about 11% of greenhouse gas emissions in the U.S. (EPA). There are two main areas of synergy between bioenergy production and agriculture that could be exploited in the Intermountain West to reduce GHG emissions.

First, as biomass or waste carbon is processed into energy, there may be solid carbon produced, called biochar. Pyrolysis, gasification, combustion, and even hydrothermal liquefaction will produce biochar as a byproduct. The biochar is used in regenerative agriculture in place of conventional fertilizers to remediate and sequester carbon in soils and help soil retain moisture. Biomass residues from anaerobic digestion (the solid digestate) may also serve as a soil amendment. Regional adoption of sustainable practices in agriculture may enable opportunities to increase bioenergy crop production (e.g., Montana Renewables and Calumet Specialty converting oil seed crops to biodiesel) or increase productivity of food or feed crops (e.g., Navajo Agricultural Products Initiative in the Four Corners region).

Second, agrivoltaics uses land for both agriculture and solar photovoltaic energy. It is an approach that intersects the food, energy, and water nexus, combining the ability to grow various crops on the same land used to generate solar electricity. Solar grazing is a type of agrivoltaics installed where livestock are grazing.

Current efforts to implement agrivoltaics across the region include Jack's Solar Farm in Boulder, Colorado, and Arizona State University's Agrivoltaic Learning Lab (ALL) located at Biosphere 2. Tucumcari Bioenergy and Trollworks, both companies located in New Mexico, are also integrating agrivoltaics into their bioenergy production processes.

Agrivoltaics is an active area of innovation [45]. Design solutions are being implemented to minimize shadows on crops and maximize electric energy generation. Solar panels can be raised to allow animals (e.g., cows) or equipment (e.g., combines) to pass through. These have been implemented over crops such as grapes, raspberries, strawberries, and pollinators. There are additional efforts to improve semi-transparent and transparent panels and light selective photovoltaic devices. For example, the application of photovoltaics in greenhouses is being used by UbiQD, Inc. in New Mexico and Heliene (a Canadian solar panel manufacturer) is using UbiQD's quantum dot glass technology that may allow for a more "optimal" spectrum of light into greenhouses. The sunlight is optimized by converting direct UV/blue light from the sun into an orange/red glow that can improve plant growth.

Bioenergy crops

Another potential area of synergy is cultivation of bioenergy crops, for example oil seed crops such as those used for biodiesel by Calumet Specialty and Montana Renewables. The Intermountain West has an abundance of non-arable land that could be cultivated with bioenergy crops and irrigated by produced water, or have its soil health regenerated with biochar or other waste carbon resources from regional biomass processing operations. Bioenergy crops cultivated with marginal water on restored land, for example from mining operations, presents an opportunity for the region to transition to bioenergy.

Discussion of unused land in the region

Non-arable land, or land that is contaminated from mining may present opportunities for regenerative agriculture and remediation of soil health for growing bioenergy crops, horticulture, or even food crops if suitable water sources can be located nearby and made clean enough for human consumption. Construction of greenhouses on such land may also make sense. Potential water sources may be low Total Dissolved Solids (TDS) produced water (Figure 47), or reclaimed water from a nearby industry.

Other synergistic opportunities

Waste, captured CO_2 as a feedstock in agricultural applications

Carbon dioxide is a carbon source for plants. In photosynthesis, plants use energy from sunlight to combine CO_2 and water to make carbohydrates, which they use as an energy source to grow. All terrestrial plants, as well as aquatic photosynthetic bacteria and algae, need CO_2 to make biomass. Bio-utilization of waste, or CO_2 captured by plants and other photosynthetic organisms, could be an effective way to boost growth while sequestering the captured carbon in the organism [46].

The use of CO_2 enrichment to enhance crop response in greenhouses has been used for many years [47]. Supplemental CO_2 increases net photosynthesis in greenhouse plants, resulting in improved growth and yield of flowering plants, as well as vegetables and forest plants. Use of CO_2 from captured waste sources [48] presents new opportunities for growers to supplement their greenhouses with CO_2 at less cost and hazard than by installing CO_2 generators in the greenhouse, and without adding to greenhouse gas emissions.

Likewise, algae cultivated for biofuels or bioproducts are routinely sparged with CO_2 to maintain biomass growth. For the past decade or more, algae cultivators have experimented with sparging of waste CO_2 collected from the flue gas produced by industrial facilities and power plants (49). Algae grown in either open ponds or greenhouses, or enclosed photobioreactors could benefit from utilization of CO_2 captured from industrial sources. Algae grown with waste CO_2 could be converted into biofuels or turned into a soil amendment to restore nutrients into marginal lands to enhance agriculture. The company Heliae in Gilbert, Arizona is focused on cultivation of algae as a soil amendment in regenerative agriculture. Their product, PhycoTerra® is a sustainably produced soil microbial supplement from algae that "works to restore the natural quality of the soil and balance in the overall soil ecosystem."

Colocation of greenhouses and/or algae cultivation ponds or photobioreactors (PBRs) with CO_2 emitting industries (e.g., power plants, biorefineries, etc.) would enable utilization of captured waste CO_2 to enhance biomass growth and yield, without the expense of transporting the CO_2 to the site of utilization. An additional benefit may be the use of "free," low-quality heat from the power plants that may be used to directly heat the cultivation environments. Ou et al. [22] reported that an algae site that sources carbon from a high purity waste CO_2 source would achieve a 9-39% reduction in life-cycle GHG emissions, and a 9-37% reduction in life-cycle fossil energy use compared to a similar site using dilute CO_2 for algae cultivation.

Biohydrogen production

Biohydrogen is hydrogen produced biologically from microorganisms (e.g., algae or bacteria). Microalgae are capable of producing high levels of carbohydrates such as starch or cellulose, which are ideal substrates for hydrogen production. Furthermore, a sustainable process can be developed where the production of biohydrogen from microalgae can be integrated with industrial CO_2 utilization, or cultivation in wastewater or produced water [50].

Special intersections with environmental and social justice and bioenergy

One of the unique features of the Intermountain West is the high number of tribes in the region. From the bioenergy workshop I-WEST held in January 2022, we learned that there are strong bonds between indigenous people and nature, and these bonds need to be understood and respected as we transition to new energy sources. In particular, advancing bioenergy and related technologies in the region needs to occur in synchrony with tribal interests and consideration of their land and resources. Agriculture is an important part of indigenous culture. Consequently, there could be competition for resources needed for food vs. energy/commodity crops; for example, arable land and freshwater availability are concerns. Some of the integrated approaches between agriculture and bioenergy technologies may help mitigate these concerns and actually turn them into new opportunities for tribal communities, as well as other rural and/or economically disadvantaged communities.

Training and engagement with local colleges, or community members (co-ops) to build a local workforce is a viable approach to growing bioenergy technologies in the Intermountain West, particularly at the interface of agriculture and bioenergy interests. Developing workforce training and degree and certificate programs in conjunction with local colleges will help to ensure a well-trained workforce locally. Additionally, training programs that offer skills development in the range of new energy technologies will be important to building a workforce that is agile in response to climate change and the portfolio of new energy sources that will be developed and deployed locally.

List of figures and tables

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Phase One Final Report | Detailed Chapter

Low-Carbon Electricity

VERSION 2.0 LOS ALAMOS NATIONAL LABORATORY JUNE 2023

About this chapter

The Intermountain West Energy Sustainability & Transitions (I-WEST) initiative is funded by the U.S. Department of Energy to develop a regional technology roadmap to transition six U.S. states to a carbon-neutral energy economy. I-WEST encompasses Arizona, Colorado, Montana, New Mexico, Utah, and Wyoming. Each state is represented in this initiative by a local college, university, or national laboratory. Additional partners from beyond the region were selected for their expertise in applicable fields. In the first phase of I-WEST, the team built the foundation for a regional roadmap that models various energy transition scenarios, including the intersections between technologies, climate, energy policy, economics, and energy, environmental, and social justice. This chapter presents work led by an I-WEST partner on one or more of these focus areas. A summary of the entire I-WEST phase one effort is published online at www.iwest.org.

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Table of contents

Introduction

Low-carbon technologies for producing electric power are important for achieving carbon neutrality. This report provides an overview of several electricity production technology pathways available, and their respective challenges.

Overview of regional electricity capacity

Electricity production in the Intermountain West relies on many fuel sources, from CO_2-emitting fossil fuels to clean energy renewables. Data for this overview are from the U.S. Energy Information Administration (eia.gov). The region has abundant natural gas and coal resources, which are currently the primary sources for electricity production. The Intermountain West has an installed capacity of 90,568 megawatts (MW) of production—33,160 MW from natural gas and 24,008 MW from coal. Coal plants provide baseload for the system and natural gas plants provide a fast-ramping source of electricity critical for load balancing. Baseload generation is approximately 30% of total capacity. Figure 1 shows the locations of all electric power plants in the region.

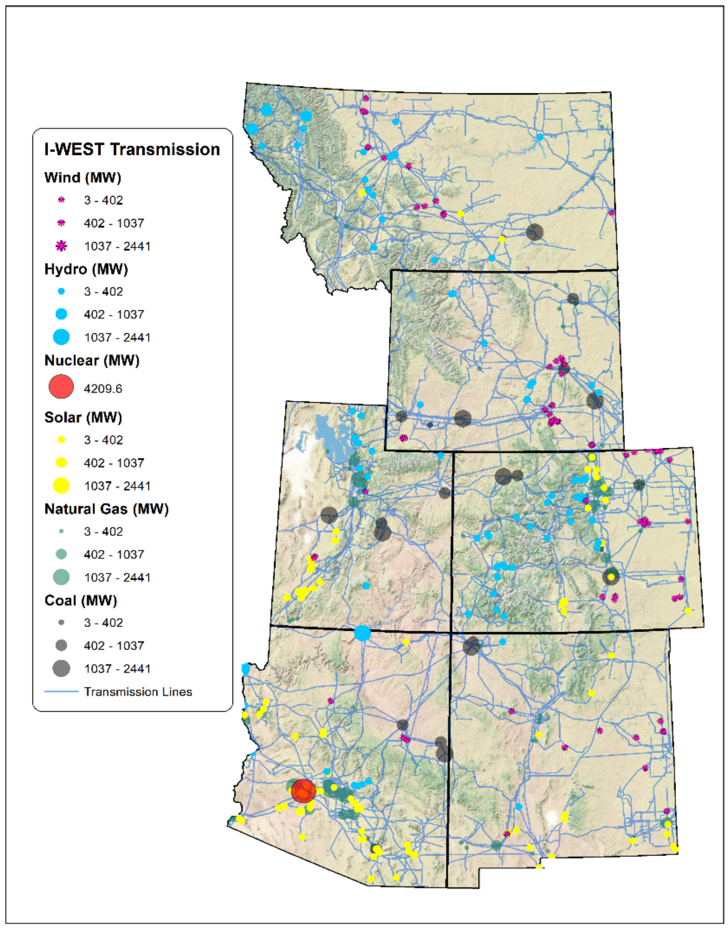

Figure 1. Electric power plants. Data from www.eia.gov.

Hydroelectric plants have installed capacity of 7,400 MW, with Glenn Canyon Dam and Hoover Dam (AZ) having a combined capacity of ~2300 MW. Montana has the next largest installed capacity of hydroelectric power at 2,653 MW.

The greatest potential for wind production of electricity is east of the Rocky Mountain range. The states with the largest installed capacity of wind production are Colorado and New Mexico. The largest wind farm is in Rush Creek, Colorado with a capacity of ~600 MW. Total wind capacity in the region is 14,556 MW.

Arizona is home to the only nuclear plant in the region, Palo Verde, with an installed capacity of 4,209 MW.

Solar production in the region continues to grow with a current installed capacity of 6,178 MW. The four southern states of Arizona, New Mexico, Utah, and Colorado have the largest solar potential. Arizona has the largest installed capacity of solar power at 2,810 MW, followed by Utah with 1,457 MW. The largest solar farm in the region, Agua Caliente Solar Project (AZ), has a capacity of 347 MW. Solar projects require a large amount of land—the Agua Caliente Solar Project takes up roughly 2,000 acres. When comparing individual power plants, it's important to note that the region's energy-dense fossil fuel plants have roughly five to eight times the installed capacity of the regional solar/wind plants and a much smaller land footprint. For example, the largest coal plant in the region is the Jim Bridger plant located in Wyoming with installed capacity of 2,441 MW, and the largest natural gas plant in the region is the Gila River Power Plant located in Arizona with installed capacity of 2,476 MW.

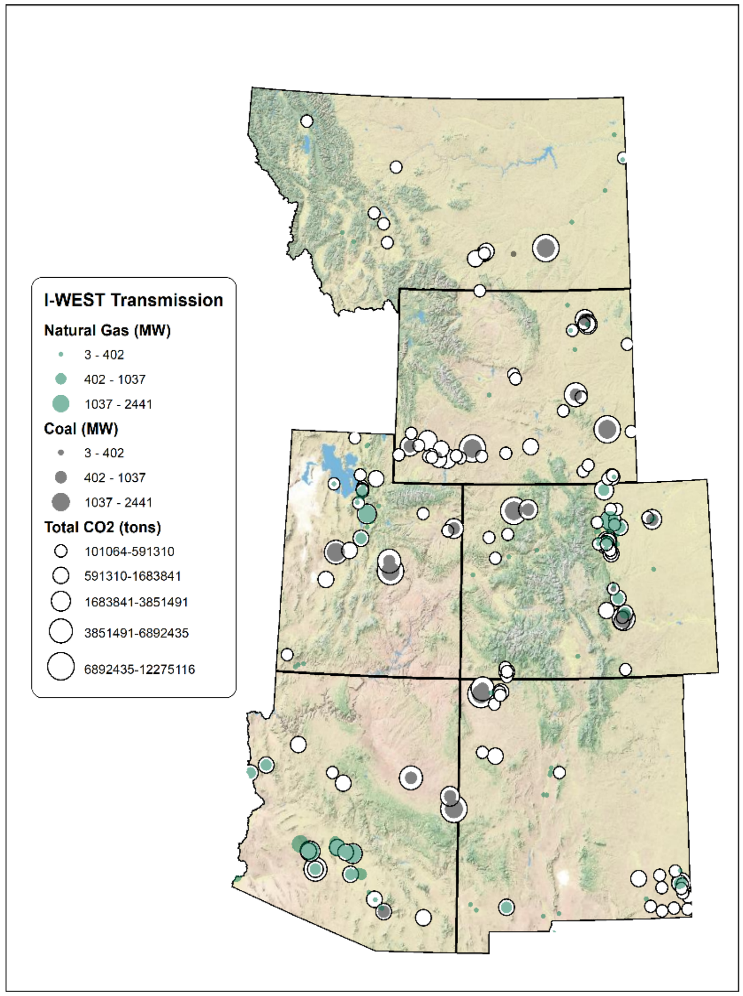

Figure 2. Point source emissions. Data from EPA.

Regional CO_2 emissions

Using 2020 data from EPA emissions atlas and EPA eGrid, we mapped the 45Q[1] point source emitters and overlay the fossil fuel electric power plants. The electricity sector of the Intermountain West emits a total of 166 million tons of CO_2 per year—129 million tons from coal plants and 37

[1] Facilities that emit CO_2 can receive tax credits, referred to as "45Q,"by applying carbon capture technologies.

million tons from natural gas plants. Figure 2 shows the point source emissions from fossil fuel plants in the region, as well as other non-electricity sources.

Beyond the electricity sector, CO_2 emissions are also produced from natural gas processing plants, oil/gas extraction, oil refineries, mining operations (excluding oil/gas), and industry processes such as cement production. However, the electricity sector is the largest emitter of CO_2 in the region.

Colorado and Wyoming produce the most 45Q point source emissions at 58 million tons/yr and 56 million tons/yr respectively. The state that produces the least emissions is Montana at 13 million tons/yr.

Regional transmission

During the I-WEST Electricity Workshop[2], regional stakeholders and industry leaders identified transmission as one of the major constraints for energy transition—adding new generation sources will require an increase in transmission capacity, storage, and reserves. The current trend of replacing fossil fuels with renewable resources has already created a backlog of interconnection requests to the transmission and distribution grids. Additionally, since the region exports electricity to the West Coast, there is a need to expand the transmission pathways to that region. Figure 3 shows the major transmission lines and associated voltages throughout the region. Also included in the figure are locations of coal and nuclear plants.

From the figure you can see that the high voltage lines (500-600 kV) are anchored by coal-fired power plants. The Palo Verde nuclear power plant also anchors several high voltage lines and exports electricity to the West Coast. These coal and nuclear plants provide the “baseload” for electricity transmission. Baseload capacity is the generation that can serve loads around the clock. As coal plants continue to be retired, the baseload they provide will need to be replaced. Carbon-neutral options for baseload include nuclear, renewables with utility-scale batteries, natural gas with hydrogen blending, and coal with carbon capture technology. Each technology has efficiency challenges and varying load-balancing capabilities. These technologies are discussed later in this report.

[2] I-WEST Electricity Workshop Summary: https://70n17f.p3cdn1.secureserver.net/wp-content/uploads/2022/07/I-WEST-Electricity-Workshop-Summary.pdf

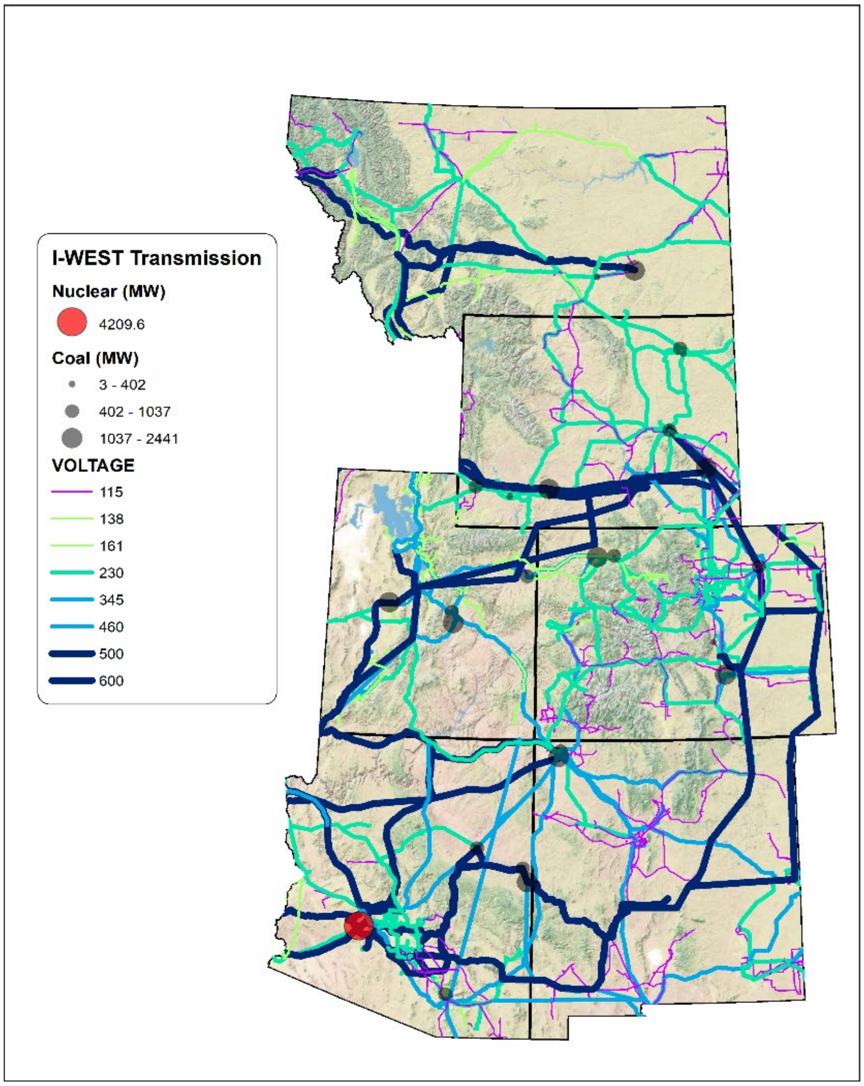

Figure 3. Transmission lines and associated voltages and locations of coal and nuclear power plants.

Regional balancing authorities

The Intermountain West has several balancing authorities, as shown in Figure 4. Currently, each utility is responsible for balancing their electricity system.

Another key takeaway from the I-WEST Electricity Workshop was that the Intermountain West states could benefit from the development of a single regional transmission organization (RTO). RTOs, such as CAISO in California or ERCOT in Texas, include generators, transmission companies, utilities, and power marketers. They use complex optimization software to dispatch power based on day-ahead and real-time bids from generators and utilities[3]. RTOs also provide better price transparency and result in more efficient grid dispatch services. Creating an RTO that spans the entire region would require the approval of the Federal Energy Regulatory Commission (FERC) as well as coordination at the utility and state levels.

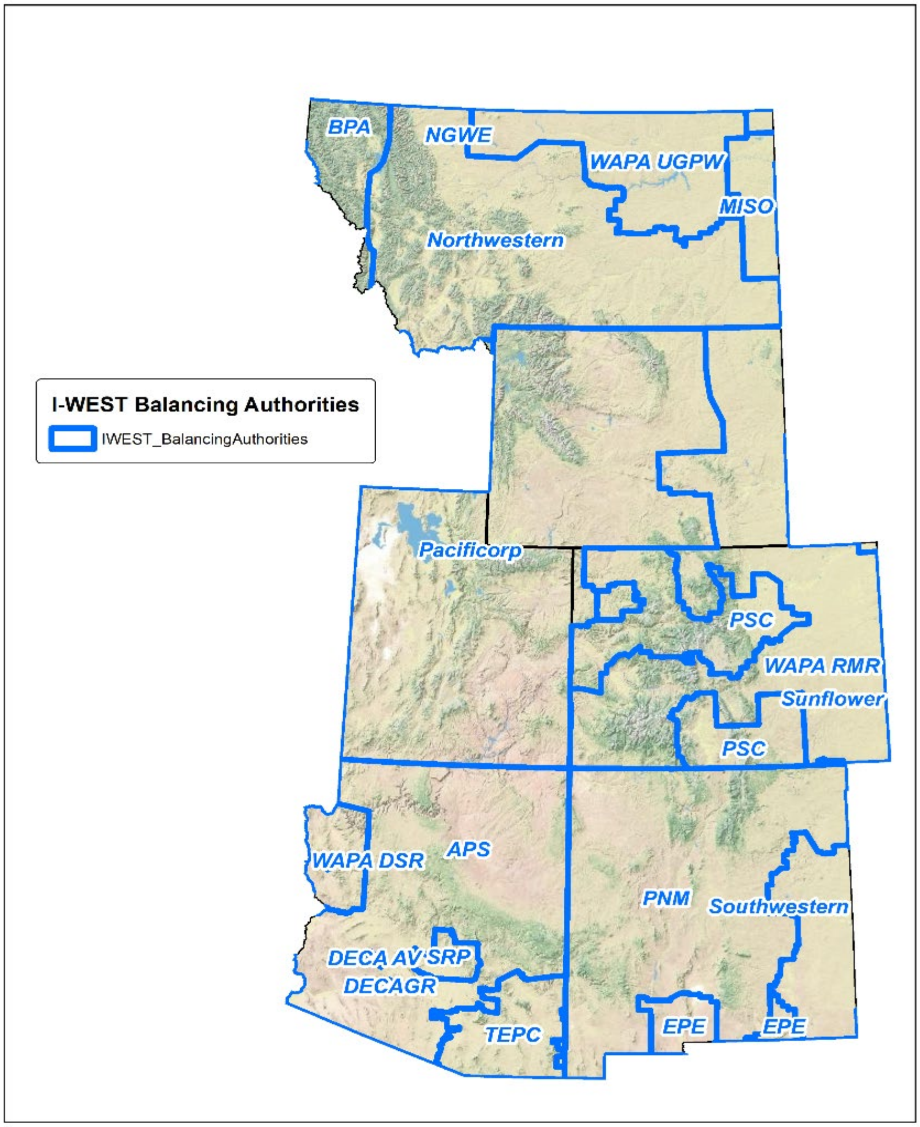

Figure 4. Balancing authorities.

[3] Eia.gov

State-by-state assessment

Montana

Montana has an abundance of water resources including the Yellowstone and Missouri rivers and is one of the top hydroelectric producing states in the Intermountain West (Table 1). Coal plants in Montana were built to complement the hydroelectric dams on the Missouri River when water levels run low, and were largely situated next to lignite mines. Coal production at the mines is ending, with the mines going through a multi-year reclamation process. As coal plants are retired, they are being replaced with natural gas facilities to maintain electricity supply to the grid. This conversion is largely driven by the low cost of natural gas.

Table 1. Montana electricity generation

Technology	MW	Water Source
Coal	1814	N/A
Largest Coal Plants		
Colstrip	1693	Yellowstone River and wells
Hardin	115	Bighorn River
Natural Gas	492	Muni, Yellowstone River
Hydro	2653	Missouri River and others
Solar	17	N/A
Wind	1121	N/A

Wyoming

Wyoming also has an abundance of surface water resources that are used for cooling coal-fired plants (Table 2). The state's natural gas plants are cooled with groundwater wells and municipal water resources. Wyoming has the smallest population of the six Intermountain West states and therefore consumes less electricity than it produces. The excess electricity is sold to the West Coast. Coal production in Wyoming peaked in 2008 and has been declining ever since. However, Wyoming still exports Powder River Basin coal to Texas, and profits from this account for a large portion of the state's revenue. Additionally, Wyoming's Black Thunder coal mine is the second largest producing coal mine in the country. Despite the potential for clean energy production in the state, Wyoming is currently dependent on its coal customers (TX) and electric power customers (CA). In terms of fossil alternatives, Wyoming has a proposed nuclear power project in development (Terra Power), and has the highest wind potential of all six states in the region with a large capacity of wind installations east of the Rocky Mountains.

Table 2. Wyoming electricity generation

Technology	MW	Water Source
Coal	7023	
Largest Coal Plants		
Dave Johnston	922	North Platte River
Dry Fork	483	Wells
Jim Bridger	2441	Green River
Laramie River	1863	Laramie River
Naughton	448	Hams Fork River
Wygen	301	Wells
Wyodak	402	Muni
Natural Gas	824	Wells, Muni
Hydro	301	N. Platte, Shoshone & others
Solar	92	N/A
Wind	3130	N/A

Utah

Utah has several water resources including the Green River, and several creeks and reservoirs, that are used for cooling coal-fired plants. Natural gas plants are cooled with groundwater wells and municipal water sources. Utah Associated Municipal Power Systems is building a small modular reactor (SMR) plant at the Idaho National Laboratory and will benefit from the electricity produced there. The reactor will be a six-module, 462 MW SMR and will cost an estimated 5.1 billion[4] to build. Utah is actively increasing solar capacity and is converting coal plants to natural gas facilities.

Table 3. Utah electricity generation

Technology	MW	Water Source
Coal	4812	
Largest Coal Plants		Green River
Bonanza	499	
Hunter	1577	Cottonwood Creek
Huntington	1037	Huntington Creek
Intermountain	1640	DMAD Reservoir
Natural Gas	3242	Wells, Muni
Hydro	265	Rivers, Reservoirs, Creeks
Solar	1457	-
Wind	389	-

[4] https://gazette.com/premium/colorado-remains-uninterested-as-others-turn-to-nuclear-power/article_e7491614-c596-11ec-86d3-638636c39afd.html

Colorado

Colorado has numerous water resources for cooling coal-fired plants including the Arkansas River and the Yampa River. The state also uses groundwater wells and municipal water for cooling both coal-fired and natural gas-fired plants.

Table 4. Colorado electricity generation

Technology	MW	Water Source
Coal	4581	
Largest Coal Plants		
Comanche	1635	Arkansas River
Craig	1427	Yampa River
Hayden	465	Yampa River
Pawnee	552	Wells
Rawhide	293	Municipality
Ray D Nixon	207	Wells
Natural Gas	8006	Rivers, Wells, Municipality
Hydro	1184	Rivers, Lakes, Reservoirs
Solar	1060	N/A
Wind	5032	N/A

Arizona

Arizona uses groundwater wells for cooling coal-fired plants and natural gas plants. Arizona also has access to Central Arizona Project (CAP) water for the cooling of some natural gas plants. Arizona has the highest hydroelectric capacity of the six states due to the Glenn Canyon and Hoover Dams. However, the drought caused water levels in Lake Powell to drop significantly in 2022, which threatened hydroelectric production at Glenn Canyon Dam. Arizona, with its high solar potential, has the largest amount of installed solar capacity in the region. This is due in part to the state's systems that encourage solar adoption. For example, Arizona uses an online permitting platform, SolarAPP+, for automated permitting approvals of rooftop solar installations. The Salt River Project launched a study on converting its Coronado coal-fired power plant to a green energy plant. Options include bioenergy, hydrogen, or nuclear— or turning the site into a battery storage plant for solar and wind energy[5].

[5] https://www.wmicentral.com/business/srp-launches-study-on-converting-coal-fired-plant-to-clean-green-energy/article_d48b52c1-ea2c-5cb6-8cd1-898afa8a7f17.html

Table 5. Arizona electricity generation

Technology	MW	Water Source
Coal	3217	
Largest Coal Plants		
Apache	204	Wells
Cholla	425	Lake Wells
Coronado	821	Wells
Springerville	1765	Wells
Natural Gas	16981	Wells, CAP, Muni
Hydro	2912	Colorado River and others
Solar	2810	N/A
Wind	617	N/A

New Mexico

New Mexico uses water from the San Juan River and Morgan Lake for cooling at the Four Corners and San Juan coal plants. Groundwater wells are used for cooling at natural gas-fired plants.

Table 6. New Mexico electricity generation

Technology	MW	Water Source
Coal	2560	
Largest Coal Plants		
Four Corners	1636	San Juan River/ Morgan Lake
San Juan	924	San Juan River
Natural Gas	3613	Wells
Hydro	81	Rio Grande, San Juan
Solar	740	N/A
Wind	4265	N/A

Technology pathways for electricity production

Renewables with utility-scale batteries installed close to load

Energy storage in the form of utility-scale batteries allows the power grid to function with more up-to-date manufacturing/sales, flexibility, and resilience. The cost of installing bulk electric storage systems has declined in recent years—the average battery energy storage capital cost in 2019 was

$589 per kilowatt hour (kWh).[6]. Co-locating battery systems with renewable power plants, such as solar and wind, allows the batteries to be charged during times of overgeneration. During peak solar hours, curtailed wind energy can be used to charge the battery systems, maximizing the use of clean energy sources. The batteries can then discharge during low solar hours. For example, Figure 5 shows the CAISO (California Independent System Operator, caiso.com) supply trend profile. CAISO has ~1600MW of battery systems that charge during peak renewable hours and discharge as renewable production declines.

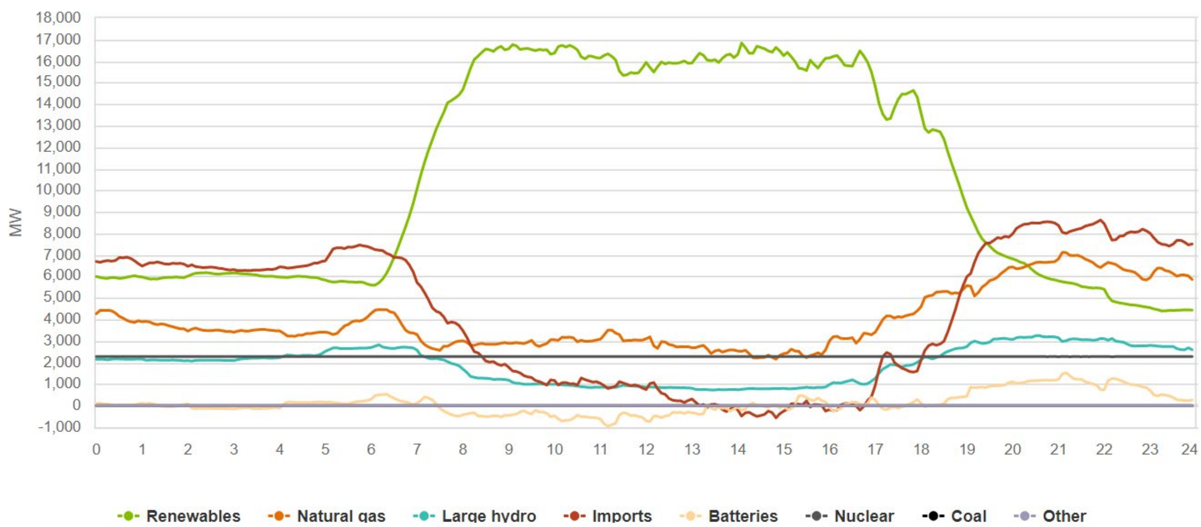

Figure 5. CAISO supply trend profile (caiso.com); energy in MW by resource, in 5-minute increments.

As of 2020, New Mexico has 1.8 MW, Colorado has 10 MW, and Arizona has 97 MW of battery storage installed. Renewables are actively increasing the variability of the system. The challenges for this technology pathway are to identify the best strategies for load balancing and planning for reserve margins, while also developing safer battery systems with more efficient fire suppression. An additional challenge is securing the vast amount of land needed for solar and wind projects, and the significant amount of lithium required to run utility-scale battery systems.

Retrofit natural gas plants with blended hydrogen/natural gas for co-fire

Interest in using hydrogen as a power plant fuel is growing in the United States. Several power plants are experimenting with blending natural gas with hydrogen for power production. One

[6] https://eia.gov/analysis/studies/electricity/batterystorage

example is the Intermountain Power Agency conversion of an existing coal plant in Utah to a natural gas plant that will use a blend of 30% green hydrogen with 70% natural gas for co-firing. SoCalGas is pursuing a project to generate hydrogen, then blend hydrogen into natural gas to generate electricity for the California Institute of Technology in Pasadena. Natural Gas is an important fuel source for load balancing the grid and will likely continue to be a component of our electricity production profile. Natural gas is also needed to produce “blue” hydrogen, which is hydrogen created through reforming of natural gas. Hydrogen substitution for natural gas frees up the natural gas for competing uses such as home heating and industrial processes. Use of hydrogen in electricity production will also be key as regional clean hydrogen hubs are established through the Bipartisan Infrastructure Law—creating both demand and supply of hydrogen is key to a sustainable new hydrogen economy. The challenge for the Intermountain West will be finding sufficient water to produce “green” hydrogen, which is produced by water electrolysis powered by renewable electricity.

Repurpose coal plants with small modular reactors

A small modular reactor (SMR) is a new generating technology using advanced nuclear reactors with power capacity of up to 300 MW per module. The modules can be assembled in a factory and transported to a specific location, making them more affordable than building a traditional nuclear power plant. SMR designs are generally simpler and safer, relying on passive systems to remotely shut down. They require less frequent refueling (every 3-7 years) and some are designed to operate for 30 years without refueling[7]. SMR modules can be installed at retired coal plants where transmission and water supplies are already present. Utah Associated Municipal Power Systems is pursuing an SMR project that will use six small reactor modules. The challenge for this technology pathway will be political and community acceptance of nuclear energy, as well as the cost. SMR technology will need to clearly demonstrate the safety improvements over traditional nuclear designs, and define spent fuel management strategies that are credible.

Carbon capture and storage

The region has several coal power plants where carbon capture methods could be used based on their existing process and current infrastructure. In New Mexico, Enchant Energy is planning a post-combustion retrofit of the San Juan Generating Station in San Juan County, New Mexico that will capture 6 to 7 million metric tons per year of CO_2 for local storage within the San Juan Basin.

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[7] https://iaea.org

Traditional methods of carbon capture, utilization and storage (CCUS) require large amounts of water. The challenge for this technology is finding enough water resources required for the various methods.

Energy transition scenarios for electricity production

A key focus of I-WEST is to assess the existing energy landscape and offer up potential scenarios for how the Intermountain West could transition to net zero carbon as quickly and sustainably as possible. Following is a series of possible strategies considered.

Scenario #1: Aggressive renewables, fuel blending, and CCUS for remaining coal plants

This scenario includes:

- Aggressively deploying renewables co-located with utility-scale batteries to replace **some** coal-fired plants
- Adding small modular reactors to replace **some** coal-fired plants
- Retro fitting natural gas plants with a blended fuel source of 70% natural gas and 30% hydrogen
- Installing carbon capture technologies at remaining coal-fired plants

Figure 6 shows the locations, fuel types, and sizes of power plants proposed for scenario #1.

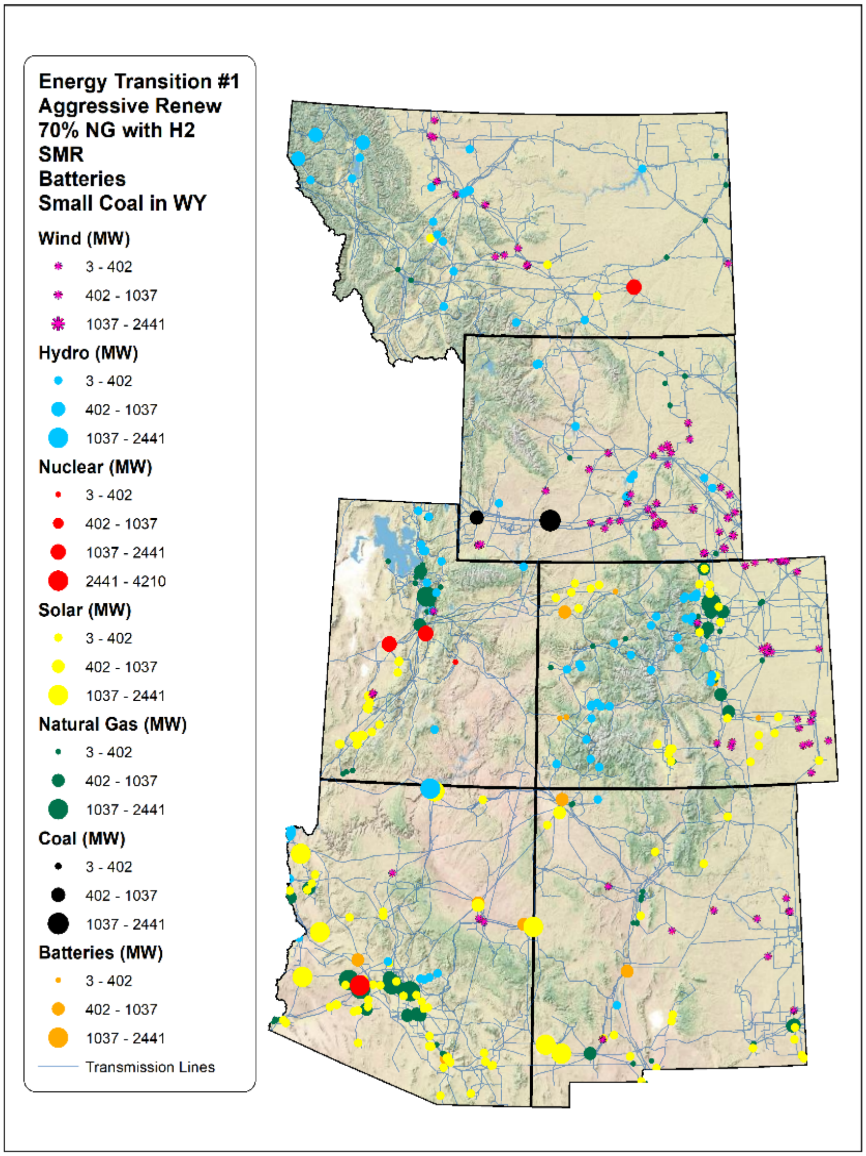


Figure 6. Locations, fuel types, and sizes of power plants proposed for scenario #1.

In this scenario, coal-fired capacity is reduced from 24,008 MW to 3,273 MW and the remaining coal-fired plants are located in Wyoming with CCUS technologies installed.

Wind capacity is increased from 14,556 MW to 18,450 MW and is mostly located in the highest wind potential areas in Wyoming and Colorado.

Solar capacity increases from 6,178 MW to 15,805 MW and the additions are located in the highest solar potential areas in Arizona, New Mexico, Utah and Colorado.

Utility-scale battery systems are added near renewable sites in Arizona, New Mexico, and Colorado, increasing total capacity in the region by 5900 MW.

Nuclear capacity increases from 4209 MW to 10541 MW with the addition of SMR technologies in Utah and Montana.

The number of plants and capacities of natural gas-fired plants do not change, but we assume that each natural gas plant is retrofitted with blended fuel of 70% natural gas and 30% hydrogen. The natural gas capacity remains the same at 33160 MW for the region.

Hydroelectric capacity remains unchanged at 7400 MW.

Load balancing is accomplished by using a broad spectrum of energy sources: nuclear, natural gas, and coal (from remaining plants, and utility-scale battery systems.

Under this scenario, CO_2 emissions are reduced from 166 million tons/year to 40 million tons/year in the electricity sector. The remaining emissions result from the natural gas-fired plants and the coal-fired plants with CCUS installed, which reduces 85% of emissions from coal plants. Further research is needed to determine infrastructure investments required and to calculate a detailed cost analysis for this scenario.

Scenario #2: Replace coal with small modular reactors, plus fuel blending

This scenario includes:

- Replacing all coal-fired plants with SMRs
- Retrofitting all natural gas plants to operate with blended fuel of 70% natural gas and 30% hydrogen
- No change to renewable energy capacity

Figure 7 shows the locations, fuel types, and sizes of power plants proposed for scenario #2.

In this scenario, SMRs are installed at locations of coal-fired plants where transmission and water resources are already established, providing easy connections to the grid and on-site cooling.

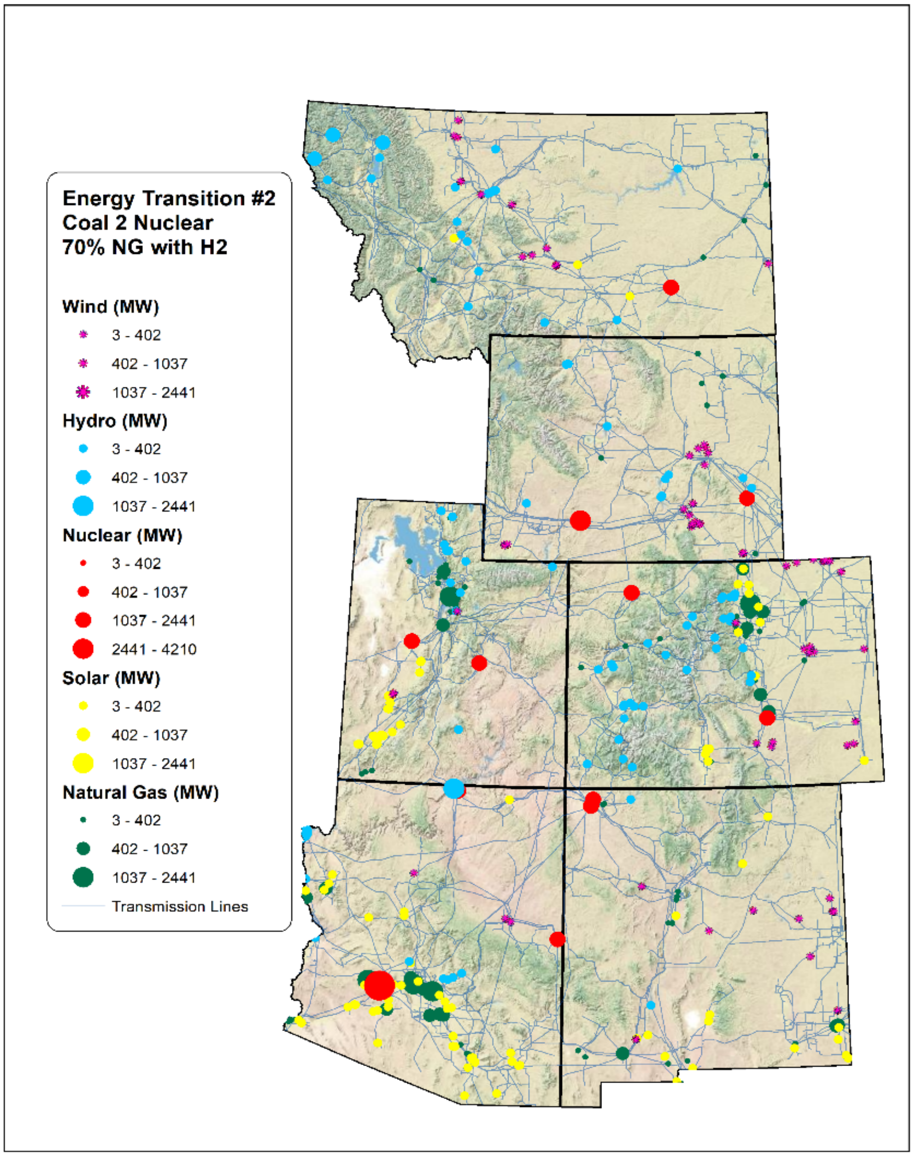


Figure 7. Locations, fuel types, and sizes of power plants proposed for scenario #2.

SMRs replace the coal capacity MW with nuclear MW— nuclear capacity increases from 4209 MW to 33069 MW.

All natural gas plants are assumed to operate with blended fuel of 70% natural gas and 30% hydrogen. There is no change to the overall capacity of natural gas.

No changes are made to solar, wind, or hydroelectric capacities.

Utility-scale battery systems are not needed/installed due to nuclear and natural gas serving as the baseload.

Load balancing is accomplished by using a broad spectrum of energy sources: nuclear plants, natural gas plants, and SMR plants.

Under this scenario, CO_2 emissions are reduced from 166 million tons/year to 26 million tons/year in the electricity sector. The remaining emissions result from the natural gas-fired plants. Further research is needed to determine the infrastructure investments required and to calculate a detailed cost analysis for this scenario.

Scenario #3: Replace coal with renewables, aggressive batteries, and fuel blending

This scenario includes:

- Replacing all coal-fired capacity with renewable energy plants (solar and wind)
- Retrofitting all natural gas plants to operate with blended fuel of 70% natural gas and 30% hydrogen
- Adding utility-scale battery systems installed close to renewable energy plants

Figure 8 shows the locations, fuel types, and sizes of power plants proposed for scenario #3.

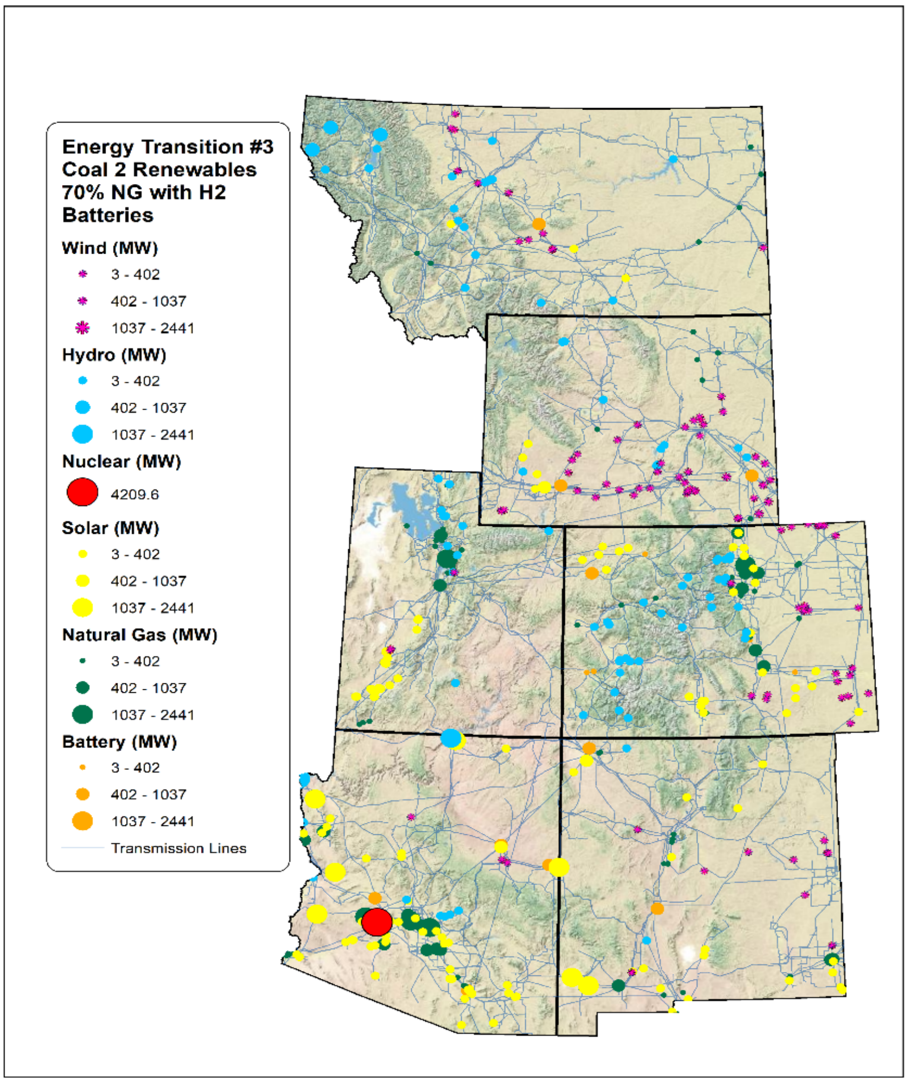


Figure 8. Locations, fuel types, and sizes of power plants proposed for scenario #3.

In this scenario, solar capacity increases from 6,178 MW to 17,409 MW with additions in high solar potential areas of all states. Where feasible, solar plants are located close to former coal plant sites.

Wind capacity increases from 14,556 MW to 18,450 MW with most of the increases located in the high wind-potential states of Wyoming and Colorado. Where feasible, wind plants are located close to former coal plant sites.

Utility-scale battery systems are added near renewables sites in Arizona, New Mexico, Colorado, Wyoming, and Montana, increasing total battery system capacity in the region to 7,500 MW.

All natural gas plants are assumed to operate with blended fuel of 70% natural gas and 30% hydrogen. There is no change to the overall capacity of natural gas.

No changes are made to hydroelectric or nuclear capacities.

Load balancing is accomplished by using a broad spectrum of energy sources: nuclear plants, natural gas plants, and utility-scale battery systems.

Under this scenario, CO_2 emissions are reduced from 166 million tons/year to 26 million tons/year in the electricity sector. The remaining emissions result from the natural gas fired plants. Further research is needed to determine the infrastructure investments required and to calculate a detailed cost analysis for this scenario.

Scenario Comparison

Table 7 compares the installed capacity for the three scenarios.

Table 7. Installed capacity for scenarios

	Current	Scenario #1 Renewables, SMR, fuel blending, coal CCUS, batteries	Scenario #2 Coal to SMR, fuel blending	Scenario #3 Coal to renewables, fuel blending, batteries
Coal	24,008	3273	0	0
Natural Gas	33,160	33160	33160	33160
Hydroelectric	7,400	7400	7400	7400
Solar	6,178	15805	6178	17409
Wind	14,556	18450	14556	19950
Nuclear	4,209	10541	28189	4209
Battery	108	5900	0	7500
Total Capacity	**89,619**	**94,529**	**89,483**	**89,628**
Total CO_2	**166 mil. tons/yr.**	**40 mil. tons/yr.**	**26 mil. tons/yr.**	**26 mil. tons/yr.**

R&D needs assessment

Over the course of several stakeholder engagement workshops on energy transition in the Intermountain West (iwest.org), it became increasingly clear that there are several pressing challenges to achieving carbon neutrality. The region, as with many others, is fragmented when it comes to electricity generation planning. The states have different priorities and within each state, local communities and industries have their own set of needs and challenges. Further, the grid industry and utilities themselves have competing objectives. This presents challenges to centralized planning for regional goals such as getting to carbon neutral, as many planning decisions are made locally. Yet, such decisions must adhere to regional requirements and standards that are maintained through regional transmission organizations (RTO), independent system operators (ISO), and, ultimately, the Western Electricity Coordination Council (WECC). Given the structure of the electricity economy in the Intermountain West, research and development (R&D) efforts must bear these constraints in mind. While a centralized planning model is needed to inform, for example, funding decisions that impact the entire region, localized considerations must be integrated into that model in order to accurately identify emerging trends, opportunities, and possibilities.

Future infrastructure investments

Core R&D for the regional electricity economy must be focused on how to support future infrastructure investments in the Intermountain West. R&D requirements of I-WEST from an electricity perspective include:

Decision support planning tools (DSPT): These tools are needed to evaluate technology pathways and their synergistic effects to identify cost effective investments that will yield desired decarbonization outcomes. Such tools should leverage existing capabilities, repurpose existing tools, and develop new features that are required for specific regional goals and aims. Features of these planning tools should include at a minimum:

> *No-regrets planning:* Since many investment decisions are made locally, DSPTs should help identify investments that account for uncertainty in how investments will be made across the region and which are most likely to yield benefits for a wide range of external investment scenarios.
>
> *Economic analysis:* DSTPs need to model investment economics and help identify incentives to encourage adoption of technologies that will yield the desired decarbonization outcomes. Many technologies will have adoption challenges unless they are economically viable.
>
> *Social analysis:* DSTPs need to model the social implications of infrastructure investments and the potential for stranded assets, which may unequally impact and benefit different areas of the region.

Variability: DSTPs need to model uncertain electricity generation capacity (wind, solar, etc.) and ensure sufficient reserve capacity is available to balance out such uncertainty with high probability.

Capacity expansion planning: DSTPs need to be able to explore the decision space of possible investments—new transmission lines, both AC and DC, storage, green generation, etc., to make recommendations on capital investments. These recommendations need to account for the features noted above.

Analysis studies: The Intermountain West could benefit from several analytical products to develop higher understandings of the needs and requirements of the region, including, but not limited to:

Transmission expansion: Grid oversubscription is becoming a problem in high-density population areas. Further studies are needed to examine line upgrades, pathway expansions, and detailed cost analysis for both. Ongoing efforts, such as those outlined in the DOE National Transmission Planning Study, should be leveraged and augmented to address the specificity of the Intermountain West.

Distribution upgrades: Rooftop solar and residential EV chargers are oversubscribing distribution feeders. Further studies are needed for considering distribution upgrades, their impact on the bulk transmission system, and detailed cost analysis.

Detailed cost analysis of each technology pathway: Economics will drive adoption of technology pathways as industry looks for the least expensive options. A detailed cost analysis will also provide governments with options for subsidies on preferred technologies.

Equipment lifetime analysis: A lifetime analysis of each technology pathway should be included in the detailed cost analysis to determine the total cost over the life of the equipment. An expensive technology that lasts 40 years may be preferred over a cheap technology that lasts only 10 years.

Deployment timelines: Carbon neutral by 2050 requires adoption of technologies with the shortest deployment timelines, so studies are needed to identify technologies that are available now or are likely to be available in the near future.

Private/industry/academic/government/tribal collaborations: Efforts and engagement are needed to include all stakeholders in technology pathway decisions.

Operational tools: Complimentary to DSPTs, are tools and capabilities to help support operations of the Intermountain West's future electricity system. Such tools should leverage existing capabilities, repurpose existing tools, and develop new features that are required for the specifics of the region's goals and aims. Such features include:

Control under uncertainty: Operational tools need techniques to handle uncertainty and variability in renewable energy production that goes beyond fast-ramping generation sources, such as those provided by natural gas units.

Definitions: As variability increases in the Intermountain West, new definitions of reliability and resilience need to be developed and deployed that go beyond today's definitions that guide operational decisions.

Demand response: Technologies in demand response need to continue to be developed, in particular to leverage and account for the expected coming wave in electrified transportation deployment.

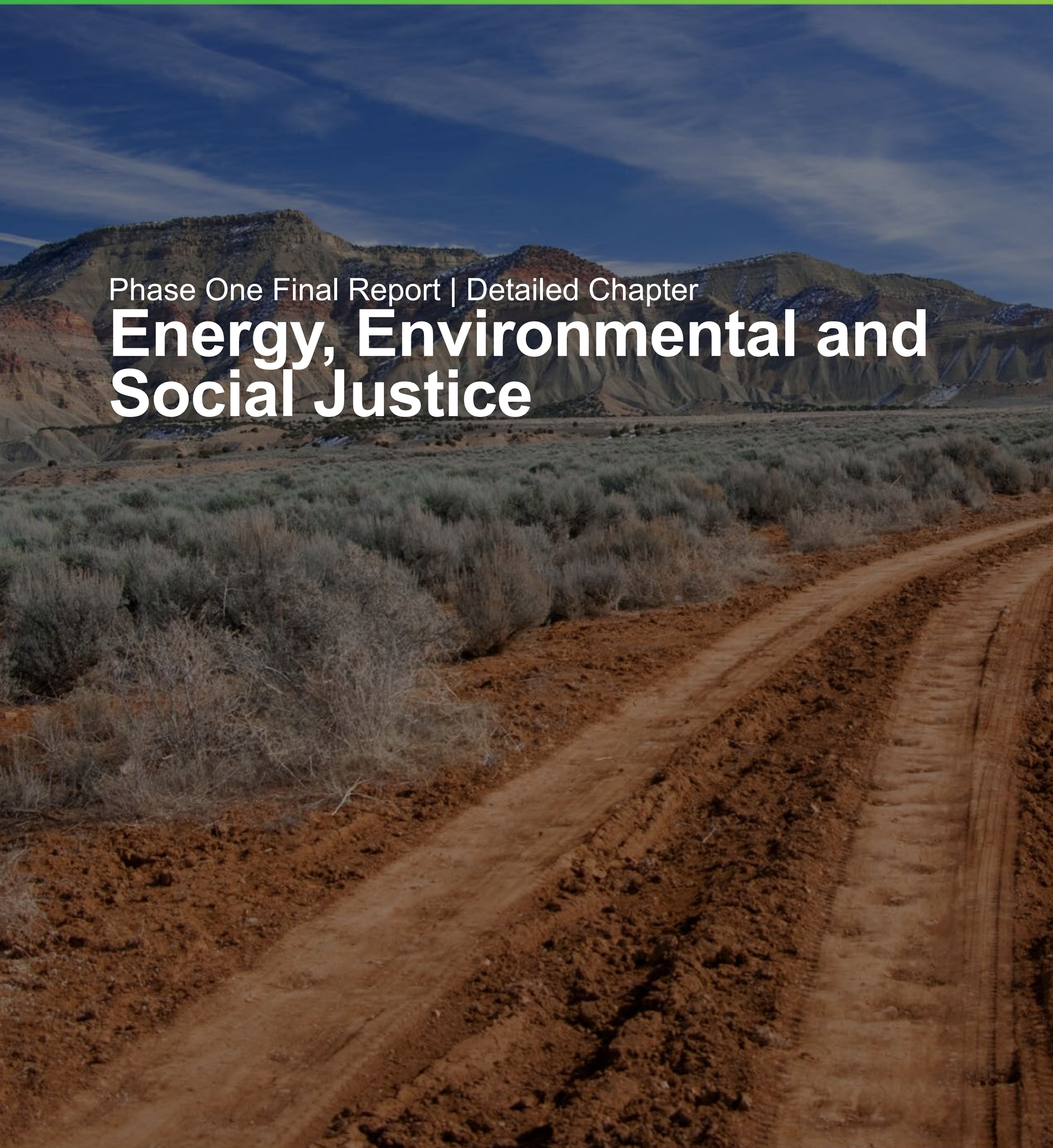
Materials: One of the barriers to decarbonization is the cost of technologies that support green energy systems relative to conventional alternatives. Examples include:

Utility-scale storage: New materials and manufacturing are needed to bring the cost of utility-scale storage down to the point where it is cost effective option for electricity utilities.

Solar: While the cost of solar panels continues to drop, such efforts should continue in order to encourage further deployment of solar.

Phase One Final Report | Detailed Chapter

Energy, Environmental and Social Justice



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About this chapter

The Intermountain West Energy Sustainability & Transitions (I-WEST) initiative is funded by the U.S. Department of Energy to develop a regional technology roadmap to transition six U.S. states to a carbon-neutral energy economy. I-WEST encompasses Arizona, Colorado, Montana, New Mexico, Utah, and Wyoming. Each state is represented in this initiative by a local college, university, or national laboratory. Additional partners from beyond the region were selected for their expertise in applicable fields. In the first phase of I-WEST, the team built the foundation for a regional roadmap that models various energy transition scenarios, including the intersections between technologies, climate, energy policy, economics, and energy, environmental, and social justice. This chapter presents work led by an I-WEST partner on one or more of these focus areas. A summary of the entire I-WEST phase one effort is published online at www.iwest.org.

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Table of Contents

Key takeaways

- Environmental justice is evolving. Early emphasis focused primarily on the distribution of harms and later benefits. Now, procedural justice—meaningful engagement and collaborative decision-making—and addressing past harms—have become equally important.
- Energy justice is gaining currency, applying justice principles to energy policy, energy consumption, energy security, energy production and systems at different scales, and energy activism (Jenkins et al, 2015). This review uses the term “energy, environmental and social justice” (EESJ) to reflect these interrelated and dynamic concepts.
- Each technology will have local impacts as projects are implemented. Therefore, each project could cause local adverse effects that must be addressed, despite overall benefits.
- The region has 63 sovereign native nations, with differing priorities and perspectives. Policy makers and project developers need to build lasting collaborations for action that advance the goals of all affected nations.
- Given the diversity of communities and perspectives, and the range of projects, no single approach will advance justice. Each project must instead develop a strategy appropriate to the project, technology, and impacted peoples and communities.
- Environmentally just processes are practices that must be adopted and evaluated for all policies and projects and evaluated to determine whether distributive outcomes further environmental justice goals.

Introduction

The transition to carbon neutrality will touch all communities. At the same time, the numerous technologies, implementation pathways, initiatives, and regulations will impact peoples and communities differently. The transition will have positive impacts by reducing carbon emissions, closing some polluting facilities and mines, and creating jobs in the new energy economy. Some communities also will experience localized negative effects when facilities and mines close without equivalent or better jobs available, and new technologies may negatively impact fence line communities, or those that abut or are in near proximity to them. New facilities might compete for water, emit pollutants, or visually disrupt valued landscapes. A given change may cause intersecting improvements and negative new circumstances, and job needs may not parallel a community's goals for health and environmental conditions. For instance, a closed coal mine or generating station can reduce environmental burdens on the local communities while also causing economic precarity. Without ongoing monitoring and investment, coal ash ponds or abandoned mines can have ongoing harmful and costly environmental and health effects. According to the Department of the Interior (Mueller & Brooks, 2020), the Bipartisan Infrastructure Deal, for example, allocated $11.3 billion for clean-up efforts, which can lead to new jobs in impacted communities.

The purpose of this chapter is to explore the potential for advancing energy, environmental, and social justice (EESJ) in the Intermountain West energy transition. This includes increasing and fairly distributing benefits and addressing adverse environmental impacts as well as facilitating engagement processes and partnerships that advance EESJ. The Biden Administration's Justice40 Initiative directs federal agencies to ensure that disadvantaged communities receive at least 40% of overall benefits from federal climate and clean energy investments. Justice40 takes a wide-ranging approach, recognizing the potential benefits and harms to communities by discontinuing fossil-fuel energy and establishing new energy production.

Justice40 furthers almost two decades of federal environmental justice action following the 1994 Presidential Executive Order 12898, Federal Actions to Address Environmental Justice in Minority Populations and Low-Income Populations. Indigenous peoples, communities of color, and low-income communities are at risk of disproportionate environmental burdens. The Environmental Protection Agency (EPA) defines environmental justice as the "fair treatment and meaningful involvement of all people regardless of race, color, national origin, or income, with respect to the development, implementation, and enforcement of environmental laws, regulations, and policies"

(EPA, 2022; Schlosberg, 2009; DOE Office of Legacy Management, 2022).[1]. What constitutes fair treatment and meaningful involvement varies across contexts. Early environmental justice frameworks focused primarily on fair treatment and addressing the inequitable distribution of environmental "bads," also known as distributive justice.

Environmental justice initiatives within the EPA, DOE, and nongovernmental organizations recognize that distributive justice is only one dimension of justice in an energy transition. Over the last several decades, additional environmental justice frameworks have emerged. Procedural justice denotes the meaningful involvement of all affected parties in decision-making, and recognition justice ensures that community values, interests, and histories of injustice are taken into account in decision-making processes (Schlosberg, 2009; Bell & Cayne, 2017; Whyte, 2011). Likewise, in recent years environmental justice as a concept has become more capacious, moving beyond documenting inequity to understanding underlying reasons for injustice. Within present understandings of environmental justice, ecological concerns intersect with racial justice, indigenous rights, food security, immigrant rights, energy access, and climate justice (Schlosberg, 2013).

This chapter takes a multidimensional approach to justice as necessary for diverse communities and stakeholders to accept promising technology pathways, and for the transition to reflect diverse goals and values. The benefits and harms must be fairly distributed, diverse stakeholders must be active participants in decision-making processes, and policy and projects must recognize and account for how historical actions shaped contemporary opportunities. This approach recognizes the need for **distributive justice** to attend to how the benefits and harms will be distributed, while elevating the important call within the environmental justice movement to reduce environmental harm overall. At the same time, **procedural justice** for a collaborative, participatory transition is equally important albeit more complex. People have a right to shape projects and processes that will impact them, and different values, cultures and lifeways must be respected and reflected in broader visions and specific projects. Finally, we discuss **restorative justice** and the need for climate action to lead to better outcomes for communities that now live with the inequities caused by previous policy and program implementation, and legal and regulatory structures. The six-state

[1] Fair treatment signifies that no population bears an unequal share of the negative environmental consequences from a private operation or from the execution of a public action (DOE Office of Legacy Management, 2022). Meaningful involvement requires all members of a community to have active, equal access to decision makers and the ability to make informed decisions to produce positive results for their communities (DOE Office of Legacy Management, 2022).

Intermountain West also encompasses 63 sovereign nations. Policy developers and project leads will need to build relationships with the nations or peoples that may be impacted in order to develop policy and projects for a shared energy future.

Current EESJ energy transition research trajectories

Assessing whether policy supports justice is neither nontrivial nor straightforward. All policy pathways generate trade-offs and unforeseen outcomes, yielding and in some cases further perpetuating structures of inequality (Carley & Konisky, 2020). Determining what constitutes justice in each community requires identifying how different community members might be impacted by a particular policy pathway and a given project. This requires identifying existing inequities, the availability of existing or need for future social insurance or relief programs, and the present and future priorities and needs of communities (Bates, et al, 2021; Pellow, Weinberg, & Schnaiberg, 2001; Carley & Konisky, 2020). Direct connections and communication with community stakeholder groups and other local organizations can provide some insight (I-WEST, 2022; Carley & Konisky, 2020). Ensuring meaningful participation is especially important considering a growing body of literature demonstrating that traditional avenues for relief for environmental injustice, such as judicial action, have not been successful beyond halting or preventing the expansion of projects that threaten quality of life for marginalized persons (Pulido, Kohl, and Cotton, 2016). In the literature, the impacts of environmental justice are often presented in terms of trade-offs related to the environmental risks (e.g., ecosystem degradation) and rewards (e.g., cleaner air) and the gains or losses of economic opportunities (e.g., job growth, revenue generation) (Bowen, 2002; Carley & Konisky, 2020). Additionally, sociocultural considerations have become increasingly central to questions of environmental justice (Sze, 2020).

Because the Intermountain West is lush with both fossil-fuel and commercial-scale renewable resources and is home to many rural communities and tribal nations, it presents a unique opportunity to identify how competing policy pathways to carbon neutrality influence environmental justice. Achieving a low-carbon future in the region is likely to involve a transition away from a fossil-fuel based economy to one powered by low-carbon alternatives, including renewable resources (e.g., wind, solar, biomass, geothermal) and advanced fossil-industries equipped with carbon capture, utilization, and storage [CCUS] technologies (I-WEST, 2022; Carley & Konisky, 2020).

Low-carbon alternatives are often framed as more just and equitable than their carbon-intensive counterparts (O'Sullivan, Golubchikov, & Mehmood, 2020; Lacey-Barnacle, Robinson, & Foulds, 2020; Crow & Li, 2020; Hernández, 2015). However, the reality is more complex. “Embodied energy injustices" can arise at various points along supply chains—from extraction and processing to transport and disposal (Healy, Stephens, & Malin 2016). Likewise, the pace of transitions has historically varied. While long, protracted energy transitions have been the norm, exceptions suggest that certain catalysts, such as social movements, political prioritization, and conflict, can accelerate transition (Sovacool, 2016). The pace of transition can become a justice issue, especially if there is little time to plan for a managed transition that adequately addresses current and future community needs. While recent reports such as the Intergovernmental Panel on Climate Change’s Working Group III Report urge a rapid shift to a low-carbon energy economy, rapid transitions can have direct consequences on the economic vitality of marginalized communities (Bumpus & Liverman, 2008; Sovacool, Martiskainen, Hook, & Baker, 2019; Sovacool, 2021). More specifically, rapid transition can negatively impact communities that have long relied on traditional, fossil-fuel based industries to support economic, cultural, social, and physical development within the community over many generations (Della Bosca & Gillespie, 2018; I-WEST, 2022; Mayer, 2018; Abraham, 2017).

When nonrenewable industries such as coal mining, uranium mining, and oil and gas production cease operations, communities surrounding these industries can be left with fewer good paying jobs (Interagency Working Group, 2021). Avoiding worker displacement and sustaining secure jobs, both during and following the energy transition, are primary concerns of public policy and other decision makers in the region (I-WEST, 2022). One way to support these communities would be to make them hubs for the construction and maintenance of renewable energy equipment; invest in critical infrastructure development (e.g., extending broadband connections, water system infrastructure upgrades, and roadway improvements); or sponsor CCUS retrofits of existing fossil-based industries (Interagency Working Group, 2021).

Green-job promotion is often considered to be a key ingredient to a “just transition” away from fossil-based industries, specifically coal mining (Abraham, 2017). While coal mining in the Intermountain West has historically provided well-paying, blue-collar jobs (Rolston 2014), there are associated health risks. Being employed in an underground coal mine has been shown to increase the likelihood of contracting pneumoconiosis (i.e., black lung disease) (Lu, Dasgupta, Cameron, Fritschi, & Baade, 2021; Potera, 2019) and localized exposure to surface mining activities has been shown to lead to higher rates of morbidity and mortality (Mueller, 2022). Prolonged exposure to surface mining–the dominant form of mining in the West–has been linked to an increased risk of being hospitalized for asthma or asthma-related health issues (Fitzpatrick, 2018). Other potential community health effects include an increased risk of contracting lung and other types of cancer (Buchanich, Balmert, Youk, Woolley, & Tallbott, 2014; Hendryx, O'Donnell, & Horn, 2008; Christian, Huang, & Rinehart, 2011) and a higher likelihood of having respiratory, cardiovascular, or kidney disease (Hendryx & Ahern, 2009; Esch & Hendryx, 2011). Truly "green" jobs to replace those lost would pay well while minimizing health and safety risks.

Strong sociocultural attachments to mining make transitioning away from coal challenging (Della Bosca & Gillespie, 2018; Sanz-Hernandez, 2020). Regional pride in the cultural heritage of fossil-fuel labor exists alongside, and sometimes in tension with, an affinity for public lands, outdoor recreation, and place-based identity, making discussions about energy transition complex and multilayered (Cha, 2019; Western & Gerace, 2020). Strong politicization of energy transitions has led to many discussions (Smith 2019; Lockwood, 2017). While the cost of implementing just transition policies for fossil-dependent workers has been estimated as a modest $600 million, with combination policies tailored to specific communities preferred over single-shot solutions (Pollin & Callaci, 2018), cultural attitudes toward transition can lead to lack of preparedness by community members to receive federal aid to support transition initiatives (Bleizeffer, August 4, 2021).

Justice issues vary by energy source, including renewables. Wind energy projects have been shown to generate instances of environmental injustice for younger, less-educated populations in rural areas (Mueller & Brooks, 2020). Similar to coal mining, social norms, attitudes, and behaviors of community members shape the justice perceptions of wind energy development (Aitken, 2010; Karakislak, Hildebrand, & Schweizer-Ries, 2021). While a wind is a low-carbon alternative, local externalities (e.g., noise, aesthetics) do exist for variable and other renewable energy resources (Devine-Wright, 2014; Ellis, Barry, & Robinson, 2007; Devine-Wright, 2007). In some places, wind turbines have implications for viewshed–an area visible from a specific location–which can impact property values and outdoor recreation and tourism, particularly in regions that expect recreation and tourism revenue to offset dwindling revenue from fossil fuels (Groothuis, Groothuis, & Whitehead, 2008). Furthermore, large-scale wind and solar projects are land-intensive and can damage local ecosystems and livelihoods. In Mexico, for example, large wind and solar projects risk perpetuating injustices experienced by indigenous communities. Concepts like consent and participation are often paid lip-service in pursuit of social license to operate (Baker, 2018; Barragan-Contreras, 2021; Ramirez and Böhm, 2021).

In addition, injustices also pervade renewable-energy supply chains (Healy, Stevens, and Malin, 2019; Heffron, 2020). Critical minerals and rare-earth elements necessary for renewable energy technology are predominantly imported to the United States from Asia, Latin America, Africa, and elsewhere. Yet, there have been allegations of human rights abuses and forced labor in global supply chains, as well as the inequitable distribution of mineral wealth (Heffron 2020; Murphy and Elimä, 2021; Owen et al, 2022). Despite recent efforts to onshore production (including in the Intermountain West) to reduce foreign dependence and circumvent supply chain issues, regulatory weaknesses and uncertainty over net benefit to local communities in terms of job creation and taxation exist (Riofrancos, 2022).

Nuclear energy, long a hallmark of the Intermountain West region, also raises concerns about justice. The 2022 Russian invasion of Ukraine has thrown into sharp view the United States' dependence on Russian uranium, with implications for emergent nuclear facilities such as Terrapower's Natrium reactor demonstration project, anticipated to be completed in Kemmerer, Wyoming, in 2028. While the Kemmerer project has been applauded for creating jobs in a rural community that had lost its coal mining industry, researchers at Stanford caution that small modular reactors will produce significant amounts of highly radioactive nuclear waste that will need to be stored and packaged (Schwartz, 2022). The legacies of nuclear energy and domestic uranium mining in the United States are also well known. For example, in impoverished rural communities on the Colorado Plateau, issues of isolation and resource dependence clash with questions on environmentally safe uranium extraction and waste-disposal practices (Malin, 2015). In the southwestern United States, the impacts of uranium mining and hazardous waste disposal, including radiation-related illness, have been most acutely felt in indigenous communities that were not involved or properly consulted by government and industry officials (Brugge et al, 2006; Kuletz, 1998).

Emergent carbon dioxide removal (CDR) technologies, such as CCUS, also present unique justice issues. During CCUS development and deployment processes, for example, claims of procedural injustice may arise from locally affected populations over lack of inclusion in planning of deployment processes or lack of transparency and availability of information. Issues like siting; transshipment and storage of captured carbon dioxide; impacts on air quality, and human and ecosystem health; and job creation are all potential sites of conflict and disenfranchisement at the community level (McLaren, 2009; Batres, Wang, Buck, et al., 2021). More broadly, varying local impacts of CDR projects, including impacts on environments and community well-being, are not yet well understood. Justice issues may also arise if technologies like CCS are used to avoid or altogether delay emission reductions and the transition to a low-carbon energy economy (Healy, Scholes, Lefale, & Yanda, 2021).

This body of research acknowledges that environmental inequities exist and suggests that inequities and their roots be strongly considered during policy design and implementation processes. This report also recognizes that many transitions are happening at once and at different paces, with different impacts on local communities and ecosystems. Facilitating a just and equitable transition demands consideration of uniquely local factors, including the distribution of environmental “goods” and “bads”; the meaningful participation of affected communities during all phases of policy design and implementation; and the recognition of cultural values.

A multiplicity of energy transitions

Energy transitions are underway throughout the Intermountain West. Each community is situated differently and will face varying economic and energy opportunities. The following energy snapshots show just a few of the complex situations evolving throughout the region. Each situation raises critical questions about environmental and social justice. These are not intended to be comprehensive. Instead, they show numerous opportunities, conflicts, and differing perspectives that help illustrate the intersecting ways that communities will be impacted and respond to energy transition. Regional communities have multifaceted relationships to energy. Uranium and coal mining, and oil and gas production have provided good jobs and opportunities, but also contributed to health problems, air pollution, contaminated soil, and volatile local economies. These and many other living legacies shape community responses.

The Intermountain West has a rich and varied history of energy production. From the hydro power that fueled 19th century and early 20th century Utah, to the uranium reserves in the Navajo Nation, all six Intermountain West states and tribal nations have diverse energy economies as well as consumption profiles. In Wyoming, commercial coal mining began in the mid-1860s when the Union Pacific Railroad arrived, and since that time over 12.5 billion short tons of coal have been mined; the Powder River Basin has been the largest supplier of coal to the U.S. market since the mid-1990s. Wyoming also has major oil and gas, uranium, and other mineral production operations – alongside a growing wind energy industry – creating financial booms as well as busts. Colorado has rich fossil fuel resources and abundant renewable energy sources including wind, solar, hydroelectric, and geothermal. Colorado coal production began in 1864, but has decreased in the last decade. Colorado ranks 8th among the U.S. for proven oil reserves, and 29 of the state's counties produce oil (Colorado Geological Survey). Coupled with the rapid growth of suburbs, just under half a million people lived within one mile of an active well in 2018 (Haggerty et al., 2018). Arizona is home to 11 hydroelectric dams as well as uranium mines that are suspected of potential contamination of the Colorado River (Arizona Geological Survey). Utah has natural gas and coal, and New Mexico has significant oil and gas reserves. All southwestern states have opportunities for solar and wind expansion.

Tribes have different energy geographies in the Intermountain West, and varied ways to participate in the new energy economy. The Southern Ute Tribe in Colorado is a major oil and gas producer, and by 2022 was exploring a zero-emission natural gas power plant. The Crow Nation in Montana has a long history of coal production, whereas the Northern Cheyenne, near neighbor to the Crow Nation, have not mined coal on their lands. Half the uranium within the United States is located in Indian Country (Regan, 2014). The Navajo Nation has coal, uranium and oil and gas. The Kayenta Coal Mine closed (see below), and the Black Mesa mine production may cease or be greatly reduced.

Spotlight on Coal Transitions in the Navajo Nation

The Navajo Generating Station, which operated along the Arizona-Utah border for more than forty years, was the biggest coal plant in the Intermountain West. It closed in November 2019, months after the Kayenta mine that fed it closed. According to owners and operators, low natural gas prices, along with increasing access to renewables (e.g., solar and wind), made the coal plant uncompetitive, and the Salt River Project (majority owners and operators of the Navajo Generating Station) reported that low natural gas prices were a driving factor. Additionally, the Navajo Generating Station was the Kayenta mine's sole customer. While the plant's closing is a step toward carbon neutrality, the local impacts are substantial. The generating station employed over 800 indigenous people—over 90% of its workforce were Diné—and it paid higher than average wages. At the Kayenta mine, the average salary was $117,000. At the same time both the plant and mine were responsible for decades of adverse environmental impacts (Arvin, 2020), emitting high rates of greenhouse gases, and polluting water and soil used by Navajo ranchers. Indigenous-led grassroots organizations guided activism to close the plant and mine and are now closely watching the restoration. The organization Tó Nizhóní Ání was established in 2001 to protect Black Mesa's water source from industrial use and waste including Peabody Energy's Kayenta and Black Mesa mines. Diné C.A.R.E. has also been advocating to retire coal plants and mines and demanding sustainable development practices.

The history of the Navajo Generating Station reflects unequal access to energy. Most of the power went to Phoenix as some Navajo and Hopi households near the generating station went without electricity (Arvin, 2020). The Navajo Generating Station highlights that any given project has people who may benefit and those who may be harmed. Sometimes the people who benefit are also the ones who are harmed. People may benefit in one way, such as from a cleaner environment, while simultaneously experiencing job losses. Environmental justice analyses are needed to account for multiple and, at times, conflicting effects. Nicole Horseherder, a founding member of Tó Nizhóní Ání, has highlighted the many dimensions of a just and equitable transition, including “clean-up and reclamation of mined land and water, new jobs at solar plants, electrification of Native communities, new water infrastructure to ensure reliable clean water and broadband internet access” (Horseherder, 2021).

Fossil fuel communities in transition

Economic dependence on fossil fuels

The coming energy transition will mean that some states and communities will gain new industries, jobs, and sources of tax revenue. Others, however, will lose the fossil industries they currently depend on for revenue. The high degree of fiscal dependence that some states and communities have on revenue from fossil energy makes the people living there particularly vulnerable to the current energy transition and raises environmental justice concerns. Fossil fuels formed the economic and cultural foundation for many Intermountain West communities. The 2021 Executive Order 14008, Tackling the Climate Crisis at Home and Abroad, identifies these areas as priorities for transition investments. The Interagency Working Group on Coal and Power Plant Communities and Economic Revitalization identified 25 of the most impacted coal regions for priority investment.

The top 25 coal-dependent areas, based on the number of direct coal-related jobs as a percentage of total jobs, include the following Intermountain West communities:

- Eastern Wyoming's Powder River Basin (ranked 8)
- Western Wyoming (ranked 9), Arizona non-metropolitan area (ranked 10)
- Central Utah non-metropolitan area (ranked 13)
- Farmington, New Mexico (ranked 16)
- Greeley, Colorado (ranked 19) and
- Grand Junction, Colorado (ranked 22)

The Interagency Working Group identified up to $37.9 billion in existing programs that could be accessed by energy communities for improvements ranging from infrastructure investment and broadband access for future economic development to environmental remediation (Interagency Working Group, 2021).

In fossil fuel states, tribal nations, counties, and municipalities, fossil-based energy continues to produce significant revenue for essential community functions such as schools, governments, and other social services. A 2022 study by Resources for the Future estimates that, between 2015 to 2020, coal, oil, and natural gas generated $138 billion annually for localities, states, tribes, and the federal government. The proportion of state and local revenue that comes directly from development of these fossil resources varies widely, but for some states in the region it is quite high, making them highly dependent on fossil-based revenue. For example, in Wyoming 59% of state and local revenue comes from fossil fuels, a total of $4,264 million annually, averaging over $7,000 per resident. Other Intermountain West states also get a significant percentage of their revenue from fossil fuels: in New Mexico, 15% of state and local revenue is from fossil fuels, in Montana 7.9%, and in Colorado 4.1% (Raimi et al, 2022). The loss of this revenue would be substantial for these states; the outcomes will have more drastic effects on the fossil-fuel producing communities within the states.

Fossil fuels generate revenue for local and state governments through severance taxes, production taxes, property taxes, petroleum-production taxes, sales taxes, and income taxes. Not all of these taxes are applied to all types of fossil fuels, and some of them generate revenue at some levels of government and not others. See the table below for a list of each type of tax, the fossil energy type it is applied to, and what level of government receives the revenue.

Revenue source	Coal	Oil	Gas	Primary recipient(s)
Severance taxes	X	X	X	States, some tribes
Production on public lands	X	X	X	Federal, tribes, states
Property taxes				Local, some tribes
Production property	X	X	X	
Pipelines		X	X	
Refineries		X		
Power plants	X		X	
Petroleum product taxes		X		States, federal, some tribes
Sales taxes	X	X	X	Local, states, some tribes
Income taxes (corporate and personal)	X	X	X	States, federal

Table 1. Major coal, oil, and gas revenue sources (from Raimi et al., 2022).

While national fossil fuel production increased recently due to global shocks in energy markets (EIA n.d.), overall fossil fuel production has been declining in states in the Intermountain West region. For example, Wyoming coal production has been steadily declining since reaching a peak of over 450 million short tons in 2008. In 2021, just 218 million short tons were produced (Wyoming Geological Survey, n.d.). Natural gas production in Wyoming has been declining since 2009 when over 2.5 billion MCFs were produced, down to less than 1.4 billion MCFs in 2021 (Wyoming Oil and Gas Conservation Commission, n.d.). Oil production has been more volatile in recent years, reaching a low of 51 million barrels in 2009, but increasing to 85 million barrels in 2021 (Wyoming Oil and Gas Conservation Commission, n.d.).

These recent shocks in energy markets, including the global COVID-19 pandemic and the current surge in oil prices, which have caused extreme volatility in fossil fuel production, make it difficult to predict future state and local revenues from these industries. Indeed, some states are experiencing higher than predicted tax revenue. So far for fiscal year 2022, severance taxes collected in Wyoming are almost 13% higher than predicted and federal mineral royalties are 13.5% higher (Wyoming Consensus Revenue Estimating Group, 2022). In 2021, the New Mexico Tax Research Institute reported that the oil and gas industry generated a record $5.3 billion for state and local governments, with $2.96 billion going into the general fund in FY21 (The New Mexico Tax Institute, 2021).

However, in the long term, revenue from fossil fuels is still predicted to decline. A recent study evaluated the impact that restrictions on federal oil and gas leases will have on eight Western states—Wyoming, New Mexico, Colorado, Utah, Montana, North Dakota, California, and Alaska. The findings estimate that a leasing moratorium would decrease state and local tax revenue in these states by $1.6 billion per year for the first five years, and a full drilling ban would decrease state and local tax revenue by $2 billion (Considine, 2020). Considering the impact that restrictions just on oil and gas drilling on federal lands are predicted to have, additional reductions in fossil energy production as a result of new technologies coming online could deeply affect the fiscal health of states, counties, and municipalities in the West. Resources for the Future also estimated declines in fossil-fuel revenue under three scenarios based on different paths to reducing emissions. In each scenario, fossil fuel revenues declined significantly by 2050—between $22 billion to $111 billion (about $340 per person in the U.S.) (Raimi et al, 2022).

Justice considerations

Below is a summary of several of the challenges that may cause a few communities to bear most of the costs of the energy transition while realizing few of the benefits.

New energy industries may be located in different places

Several lower-carbon energy industries are poised to replace conventional fossil industries, including wind, solar, hydrogen, rare earth element and critical mineral extraction and production, bioenergy, and nuclear. These new industries will provide new jobs and new sources of tax revenue for states and communities. Indeed, studies suggest that these new energy industries may eventually create even more jobs and grow to be larger than fossil energy industries. However, these industries will not always be located in the same places as fossil industries were (Carley and Konisky, 2020). For example, wind farms will be sited where the wind resources are located, which may not be where coal mines or fossil power plants were located. The communities where the new lower-carbon energy industries move in will benefit from new jobs and tax revenue sources, while the communities where fossil energy industries were located will lose jobs and tax revenue with nothing to replace it.

Communities bear the costs for experimental industries

Another environmental justice challenge associated with transitioning to new energy industries is the cost that is often borne by the public for investing in experimental industries. For example, in Wyoming many companies have tried to develop industries for alternative uses of coal (e.g., coal drying, coal to liquids, coal gasification, and coal to activated carbon). These projects are often private-public partnerships with different levels of governments investing in them as potential new industries that will continue using fossil resources and bringing in tax revenue. Over the last 30 years, much public money—federal, state, and local—has been invested in these projects and only one has achieved any commercial success. This means that public money that has been invested has not benefited the state of Wyoming or the people of Wyoming, but rather cost them. These investments have continued Wyoming's dependence on fossil resources instead of investing in economic diversification (Powder River Basin Resource Council, 2020).

Lack of access to energy transition opportunities

For communities transitioning away from fossil resources, federal assistance and grant money are needed to assist in economic diversification and opportunities (Roemer & Haggerty, 2020). And while there is much federal grant money currently available for communities in transition, the ability of communities to be successful at being awarded this money depends on them having the resources to apply. States or communities would benefit from experienced personnel with the time and expertise in successful grant writing or resources to hire such personnel. However, communities that are already underfunded and understaffed often do not have sufficient resources to pursue and win federal grants. It will be more difficult for these communities to secure resources for economic diversification and new energy opportunities.

Opportunities

While the transition to lower-carbon energy industries poses many challenges to states and communities that are currently dependent on revenue from fossil resources, it also offers opportunities. Ensuring social and environmental justice for people likely to bear the burden of the energy transition will require long-term planning and investment to increase community resilience. The literature suggests many options that would decrease the financial dependence of states and communities on fossil revenue. Some of these include modifying fiscal policy to incentivize renewables and conservation (Headwaters Economics, 2020); investing in economic development that diversifies regional revenue streams including land management opportunities, and recommissioning/restoration opportunities (Powder River Basin Resource Council, 2020; Haggerty, Walsh and Pohl, 2021; Haggerty et al, 2018; Haggert, Walsh and Pohl, 2021); and adopting policies that coordinate the energy transition, including providing certainty around closure dates, and time and resources for community planning (Roemer & Haggerty, 2020). These may enhance "community resilience," or the capacity of a community to mobilize its resources and work together when faced with a shock (Roemer & Hagggerty, 2020).

Access to affordable electricity

Ensuring access to reliable and affordable energy is a primary social justice consideration in the energy transition. A primary goal is to supply every household with affordable, reliable electricity. Low-income households face higher energy burdens—the percentage of income spent on energy—than high income households, or the percentage of income spent on energy. Low-income households spend on average 8.6% of their income on energy nationally, an energy burden three times higher than other households. For some households, that amount is as high as 30% of their income. If electricity becomes more expensive, low-income households may increasingly restrict their energy use or reduce spending on other essentials. Key metrics for assessing pathway impacts for residential consumers include energy savings, energy costs savings, changes in household energy burdens, changes in a household-human development index, and impacts to energy insecurity, energy poverty, and energy vulnerability (Preziuso, Tarekegne, & Pennell, 2021). These types of measures require data on energy use and expenditure data, disposable household income, and program data, such as implementation costs and enrollment. In 2019, the Department of Energy (DOE) and National Renewable Energy Laboratory (NREL) launched the Low-income Energy Affordability Data (LEAD) Tool (epa.gov/environmentaljustice/plan-ej-2014) to assist users to address energy burden and develop plans to reduce household energy costs.

In addition to affordable energy, supplying all households with electricity continues to be a challenge. The World Bank Group (2022) reports that 100% of the U.S. population has access to electricity. However, this oversimplifies the situation. In 2019, as many as 30% of homes in the Navajo Nation, or 15,000 houses, did not have electricity (Tanana & Bowman, 2021). The LEAD tool also shows extensive disparities with the energy burden in Indian Country. The average energy burden in New Mexico is 3% of annual income. In Zuni Pueblo, it is 6% and in the Jicarilla Apache Nation, it is 8%. Colorado's average energy burden is 2% but both the Southern Ute and the Ute Mountain nations spend on average 4% of their income on energy. In addition, unreliable infrastructure may be at increased risk from weather related damage. Many residents of Puerto Rico do not have reliable electricity after hurricane damage in 2017 and 2022; the loss of electricity also means that many households lack clean water (Romo, 2022).

Another consideration is the effects of programs that incentivize household energy production. Rooftop solar incentives come in the form of state and federal tax credits. This requires a household to cover the upfront costs of installing the system, and it is less likely that landlords will install a system when the electricity costs are borne by the tenants. Over time, as the systems pay for themselves, rooftop systems reduce household electricity costs.

Spotlight on rooftop and community solar

Renewables, particularly solar, will be implemented at multiple scales. Rooftop solar has the advantage of producing energy while reducing additional land use impacts and will not result in unwanted solar farms in outlying areas. In hot areas with bright sun, rooftop solar can contribute significantly to supplying the daytime energy needs during months when demand for air conditioning is high. Rooftop solar has an advantage of using underutilized roofs in already developed areas, minimizing additional impacts. However, rooftop solar can impact the integrity of historic structures and districts if not thoughtfully designed and implemented. However, the cost reductions from net metering or selling the energy back to utilities could disproportionately benefit wealthier homeowners with large houses (and roof areas) and who can afford the upfront installation costs. Current incentive programs are most likely to be tax credits, which require upfront investment that low-income homeowners may not be able to afford. Owners of rental properties often require tenants to pay electric bills and offer no incentive to provide rooftop solar. Without alternative policy and programs, low-income households are unlikely to participate.

The Colorado Energy Office's Weatherization Assistance Program addresses energy consumption and energy burden at two scales through technical assistance available to all households to increase efficiency and reduce energy usage (Colorado Energy Office, n.d.). On a limited basis, it is installing rooftop solar for eligible low-income households as part of its weatherization assistance program. In addition, the Colorado Energy Office launched a community solar pilot project in 2015 to demonstrate the feasibility of developing 100% low-income community solar projects and to reduce the energy burden on participants. GRID Alternatives received the grant to implement the pilot and developed six community solar models, partnering with seven utilities, and low-income subscribers received credits from the utilities. These initiatives demonstrate the potential to reduce the energy cost burden while increasing community and household scale solar projects.

Community solar also has the potential to support energy sovereignty. In 2018, Picuris Pueblo, in New Mexico, partnered with Kit Carson Electric Cooperative to raise revenues for the tribe, meet 100% of the Tribe's daytime electrical needs, and all Picuris residents received a credit on their electricity bill. Picuris Pueblo is expanding its solar capacity, which will help Kit Carson meet its goal of solar for 100% of daytime needs of all its members (Peart, 2021).

Anticipated local land use and environment impacts in new energy economies

All energy systems and industries have local land use and environmental impacts. Anticipating and mitigating the potential negative impacts of particular projects in the new energy economy through long-term planning and impact assessments will help advance environmental and social justice. When benefits outweigh local burdens or potential harms are mitigated, local populations are more likely to accept new projects and technologies. It is also important for new benefits to reach diverse groups of residents, especially the people in communities that have been disadvantaged or harmed by past policy or programs.

Common local impacts that concern community members include but are not limited to the following:

- Job availability
- Public sector revenues
- New or intensified land uses and land disturbance for renewables, pipelines, facilities, or mines
- Damage to cultural sites or cultural resources
- Water availability
- Water, air, soil pollution
- Ecosystem or species impacts

Because the impacts are varied and community perspectives differ, engaging with each potentially impacted community will be necessary to advance procedural justice, including sharing information about possible impacts, and understanding and incorporating community perspectives into project design or future actions.

The new energy economy will introduce a host of new facilities including solar and wind farms, CCUS facilities, direct air capture (DAC) facilities, and new pipelines. All have the potential for short- or long-term impacts on the communities near or through which they pass. The fracking boom, for example, highlighted the need to also plan for housing, community facilities and transportation when communities will experience an influx of short-term or seasonal residents as well as potential adverse health impacts for nearby residents. Particular attention should be paid to communities relying on self-caught fish or wildlife, and subsistence agriculture. In arid and semi-arid regions, access to water and the implications that purchasing water rights may have on other uses must be considered. Concerns about water rights are compounded in the Intermountain West region because many indigenous nations have unresolved water claims (Sanchez, Edwards & Leondard, 2020).

The emerging energy landscape will also have benefits. A regional EESJ analysis is needed to evaluate where those benefits are located. All technology will bring direct and indirect employment opportunities from manufacturing the devices, operating the farms, and sequestering the CO_2 or turning the carbon into products. However, these may not be located in the same communities where jobs are lost, or local people's skills may misalign with the needs of new industries. Overall, new employment may make up for jobs lost in oil fields, power plants, and strip mines. Some jobs and revenue loss can be compensated for if facilities are converted to use in the new energy economy.

New energy technologies have the potential to create new local businesses and enhance existing ones. For example, greenhouses using CO_2 from DAC ought to be more productive. DAC at small scale could be owned by small entrepreneurs or communities. The DAC device/farm to feed CO_2 for agriculture or other products could be small and locally owned. This also might be an effective way for smaller investors to earn revenue for capture and utilization or sequestration. Likewise, there is an intersection between biofuel production and the agriculture and forestry sectors. Biochar is a byproduct of biomass pyrolysis and can be used to restore carbon to soils. Thinning of forests and forest residues will help reduce risks from wildfires.

The sections below explore some of the potential effects of specific new energy economy technologies. Attention to technology specific impacts underlies assessing distributive equity of both harms and benefits on local communities. It also aligns with procedural justice by providing solid information about potential impacts and community concerns, and engaging the public to understand perceptions, local values, and perspectives. Advancing restorative justice requires understanding community histories and which new investments will create better conditions.

Solar and wind environmental and social justice considerations

Both solar and wind will play a key role in helping to decarbonize U.S. energy systems. While their benefits for reducing greenhouse gas emissions are clear, justice considerations remain for the people and places that host such facilities. Both wind and solar energy provide jobs in manufacturing, construction, and installation, for example, but they create few ongoing local jobs.

Wind power is one of the fastest growing energy sources, typically generated at utility scale facilities located near agricultural land or residential communities. Perceptions of wind energy vary by community, with acceptance documented among rural residents who already have a productive view of nature (Phadke, 2013). Studies of wind farm development highlight a more general dilemma for renewable energy projects: a “social acceptance gap” between professed support of such projects in general, and an opposition toward specific projects (Bell et al., 2013). Large wind farms may have strong regional, local, or global, climate and weather impacts (Baidya, Pacala & Walko, 2004; Barrie & Kirk-Davidoff, 2010). Wind farms also change the visual landscape and can adversely impact endangered or culturally relevant species including birds, bats, and mammals.

Spotlight on wind energy in Montana

Montana has a diversified energy portfolio, with just over 40% of its energy generation coming from coal, 40% from hydroelectricity, 12% from wind, and the remainder from oil and gas. The National Renewable Energy Laboratory ranks Montana fifth in the nation for potential wind-energy generation. By the end of 2020, Montana was home to 16 utility-sized, operational wind-energy facilities with a combined capacity of over 1100 MW (Riek, 2021).

In 2022, construction began on what will become the state's largest facility, NextEra Energy's Clearwater Wind Project (Willardson, 2022). Located in the southeastern region of the state, the facility includes 131 turbines with a capacity of 750 MW – almost doubling the state's wind energy production. The project received praise for helping to decarbonize the national energy grid and provide economic benefits to local governments. Over the next 30 years of its operation, it is projected to generate $217 million in tax revenue and providing approximately $226 million to landowners. While there is evidence of strong support, some local residents criticized the company for exporting the energy outside of the state while asking locals to shoulder the environmental and social burdens of construction and production.

In 2022 construction began on another project that would be a first for Montana: a wind farm integrated with battery storage (Halstead-Acharya, 2022). The Beaver Creek Wind Farms project, located in the south-central region of the state, would add an additional 160 MW of energy production. Battery storage addresses the inconsistency of wind energy generation, as batteries can store excess energy when demand is low and release it when demand increases. The lithium-ion batteries, however, place further demands on the production of rare earth elements and take up additional land space, in this case, an additional three acres of agricultural land. While construction requires 175 workers for one year, only 15 to 20 permanent, on-site workers will remain. The project is criticized for creating economic winners and losers: while some ranchers will benefit from lease payments and/or royalties because the infrastructure is directly located on their land, neighboring ranchers will not, even though they will experience the negative environmental and social impacts. While the project is praised for reducing the area's historic economic dependence on mining, residents also wish that it would lower their own energy costs instead of being exported out of state.

Solar plants have similar local land use considerations and nearby residents respond to both the changes to the scenery/landscape, and environmental impacts. Utility-scale solar plants use large tracts of land that fragment wildlife habitat. Because the sites are cleared of vegetation, they can increase dust. Solar panel manufacturing and cooling can use significant amounts of water. Unlike wind, the land is not as easily shared with other uses such as agriculture, although it is possible to install solar on less productive agricultural land or use structures that support solar to shade light sensitive plants. Some adverse effects from large-scale solar installations can be reduced by using lands that are already impacted by prior industrial or mine use, although nearby residents may prefer regenerative proposals over industrial projects, especially if the impacts are not offset with new jobs.

Rooftop solar has potential as an alternative energy source without the additional land use disruption. In hot areas with bright sun, rooftop solar can contribute significantly to supplying the daytime energy needs during months when air conditioning demands are high. Rooftop solar has an advantage of using underutilized roofs in already developed areas, thereby minimizing additional impacts, although rooftop solar can impact the integrity of historic structures and districts if not designed and implemented sensitively. However, without programs designed otherwise, the cost reductions from net metering or selling the energy back to utilities will disproportionately benefit wealthier homeowners with large houses (and roof areas) and who can afford the upfront installation costs.

CORE-CM environmental and social justice considerations

The acronym CORE-CM denotes carbon ore, rare earth elements, and critical minerals, all of which are critical for manufacturing low-carbon energy technologies and achieving carbon neutrality. Carbon ore processing provides added value to coal by converting it into feedstock for high-value carbon products such as nanomaterials for computers and building materials.

Critical minerals and rare earth elements are particularly important for the development and deployment of electric vehicles and wind, solar, and nuclear energy. The need for these minerals requires mining in new locations and additional manufacturing. Materials are predominantly imported to the United States from Asia, Latin America, Africa, and elsewhere. Injustices exist upstream in the supply chain, including allegations of human rights abuses, forced labor at extraction sites, and the inequitable distribution of mineral wealth. A recent study suggests that the majority of these projects “are located either on or near Indigenous Peoples’ or Peasant lands with adverse conditions for human rights-compatible permitting, consultation, and consent” (Owen et al., 2022). Moreover, the urgency associated with energy transition raises a serious concern that projects will be “fast tracked,” or approved without proper assessment and consultation (Owen et al., 2022).

There have been recent efforts to onshore production (including in the Intermountain West states) to reduce foreign dependence and circumvent supply chain issues. The Department of Energy’s ongoing CORE-CM initiative for U.S. Basins, for example, is intended to explore the extent to which the materials extraction can promote local and regional economic growth and job creation. However, concerns exist over possible regulatory weaknesses and uncertainty over net benefit to local communities in terms of job creation and taxation. For example, workers in Nevada (https://news.stanford.edu/2022/05/30/small-modular-reactors-produce-high-levels-nuclear-waste/) are preparing the first new domestic lithium mine to be opened in decades, drawing protesters, including some from Native American tribes, because of concerns over water use, waste, and improper consultation (Penn & Lipton, 2021).

Spotlight on critical minerals production in Utah

Utah has long been a mining powerhouse. The state is home to the Bingham Canyon copper mine, which is visible from space and claimed to be the largest man-made excavation and deepest open-pit mine in the world. The state also produces beryllium, magnesium metal, high-value potash, and helium, and it has known reserves of indium, aluminum, and fluorspar. The growing market for critical minerals and rare earth elements has created a market for the byproducts of mining. The state already produces lithium byproduct material and byproducts of the Bingham Mine include platinum, palladium, and rhenium. There is also rare earth element byproduct material in the tailings (mine waste) from beryllium production at the Spor Mountain mine (Mills & Rupke, 2020).

The industry’s adaptive management of byproducts has raised significant social and environmental justice concerns. The White Mesa Mill is the only operating conventional uranium mill in the United States. Located in the Four Corners region of southeast Utah, just outside of the Bears Ears National Monument, it is only a few miles from the Ute Mountain Ute Tribal reservation. It is currently operated by Energy Fuels, a Denver-based company that previously operated multiple uranium mines and mills on Colorado’s western slope. The White Mesa Mill began producing mixed rare earth carbonate in 2021 and planned to process up to 15,000 tons of monazite per year. The mill is one of the largest economic drivers in the county, where almost a fifth of residents live at or below the federal poverty line.

While industry boosters praised the mill for creatively helping to meet growing demand for rare earth elements, tribal members and activists drew attention to the mill's questionable environmental management practices. The mill was originally built in the late 1970s to produce yellowcake from uranium ore. When the uranium industry collapsed in the early 1980s, it began charging fees to process waste from military and industrial sites around the country and the world, recovering trace amounts of uranium and discarding the remainder in its waste ponds. What the mill and the Nuclear Regulatory Commission consider to be "alternate feeds," critics view as radioactive waste. Tribal members, activists, and some state regulators argue that the waste ponds were not designed to manage these materials and that they pose a significant risk to water sources. Leaks have been documented in several of the ponds' plastic liners, and nitrate and chloroform plumes have been detected in the groundwater beneath the mill. Other radioactive and toxic pollutants emitted by the mill include radon, sulfur dioxide, and nitrogen oxide (Grand Canyon Trust, n.d.). As of 2022, the EPA prohibited the mill from accepting waste from Superfund sites. The company maintained that the pollution was not coming from their operations and was pursuing continued expansion.

Nuclear energy environmental and social justice considerations

Nuclear technologies have the advantage of producing significant amounts of carbon free energy. The technologies are well developed. The United States has 55 nuclear power plants with 93 nuclear reactors generating nearly 20% of U.S. electricity. Nuclear power plants are costly and slow to develop. Small modular reactors, however, can be manufactured in factories and placed on former coal generating plants—this new technology has the potential to maintain electricity production and distribution at existing facilities, which would help retain local jobs.

Despite these benefits, there are environmental costs associated with nuclear energy. Radioactive elements such as uranium are toxic to people and their environments. Increased nuclear energy will require increased uranium mining, and uranium tailings can contaminate soil and water, as has already occurred at sites around the globe. Nuclear waste must be managed for thousands of years. Power plants can be a source of low-level radiation that may impact workers and those living near the plants, especially children (Kyne & Bolin, 2016). Uranium mining and uranium tailings have contaminated communities in the Intermountain West, notably on the Navajo Nation (Voyles, 2015).

Unlike wind and solar, which have widespread support even though people may oppose specific facilities, nuclear energy has opponents that extend beyond those potentially impacted by a given facility or uranium mine. Both the scale and longevity of the adverse effects that followed the 1986 Chernobyl disaster and 2011 Fukushima disaster raised awareness of the dangers of nuclear energy and created skepticism about safety claims. In addition, nuclear energy production raises concerns about the potential for nuclear weapon proliferation.

To ensure safe nuclear power, “cradle to grave” or “cradle to cradle” management practices are needed. Researchers from Stanford and the University of British Columbia (https://news.stanford.edu/2022/05/30/small-modular-reactors-produce-high-levels-nuclear-waste/) found that small modular reactors may increase the volume of nuclear waste that would need to be disposed of and managed by factors of 2 to 30 when compared with nuclear power plants and will have increased neutron leakage.

Bioenergy environmental and social justice considerations

Biomass can be converted to liquid transportation fuels and can be used to generate electricity. When new facilities are built, they will have land use impacts for local communities. Refineries raise soil and water pollution concerns and have local water demands. In one case, protests emerged against a proposed bioethanol facility because residents feared health risks and dangers of explosions (Tittor & López, 2020). Converting existing fossil refineries or other fuel production facilities may lessen the local land-use impacts, but they may raise concerns for local communities who already live with the impacts from the former refineries.

Biofuel crop production is another area of concern. First-generation biofuels are produced from food crops such as corn and raise concerns about competition between energy production and food security, and water use. Crops also have local impacts, such as land-use change if crop production is expanded, or pesticide contamination of soil and water (Lehmann & Tittor, 2021). Second-generation biofuels use feedstocks such as agriculture residues or forest waste such as dead trees. This approach has the opportunity to create additional value for farmers or ranchers, or create value by clearing overgrown forests of downed, combustible material. Third-generation biofuels are produced from microalgae, which could be produced on land not suitable for food crops and utilize non freshwater sources for cultivation.

Because refineries and fuel sources may be located in different areas from one another, biofuel production may lead to new transportation and storage demands that will impact nearby communities. Other options, under development, include use of small modular technologies that can be brought to the feedstocks and used to do pretreatment or processing on site, reducing transportation and storage demands.

CCUS environmental and social justice considerations

Carbon capture, utilization, and storage refers to a combination of technologies that include: (1) technologies that capture CO_2 at facilities such as fossil-fuel fired power plants, refineries, oil/gas processing plants, steel manufacturing plants, cement plants, bioethanol plants, etc., (2) technologies that transport captured CO_2 such as pipelines, trucks, rails, and (3) technologies that either inject CO_2 underground for geologic storage or enhanced oil recovery or that convert CO_2 into value-added products such as fuels, aggregates, and others. Deployment of CCUS technologies requires either construction of entirely new facilities (e.g., pipelines or plants where CO_2 is converted into value-added products) or modification of existing facilities (e.g., capture technologies). Multiple justice concerns are associated with CCUS. Distributive justice would ensure that the populations who shoulder the potential risks of CCUS also experience its benefits (Buck, 2019).

Pipelines, in particular, have raised concerns about distributive, procedural, and recognition justice. CO_2 capture facilities deployed at point sources will typically be sited within the close vicinity of the source facilities and occupy only a fraction of the land area of the original facilities. The length of the pipelines transporting captured CO_2 to storage or utilization facilities will vary depending on how far these facilities are located from the CO_2 source and may range from a few hundred meters (such as the pipeline at the ADM CCS facility in Illinois) to a few hundreds of miles. The land-based impacts resulting from construction of new CO_2 transport pipelines will depend on the locations where the pipeline will have to be constructed. Irrespective, any construction of new CO_2 transport pipelines will have to follow existing regulations governing them and the land-based impact will have to be managed according to the requirements of those regulations. The failure to properly consult indigenous communities in Saskatchewan on a proposed CO_2 pipeline led scholars to conclude that

CCUS was a form of settler colonialism that threatens indigenous sovereignty (Alexander & Stanley, 2021). Rural communities in the U.S. also worry that pipelines will interrupt local livelihoods, thus contributing to rural depopulation, without creating substantial jobs (Buck, 2021).

Geologic CO_2 storage facilities require construction of one or multiple underground wells (including for CO_2 injection and monitoring) as well as above ground facilities for injection and distribution of CO_2. The land-based impacts during the construction of new wells would be similar to the impacts associated with drilling underground wells in general, such as in oil and gas production. Experts proposed that the land-based impacts of these facilities will be primarily associated with the construction phase and will become minimal once the facilities have been built and are operational. The question of risk, however, is complicated: local residents who live close to CCUS facilities, such as storage sites, hold different perceptions of risks, such as leakage, than do technical experts (Boyd, 2013, Low & Schafer, 2020). Many are aware that fracking may have the unintended effect of causing earthquakes, which causes people to be skeptical of claims that new injections will have no effect.

Spotlight on BE-CCUS (Bio-Energy Carbon Capture, Use, and Storage)

Coupling bioenergy generation with CCUS holds the promise of generating energy while reducing CO_2 concentrations, but generally remains at a pilot scale. The intermountain West is one geography that presents overlaps between industrial agriculture and suitable CCUS sites. For example, in 2022 a company named Carbon America proposed to gather 350,000 tons of CO_2 a year from ethanol-fermentation plants in Yuma and Sterling–two small agricultural communities in the northeastern region of Colorado—and inject it into underground wells in the Denver-Julesburg Basin, a center of oil and gas production. The project needs to be approved through an EPA impact assessment process to be built. While proponents emphasize that the project is a win-win, sustaining rural livelihoods while capturing CO_2, thus helping Colorado meet its aggressive decarbonization goals (Booth, 2022), existing research on CCS would ask the following questions: Which kinds of jobs would be created and for whom? What risks are associated with the required pipelines? How will determinations of feasibility recognize different judgments of the world, including acceptable risk?

The Intermountain West is home to other community-scale BE-CCUS projects that have the potential to distribute benefits more equitably, and in some cases, reduce environmental harms. Tucumcari Bio-Energy Company, in Tucumcari New Mexico, is proposing to retrofit an idle ethanol plant to meet multiple environmental objectives while creating a new income stream for agriculture and ranching operations. The intent is to use manure and bio waste to produce fertilizer while capturing methane, carbon dioxide, and hydrogen. Greenhouse and aquaponics growers can use the carbon dioxide and the fertilizer can be returned to agricultural uses. The proposal reflects the fuel available because of intense feedlots and dairy operations in the area. It has the potential to turn sources of pollution and waste into multiple usable products, creating value from waste products, producing energy, and increasing food production productivity.

Hydrogen production environmental and social justice considerations

Hydrogen can be produced in myriad ways, drawing on different forms of energy and inputs. Each has different local and potential environmental effects that may influence neighboring communities or elicit a response from interested organizations. All hydrogen production will involve industrial-scale facilities. If these can be co-located with operating facilities, or re-use obsolete industrial sites, they will have limited increased land use. New facilities, in contrast, will create localized impacts when they are sited. Blue hydrogen is made from non-renewable energy sources, and its production processes produce CO_2, necessitating CCUS. It also engenders diverse responses from communities, both negative and positive, often related to how it might prolong the use of fossil fuels.

Green hydrogen splits hydrogen from water molecules. While green hydrogen production does not create CO_2 if produced using renewables, it is water intensive and may impact local water availability. It could be produced by renewables during times that supply exceeds demand, creating energy that can be used when energy demands exceed supply. Nevertheless, it is also expensive and could impact energy costs to consumers.

Both blue and green hydrogen are improvements over gray hydrogen, which is produced from natural gas without CCUS. Because of the usefulness of hydrogen as a fuel, both will play a role in the transition. Both the facilities and distribution systems have the potential for local land impacts. Hydrogen can be transported through pipelines, and similar to natural gas, it may be possible to adapt current pipelines and distribution systems.

Direct air capture environmental and social justice considerations

Direct Air Capture (DAC) is a set of technologies that aim to capture CO_2 from the air and then sequester or use it. The potential impacts involve both how the CO_2 is captured and whether it will be used or sequestered. DAC could be deployed in different ways. Fan-based (active) capture has a large energy draw and tends to use large and complex devices. Industrial capture using existing airflows within a factory may be less energy intensive, as the DAC scavenges energy that has been employed for another purpose. Passive DAC is the least energy intensive with devices likely to be manufactured in factories, reducing cost, and increasing quality.

DAC has the possibility to be effective in any location and devices could be co-located with an end use, often with little or no additional impact. For the end use of sequestration, DAC will be positioned near or co-located with sequestration sites. Mineralization would be open to locations that are not dictated by existing wells or geology. This technology only has been evaluated at lab scale. For the end use of utilization, products from captured carbon will also result in siting facilities near labor centers. Products could result in different locational decisions. For example, a small DAC facility to provide CO_2 for a beverage facility or a greenhouse would be located on the industrial site or farm, respectively. The DAC footprint would be quite small for most of these applications, possibly 100 square feet. If the captured carbon is to be used to make methane (natural gas) then the focus would be sites near natural gas pipelines co-located to a source of hydrogen. Impacts from construction will depend on the DAC technology.

The impact of DAC on land-use will scale with sequestration needs. Early DAC locations will be near oil and gas wells. DAC could impact forestry or agriculture depending on the geologic formations that are used for storage. As CO_2 can be piped, one would assume less valued land will be used for a DAC farm and piping would be applied where required to reach sequestration sites that have other values. Pipelines are costly to build and operate, take a long time to permit and construct, and come with many environmental challenges.

While DAC systems will likely have little impact on air quality, it will be important to monitor this and recognize that communities may be concerned about the impacts. Given that new sorbents are being developed in labs around the world, care needs to be taken at each step to assure that contaminants, volatiles, or small particulates are not introduced into the environment. Current testing indicates that this is not yet a problem. DAC systems use differing amounts of water so reducing water use may be a primary design consideration. DAC is an emerging technology that will come in many forms and configurations, including some that use significant energy. If DAC is employed in ways that are passive or borrow from existing energy use, such as in industrial applications, the effects will be lessened. If DAC facilities reuse existing fossil facilities, the impacts will be lessened. Nevertheless, if DAC technologies are used extensively, they will take up significant space.

A framework to advance justice in the Intermountain West energy transition

Environmental justice is an evolving concept. The 1994 Presidential Executive Order 12898, Federal Actions to Address Environmental Justice in Minority Populations and Low-Income Populations, directed each federal agency to make achieving environmental justice part of its mission. Since that time, DOE and other federal agencies collaborated on how to meet this goal, and the DOE adopted its first strategy in 1995 (U.S. Department of Energy Environmental Justice Strategy). In 2007, DOE updated this strategy and adopted an implementation plan. The strategy was subsequently updated in 2017 with an updated implementation plan issued in 2019.

The DOE strategies recognize the need for distributive justice and for meaningful engagement, discussed below as procedural justice. More recently, increased public actions have amplified the call for restorative justice to reflect the multigenerational impacts of prior harms that led to the conditions people live and work in today. In energy communities, this includes air and water pollution from mines, generating stations, and oil fields. Distributive justice also includes providing access to jobs in the new energy economy for community members who may lose fossil fuel-related jobs or those who were previously denied good jobs and training. These communities are vulnerable to receiving undesirable facilities in the new energy economies (McCauley & Heffron, 2018).

Tribal sovereignty

Sovereign tribal nations hold a unique position. The U.S. government has mandated consultation with tribal nations on a government-to-government basis in good faith, with a commitment to respecting tribal sovereignty and self-determination. Despite this mandate, consultation processes often fall short. If a proposed action might influence an indigenous nation, shared governance needs to extend from initial steps such as setting policy goals, all the way to project development. Building lasting relationships is the first step. All projects and policy must address potential impacts to cultural sites, whether on or off tribal land, and follow appropriate engagement processes.

When working with or on projects that may impact sovereign tribal nations, Roger Fragua and Ryan Mast of Flower Hill Institute of Jemez Pueblo, New Mexico, have emphasized the need for partnerships. This differs from acting as if tribal nations are applicants in federal programs or establishing minimal consultation processes. Project leads must recognize that tribal nations have national governmental structures, and they approach the nation according to its established processes, laws, regulations, and customs.

Advancing social and environmental justice requires particular care to consider how new actions could affect tribal lands and cultural and sacred sites that may be located outside of the tribal nation's boundaries. One example is the federal initiative and public support to create a 10-mile buffer zone to protect Chaco Canyon from oil and gas development on federal lands, which emerged because the national park boundaries were determined to be inadequate to honor and protect Chaco Canyon's significance (Black, Toledo, & Brown, 2022). Due diligence about areas that may be impacted, and early conversations with indigenous nations and communities that may have claims to lands, are necessary to ensure that these conversations occur prior to intense facility planning, pipeline routing or regional changes that could impact the local environment.

Programs that are designed without native involvement fail to recognize indigenous expertise (Fragua & Mast, 2022). In all project development and engagement processes, recognizing and respecting indigenous sovereignty is paramount, and this includes following research and engagement protocols established by the nation or community, respecting differences in land tenure and tribal enterprises, recognizing that tribal nations and indigenous communities who do not live on tribal trust land retain their interests in an issue or place whether or not they develop partnerships or participate in established engagement processes.

Spotlight on respecting indigenous sovereignty: pipelines

The Dakota Access Pipeline highlights the profound need for partnerships with tribal nations that reflect tribal sovereignty and culture. Though outside the Intermountain West region, this 1,172-mile-long (1,886 km) underground oil pipeline that runs through North Dakota, South Dakota, Iowa, and Illinois, demonstrates how much is at stake when there are divergent perspectives during construction on pipelines or new facilities. In 2016, Energy Transfers Partners, LLC, through its subsidiary Dakota Access, LLC, successfully obtained the four-state approvals necessary to build the pipeline. The original plan had the pipeline running north of Bismarck but the potential threat to the city's water supply led to a redesign; its current route runs through the Standing Rock reservation (McKibben, 2016). The pipeline was permitted to cross under the Missouri River, a key water supply, and under Lake Oahe, a sacred site to the Standing Rock Sioux.

As a sovereign nation, the Standing Rock Sioux opposed the pipeline because its construction violated Article II of the Fort Laramie Treaty, which guarantees undisturbed use, and occupation of their lands. The Tribe also opposed the pipeline based on intersecting harms of a threat to its lands and water, tribal sovereignty, and religious and spiritual freedom. The Cheyenne River Sioux also opposed the pipeline. While the water source as a supply of drinking water was important, for many Lakota participants, the spiritual dimensions were equally important (Goeckner et al, 2020).

The Tribes organized numerous actions and established a camp. Over 15,000 people came from across the globe to protest the pipeline with additional actions held in solidarity elsewhere. The pipeline was eventually approved and became operational in 2017. Because of the actions by the Standing Rock Sioux and their allies, the U.S. Army Corps of Engineers (USACE) revoked the permit allowing the pipeline's Lake Oahe crossing and instead required a full environmental review (Sisk, 2021). As of 2022, the USACE is still embroiled in disputes about the Dakota Access Pipeline and as of May, the draft environmental impact statement (EIS) had not yet been released. In January 2022, the Standing Rock Sioux who had served as a cooperating agency, withdrew from the development of the EIS (USACE, n.d.), signaling that the EIS process was not sufficient to guarantee procedural justice.

Pipelines are a challenging infrastructure. While the Dakota Access Pipeline is associated with transporting oil and gas, other pipelines are being proposed to transport carbon. Summit Carbon Solutions, LLC is currently working on a pipeline to move carbon through North and South Dakota, Minnesota, Nebraska, and Iowa. Property owners along Summit's line worry about the use of eminent domain and the pipeline effects on their property (Sisk, 2022). These examples highlight the widespread potential impact from pipelines and other energy projects, and the need for engaging stakeholders early, and for co-designing projects with tribal nations whose lands may be impacted.

Assessing the distribution of impacts and outcomes

According to the EPA, no group of people should bear a disproportionate burden of environmental harms and risks, including those resulting from the negative environmental consequences of industrial, governmental, and commercial operations or programs and policies (U.S. EPA, 2011), and more recently that positive environmental and health outcomes and reduction of risks should be experienced fairly across populations (U.S. EPA, 2015). Distributive justice focuses on *who* enjoys the benefits or shoulders the harm and *what* will be distributed in terms of harms and goods (Bell, 2004; Svarstad & Benjaminsen, 2020). Assessing distributive justice has three components: (1) a given action or project's anticipated effects including changes to land uses, environmental impacts, job gains or losses, and community impacts; (2) where these will occur, the geographical areas that will be impacted, which may differ by impact, as well as the cultural meanings of the places; and (3) the people it will impact with attention to the diversity within the impacted community and the relative situation of one community when compared with others. Analyzing these in conjunction with one another lays the groundwork to assess the distribution of harms and benefits, and to determine with whom to engage (discussed in more detail in the next section). For some environmental situations, such as clean water or air, the goal is for everyone to have access to a minimum standard. In other cases, equality may be the goal, or differences based on a community's priorities and values (Bell, 2004; Svarstad & Benjaminsen, 2020).

Numerous screening tools have been developed to help determine environmental justice considerations for given populations in an area. The EPA's Environmental Justice Screening and Mapping Tool called EJScreen (https://www.epa.gov/ejscreen) combines environmental and demographic information to help communities and other interested parties understand both demographic and environmental factors in a community. The Council on Environmental Quality has developed a Climate and Economic Justice Screening Tool (https://www.screeningtool.geoplatform.gov) to help federal agencies identify communities that are underserved and overburdened by environmental harms. Both tools can help identify who lives in an area and existing circumstances. They can also evaluate what types of environmental risks community members face and how the risks are concentrated to consider cumulative impacts. The

American Community Survey (https://www.census.gov/programs-surveys/acs/data.html) has data tables at different geographies that can help understand housing and community characteristics.

To achieve distributional justice, an EESJ approach must be used at the project scale, assessing within the project area who is impacted and in what ways. A project or a program intended to benefit particular populations (such as residents with low incomes or people who formerly worked in an industry) requires knowledge of the distribution of the population within an area of interest. An analysis of target populations can identify how many persons within an area are eligible for support programs, and where people are concentrated in a specific area (e.g., neighborhood). This helps identify outreach techniques.

These outcomes also need to be tracked across the region and within the different states to understand the overall redistribution of both benefits and harms. Measuring the equity implications of competing policy pathways will require a process to develop sound, agreed upon equity and justice metrics. The ways to measure progress towards environmental justice and equity are still being defined. Most of the environmental justice and equity metrics developed to date focus on measures or assessments of inequity or injustice, rather than equity and justice (Lanckton & DeVar, 2021).

Metrics, indicators, and indices are three mechanisms available to aid in efforts to quantify the environmental justice and equity implications of competing policy pathways to carbon neutrality (Preziuso, Tarekegne, & Pennell, 2021). While oftentimes used interchangeably, metrics, indicators, and indices are different from one another and can each uniquely contribute to advancing our understanding of the equity and justice impacts of competing policy pathways (Preziuso, Tarekegne, & Pennell, 2021).

Metrics are quantitative measurements of a qualitative outcome. Metrics can measure a specific equity outcome and are instrumental for tracking progress toward the goals of justice and equity (Preziuso, Tarekegne, & Pennell, 2021). Indicators are a representation of a specific equity or justice outcome within a community, municipality, state, or other area (Lanckton & DeVar, 2021). Indicators are used to discern the status of equity or justice at a single point in time and are therefore effective tools for establishing a baseline level of equity or justice (Preziuso, Tarekegne, & Pennell, 2021; Lanckton & DeVar, 2021). Multiple indicators can be aggregated to form an index (e.g., energy insecurity index, human development index) (Preziuso, Tarekegne, & Pennell, 2021).

Metrics that can be leveraged to understand the effects of investments across different types of impacts can help demonstrate how specific types of investments or projects will contribute to or detract from an equitable and just system. Some of these include community-acceptance ratings, estimates of program funding impacts, energy use impacts, energy quality, and workforce impacts. Investment metrics require data on community satisfaction, the impacts of investments on health and the environment, as well as the budget available to support community programs and the number of jobs created or supported (Preziuso, Tarekegne, & Pennell, 2021). Deciding future investments requires an understanding of previous investments, their positive and negatives outcomes, what is needed, which communities are likely to support a specific type of investment, and to what extent and which ways a community's members will be impacted (e.g., how many jobs will be gained, potential environmental impacts).

Targeting injustice and inequity requires an understanding of who the target population is, what types of investment or programs are needed, and what the impacts of those investments or programs might be (Preziuso, Tarekegne, & Pennell, 2021). Community descriptive metrics to identify a target population include but are not limited to a program equity index, an energy cost index, an energy burden index, a late payment index, and measures of program accessibility. Each index mentioned requires data on the cost of energy bills, the frequency of late payments, area level demographics, and the type of assistance offered through specific programs (Preziuso, Tarekegne, & Pennell, 2021). While the above outlines several dimensions of measuring the equity implications of carbon neutrality pathways in the Intermountain West, metrics for measuring equity and justice is a robust area of research with new ideas being born each day. Metrics are still needed that can capture community needs, assess the quality of the jobs generated, the non-cost benefits of lessening home energy burdens, and measuring health and safety (Preziuso, Tarekegne, & Pennell, 2021).

It is important to recognize that using a EESJ justice lens differs from other approaches to assessing when projects or policies are functioning well. Welfare economics, the basis of the science behind how economists make policy recommendations related to the dissemination (i.e., allocation) of scarce resources (Perman, Ma, McGilvray, & Common, 2003), assumes policy pathways are economically efficient when they result in an allocation that makes someone better off without making anyone else worse off (Bergstrom & Randall, 2016). This does not necessitate an equitable or just distribution of society's scarce resources (Harker Steele, 2019; Bergstrom & Randall, 2016). Efficiency also ignores which individuals/groups gain and which lose, so long as no one is made worse off (Bergstrom & Randall, 2016). In contrast, an EESJ approach should take into consideration how the benefits and costs will be distributed across groups (Goulder & Parry, 2008).

Processes to engage communities and sharing decision-making power

Environmental and social justice analyses require a baseline assessment of the current distribution of harms and goods, and the inequalities facing diverse groups. This information helps inform processes to engage diverse rightsholders and relevant stakeholders, particularly those who otherwise would have systematically less power in established policy and project development processes that rely heavily on expert, technical information that is not grounded in a given location, or local knowledge and value systems. Procedural justice refers to developing processes that share decision-making power with communities to shape project and policy formation. An underlying premise of procedural justice in the energy transitions is that impacted communities must both benefit from *and* have meaningful opportunities to shape actions including energy projects that will impact them. To advance an EESJ approach, the processes need to recognize differences among peoples and communities and engage in appropriate ways with each.

David-Chavez and Gavin (2018) have developed a scale of community participation for research projects with indigenous communities that can be useful for energy transition engagement processes. They develop a participation continuum from “contractual” where community members are hired but outside researchers make decisions to an “indigenous” process where the community has decision-making authority on all aspects of the project. In between “contractual” and ”indigenous” are “consultative,” “collaborative,” and “collegial.” They also develop indicators in the form of questions for responsible research practices with indigenous communities. The questions below are adapted from David-Chavez and Gavin (2018) to apply to energy projects. It is important to recognize the indigenous communities have maintained diverse knowledge systems that therefore may bring different perspectives that do not align with the project development process. Relationship-building must begin early to incorporate new knowledge and perspectives.

- Indicator 1—Access: are benefits accessible to indigenous community members? Are indigenous community members engaged in decision making processes?
- Indicator 2—Relevance: are potential options, issues, and benefits reported in the context of concerns, issues, or interests defined by indigenous community members?

- Indicator 3—Credit: how were indigenous community members credited for their knowledge contributions and efforts?
- Indicator 4—Ethics: how does the project report ethical guidelines followed?
- Indicator 5—Cause no harm: did the engagement process address intellectual property rights or risks for indigenous communities?
- Indicator 6—Outputs: did the project report any outputs or outcomes for the indigenous community?

The screening tools discussed in the previous section or a demographic analysis that considers the range of scales and types of impacts can identify which communities to engage in participatory processes. In many cases, communities are place based, or connected because they live or work in an area. In other cases, it is equally important to engage with communities of interest, those that have common circumstances. These communities may be based on race or ethnicity, or job type such as migrant workers or agricultural workers. One step in developing a process to advance procedural justice is to determine who needs to be engaged in project or policy development. Understanding local demographics and situations is important, and it is equally necessary to consult with local public officials and local leaders to understand the regional power landscapes.

Engagement processes have two main objectives beyond fulfilling public meeting requirements. Participatory processes contribute knowledge otherwise unavailable to project development. Participants bring knowledge about their communities, history and values, and their lived experiences. They also bring knowledge about community members' perspectives on given technologies or concerns about how their communities might change. Projects that are focused on technical solutions may overlook relevant historical, political, and social dimensions.

The second important contribution of participatory processes is that they assist with project or policy acceptance, whether participatory decision-making processes are associated with the public sector, private sector, or community-led initiatives. How people understand a project will influence how they respond to it, and opposition can slow or halt a process. Participatory processes that appear fair can help build trust which makes shared benefits and solution building more possible. Conversely, weak processes can erode trust. Trust in an industry greatly influences residents' views of technologies, and its risks and benefits (Mayer, 2016).

Specialized expertise in developing and facilitating participatory processes can help to effectively navigate and integrate diverse viewpoints on needs, objectives, and preferences. Acknowledging and incorporating differing expectations, perceptions, and experiences in participatory decision processes and the solutions or outcomes are steps to advancing procedural justice (Simcock, 2016).

Justice as recognition is a critical component, where recognition is connected to social status, and misrecognition takes the form of cultural domination or disrespect (Svarstad & Benjaminsen, 2020). At the same time, it's important to acknowledge that recognition does not have to come from the state in the sense of formal recognition of an ethnic group or tribal nation (Pulido and de Lara, 2018). Acknowledging the lived experiences of people affected by environmental injustice, or affected people's senses of justice, "the ways they subjectively perceive, evaluate and narrate an issue, such as their perspectives on an environmental intervention" is a component of countering power asymmetry and conveys knowledge that aids informed policy-making processes (Svarstad & Benjaminsen, 2020, 4). This validates values, lifeways, and worldviews, which also must be built into the engagement processes.

During the I-WEST workshops, participants repeatedly stated that having one public meeting was inadequate to engage community members at any level, and a far cry from developing the partnerships necessary to develop an energy transition that reflects the multiple perspectives of the indigenous nations and diverse communities. When designing projects, numerous participatory tools can be used, and employing more than one will help reach a wide range of participants. The appropriate tools depend on the particular circumstances in a community and the broader area. Because of the uniqueness of each community and its circumstances, collaboratively identifying appropriate tools occurs at the beginning of the participatory process (David-Chavez & Gavin, 2018).

- Hired community liaisons to help develop engagement plans and spearhead outreach can bring local knowledge into the engagement process.
- Advisory or guiding community committees can create a formal structure that develops in-depth knowledge about the process. It is necessary to create a broadly inclusive committee and to mitigate potential power imbalances within the committee.
- Public meetings can reach any interested parties. However, some residents have more opportunity to participate so care must be given to ensure the participants reflect the range of impacted and targeted communities.
- Focus groups can facilitate conversations among sections of the communities with common interests such as a neighborhood, or workers in an industry or ethnic group.

- Surveys can elicit feedback from people who otherwise do not participate in a public meeting or other form of engagement.

Engaging a wide range of participants comes with challenges. As the energy sector changes, decision-making processes grow more complex (Bertsch & Fichtner, 2016). Intentional ongoing participatory processes have slower timelines than project development without local engagement, and the time and engagement work adds expenses. Co-developing realistic and reasonable work plans with engaged rights holders and stakeholders that center on inclusivity and equity can result in an achievable timeline with fewer conflicts or community-initiated delays. Decision-making processes require that all participants are treated with dignity and respect, have opportunities to voice viewpoints freely, and have their perspectives heard and considered. Transparent decision-making processes and trustworthy intentions and motivations are also essential.

Discussions about the energy transition embody a sense of urgency that is a barrier to engage in inclusive and meaningful decision-making processes. Thoughtful dialogues require relationship building, which in turn require trust and time to establish. Whyte (2020a,b) has written that, without refocusing on reconstituting relationships, rather than the urgent adoption of climate solutions such as transitions to carbon neutrality, the proliferation of dangers to indigenous people will continue. "Indigenous peoples often show that the relationships they have with other societies are lacking in certain qualities. For example, indigenous peoples are concerned about ongoing disrespect against their *consent* (or dissent) to oil and gas pipelines, the *distrustful* behavior of nations seeking to dispossess indigenous peoples of their lands through forest conservation or hydropower, and the failure of *accountability* and *reciprocity* in governmental programs that seek to foster clean energy development or community resettlement." The pace of rebuilding relationships is different from implementing a given energy project.

In participatory approaches to policy making, power dynamics shape interactions between nature, society, and science (Hejnowicz & Thorn, 2022). Therefore, understanding power dynamics and paying close attention to language use could prevent stigmatizing and othering of engaged community members during participatory processes. Consideration for the role of knowledge in environmental governance is critical for "enabling well-informed governance arrangements" (Van der Molen, 2018). Lived experiences of the involved communities and their subjective perceptions must be viewed as critical knowledge and integrated into policy-making processes (Beauchamp et al., 2021).

Power imbalances are frequent barriers to legitimate and co-produced sustainable development (Hejnowicz, 2022). Without balanced power in decision-making processes, policies may not adequately address forces that uphold injustice. Acknowledging power dynamics, along with local social and cultural norms, is critical to avoid negative outcomes coming from positive intentions (Beauchamp et al., 2021). Engagement processes must identify and address power imbalances to ensure meaningful inclusion of intersecting and marginalized communities to respecting indigenous self-determinism in policy making processes; we have meaningful ways to shape energy policies that impact the local communities as intended. While conventional outcome assessments and accountability measures for energy policies are useful metrics for evaluating energy policy efficacy, community resilience and wellbeing beyond such qualitative and technocratic methods must be integrated to adequately engage in environmental justice as a practice.

Considerations for empowering collective decision making include

- Recognize manifestations of privileged positionality, particularly the detrimental effects of power hoarding (https://data.worldbank.org/indicator/EG.ELC.ACCS.ZS).
- Identify intersectional power dynamics, particularly those that lead to boundaries and barriers to collective decision making (Ryder, 2018).
- Examine the impacts of power dynamics on the collective in order to develop strategies for managing and mitigating resulting boundaries and power differentials (Kellam, 2020).
- Co-develop protocols to engage in collaborative decision making during designing outreach and engagement processes by paying particular attention to power differentials.

Considerations when designing outreach and engagement processes include

- Respect indigenous sovereignty and all processes that a tribal government has in place. Such practices include investing in relationship-building and approaching potential nations as partners and rightsholders from the beginning.
- Engage indigenous communities in collaborative decision-making throughout a project development including initiation, design, implementation, analysis, dissemination, and areas for future action (David-Chavez & Gavin, 2018).
- Avoid overburdening stakeholders and rightsholders while ensuring reciprocal relationships and mutual benefits. Such practices include recognizing the rights of stakeholders,

rightsholders, and communities to refuse to engage without diminishing their stakes or interests.

- Recognize forms of privilege (race, ethnicity, gender, class) and intersectional marginalization (such as how gender intersects with race and ethnicity) in participatory decision-making processes. Recognize manifestations of privilege positioning (https://doi.org/10.1016/j.erss.2021.102135) and determine ways to counter them in an immediate and consistent manner.
- Recognize relational power dynamics (Young, 2020). Assessing who is given the opportunity to participate in decision processes is critical from the beginning of the participatory process. Particularly during the policy planning phase, ensuring an inclusive and collective decision-making process by attending to the existing power dynamics and counteracting its impact through power sharing. Such strategies may include engaging facilitators with EESJ expertise and fostering an environment to openly discuss power.
- Identify local stakeholders to co-develop outreach and engagement plans, and timelines that reflect local cultures to ensure inclusivity and equity in participatory decision processes.
- Consider both land tenure rights and claims, and who could improve resource stewardship if they secured them (Mbidzo et al., 2021). Land claims can be diverse such as residents or workers who rent or lease land, those who use the land or for whom the land is sacred.
- Recognizing the lived experiences of the involved communities and their subjective perceptions are critical knowledge to be integrated in the process (Beauchamp et al., 2021).
- Solicit household-level responses to planned policy adaptations (Angula et al., 2021). This can be accomplished through surveys or other mechanisms to reach those who do not participate in meetings or focus groups.

Addressing past harms to advance just futures

Restorative justice centers on those who have been harmed by past actions with the intent on repairing past harms, stopping ongoing harm, and preventing the reproduction of the harm. Inequalities in wealth and income that exist in other parts of the country (www.census.gov) are visible in the Intermountain West as well, and have ongoing impacts (Figures 1, 2). For example, communities with less wealth and lower incomes are more likely to accept jobs that may damage their health and environment without making demands for fair wages and environmental protections.

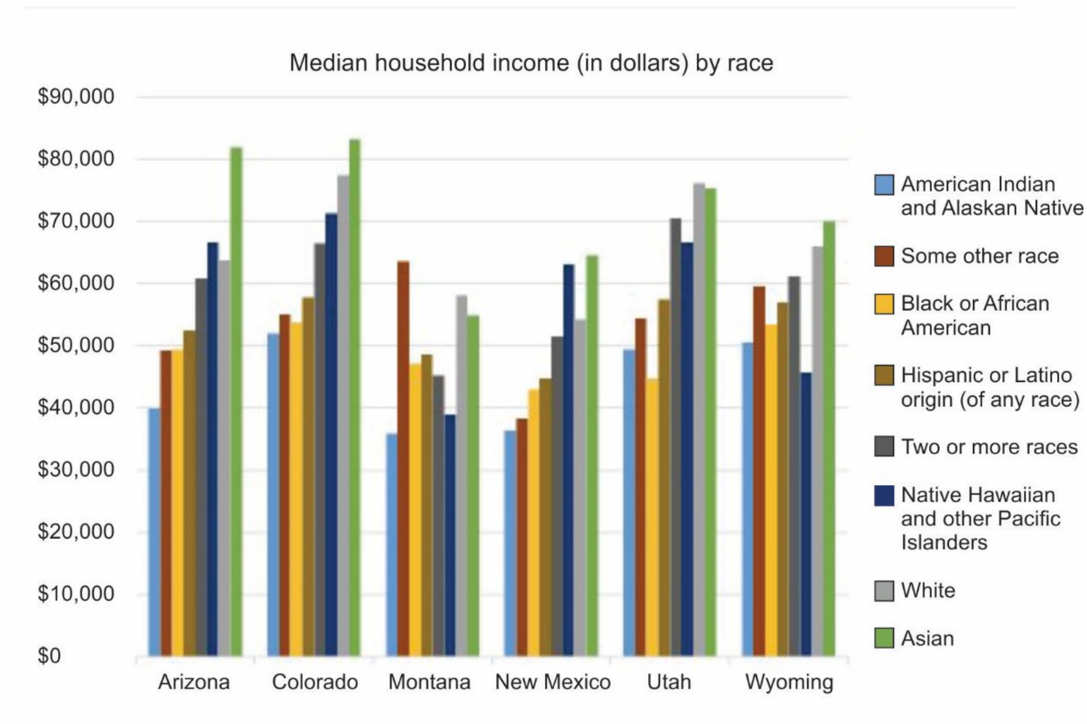

Figure 1. Median household income by race for states in the Intermountain West. From U.S. Census Table S1903, ACS 2019 5-year estimates.

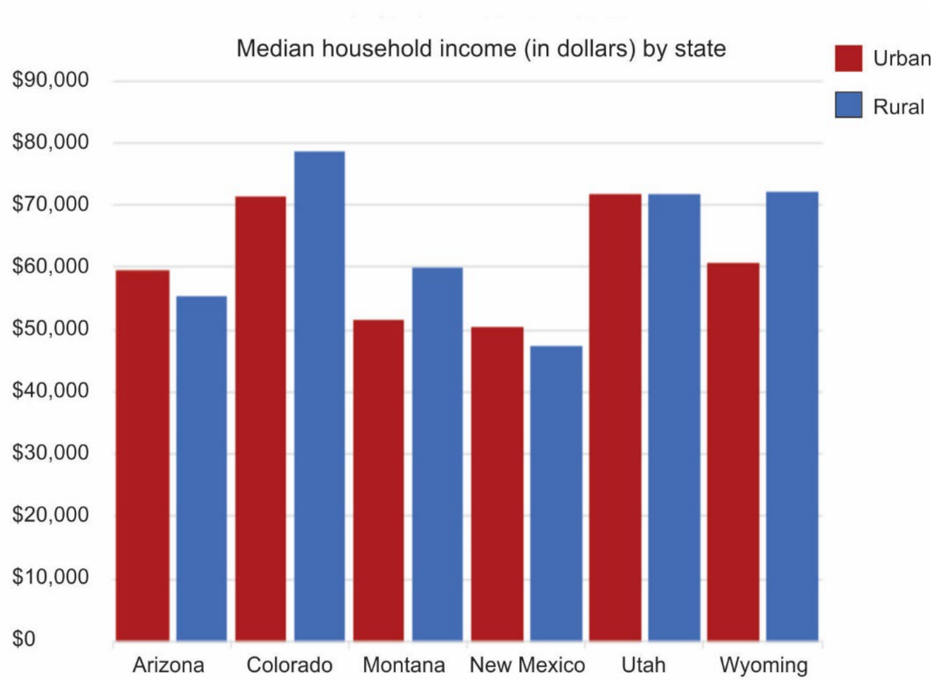

Figure 2. Median household income by state, rural and urban populations. From U.S. Census Table S1903, ACS 2019 5-year estimates.

Environmental justice research has shown that communities of color and low-income communities also face disproportionate pollution and other exposures that lead to poor health and financial loss (e.g., Perera, 2018). A restorative lens considers how varied factors interact, recognizing that people can lose jobs while environmental conditions improve without obscuring the interactive effects, and adding actions that address legacy impacts.

A restorative approach addresses these realities directly and provides financial and technical assistance to ensure communities that have been disadvantaged do not have to accept disproportionate tradeoffs. These are complex decisions, and impacted people need power in the decision-making processes, focusing attention back on the relationship building rather than only measuring distributive effects of the outcomes.

Recommendations and next steps

Advancing environmental and social justice requires that EESJ advancing practices are built into all projects, all participants have the training and resources to implement them well, and that accountability measures track what is occurring in ways that lead to further improvement. In addition to guidelines at the project scale, and tracking the cumulative outcomes of projects and actions, initiatives such as I-WEST might also benefit from an advisory committee or other mechanisms to bring additional voices to decision-making processes.

Develop guidelines

Action step

Develop guidelines for working with and developing partnerships with tribal nations to assist teams who are developing energy projects that could affect tribal lands, communities, or important places. These must be developed in partnership with tribal representatives who are working on energy issues. The tribal partners' expertise must lead the conversation and the representatives compensated for participation in developing the guidelines.

Action step

Develop guidelines for working with impacted communities, that include how to conduct a local and regional power analysis to determine who needs to be included in subsequent engagement processes. When developing the guidelines, identify people and organizations with specific expertise in engagement and tools to advance justice, and compensate for their contributions.

Considerations

- Recognize the barriers to participation and identify strategies to overcome these barriers
- Include adequate resources to facilitate meaningful engagement
- Include metrics to evaluate community engagement
- Recognize that different stakeholders bring their expertise to the conversation and value the expertise
    - This may involve compensating people for time and expertise
    - This may involve incorporating different worldviews, lifeways, and value systems

Requiring EESJ practices

Action step

Require that all proposals include an EESJ component that includes a preliminary demographic analysis of potentially affected areas, potential adverse effects and benefits on local communities, metrics, and evaluation tools for evaluating both the engagement processes and project outcomes, and a budget that shows the costs of implementing the EESJ component.

Considerations

- This can expand on the increasingly common DEI plans in proposed projects
- Recognize the need for ongoing engagement
- Recognize the need for project teams to have expertise for implementing strategies that will advance EESJ
- Recognize that diverse teams lead to better creative and community outcomes
- Possible need for a budgeting tool to use during project development
- Ongoing training about environmental justice to research teams about what it means to incorporate environmental justice and what is expected, including the difference between societal benefits and localized impacts

Evaluating EESJ outcomes

Action step

Create reporting and accountability mechanisms.

Considerations

- Develop metrics to assess community engagement and project outcomes
- Develop reporting systems that create ways to be honest about challenges as well as successes, and to report barriers to full success
- Develop indicators for different dimensions and an index to track progress in the Intermountain West, and to help with future prioritization

Learning from and highlighting successful EESJ processes and outcomes

Action step

Create mechanisms to recognize and share promising practices.

Considerations

- Highlight successful projects that include different dimensions of energy, environmental, and social justice
- Highlight and recognize meaningful partnerships
- Create incentives to share challenges and “lessons learned” in productive ways
- Develop a resource guide that includes cases and lessons learned

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I-WEST

Phase One Final Report | Detailed Chapter

Policy

VERSION 2.0 RESOURCES FOR THE FUTURE JUNE 2023

About this chapter

The Intermountain West Energy Sustainability & Transitions (I-WEST) initiative is funded by the U.S. Department of Energy to develop a regional technology roadmap to transition six U.S. states to a carbon-neutral energy economy. I-WEST encompasses Arizona, Colorado, Montana, New Mexico, Utah, and Wyoming. Each state is represented in this initiative by a local college, university, or national laboratory. Additional partners from beyond the region were selected for their expertise in applicable fields. In the first phase of I-WEST, the team built the foundation for a regional roadmap that models various energy transition scenarios, including the intersections between technologies, climate, energy policy, economics, and energy, environmental, and social justice. This chapter presents work led by an I-WEST partner on one or more of these focus areas. A summary of the entire I-WEST phase one effort is published online at www.iwest.org.

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Table of Contents

Introduction

Before beginning to define the role for policy in decarbonizing the Intermountain West, there must be clarity about the existing policy landscape and, therefore, more broadly, the policy readiness of the region to move forward. Providing that baseline information is the primary goal of this chapter. In addition, given this baseline, we present future policy options gleaned from the I-WEST workshops, reports, interviews, and our own expertise.

Scope of the analysis

With many potential policies to discuss, analyze, and contrast, we need boundaries and a clear definition of what a policy is in the context of I-WEST.

Policy definition

We define policy as a legislative, regulatory, or other action by government that plays an important role in fostering or impeding decarbonization. Government policies often involve mandates and requirements on stakeholders (such as industrial carbon emitters) but need not. For instance, we consider a state's transition roadmap to be a policy. One could consider corporate decarbonization goals a "policy" as well, but for this report, we did not.

Policy jurisdictions

We describe the policy landscapes of the six states under assessment by I-WEST, as well as a limited review of tribal nation and federal policies.

The six Intermountain West states have bicameral legislative branches that mirror that of the federal government. The legislature works with the governor to pursue policy development and change. State policymaking is key to decarbonizing the region. Here, state governments have the opportunity to fine-tune policies to ensure that the specific challenges faced by each state or community are addressed.

There are some 60 tribes in the region, each with their own governance structures, histories of energy development, and priorities for future economic development—including energy development—and environmental protection. Tribes differ in numerous ways from states. Although their sovereign status allows them greater degrees of flexibility in some respects, the interaction between tribal policies and state or federal policies can be complex, and in some cases can impede energy development.

Federal policies are also important because in some areas, such as research, development, and deployment (RD&D) spending, they dominate the policy landscape. Federal spending also represents a huge share of government spending in the U.S., compared to even all 50 state budgets. Thus, a federal policy can have a greater impact on decarbonization than the six states and the tribes contained in the region. Finally, federal policy, by its nature, can solve issues of interstate coordination, while states must negotiate amongst themselves.

Out of practical necessity, we give local policies little attention. There are simply too many localities and too many interests to capture local policies in a comprehensive manner. Nevertheless, where a compelling policy issue crosses all localities, we will include local considerations. In any follow-up work where location for development becomes more specific, local issues should be considered carefully.

Finally, we acknowledge that other states, particularly those in the West, impact the Intermountain West region. When we judge that another state's policy is of sufficient importance for regional decarbonization, by setting an example or through direct impacts, we mention these states as well.

Policy timeframe

While the policy landscape focuses on currently implemented policies, where compelling, we include policies that have been promised or are in process—such as undergoing a rulemaking process—but have not yet been implemented. We also include policies that are so consequential that even if they are not yet law, enacting them would have very large implications for decarbonization. For example, the Biden Administration's Build Back Better legislation contains many elements relevant to decarbonizing the Intermountain West and is thus too consequential to ignore.

This report was written before the announcement and passage of the Inflation Reduction Act (IRA). Passed during reconciliation and signed into law in August 2022, the IRA is widely considered to be historic climate and energy legislation for the U.S. and covers many of the provisions in Build Back Better. While the IRA institutes and supports many programs that will impact decarbonization in the Intermountain West, this report does not capture those programs in any detail, except insofar as they appeared in the earlier failed Build Back Better bill.

Since the IRA was passed through reconciliation, the focus was not on introducing or altering regulatory programs, but rather on sending money from the treasury to support 2050 climate goals. The release of $205 billion (CRS 2022) from the Treasury comes primarily in the form of clean energy tax credits and support for innovation through grants and national lab funding. These credits and grants could help close the funding gap for clean energy projects in the Intermountain West. Additionally, the IRA takes a particular focus on supporting rural and energy communities, which makes up a great deal of the region. Based on our assessment of the regional policy landscape, some of the most relevant opportunities are listed here: Clean Hydrogen Production Tax Credit (45V), Advanced Manufacturing Production Tax Credit (45X), Clean Energy Production Tax Credit (45Y), Extension of the Energy Investment Tax Credit (Section 48), Clean Energy Investment Tax Credit (48E), Clean Fuel Tax Credit (45Z), Extension of Carbon Capture and Sequestration Tax Credit (45Q) , Advanced Industrial Facilities Deployment Program, Environmental and Climate Justice Block Grants, Increased financing for the U.S. Department of Energy (DOE) Loan Programs Office, and Greenhouse Gas Reduction Funds.

For a detailed summary of these key tax credits, competitive grants, and consumer rebates, we recommend readers consult the following:

- Inflation Reduction Act (IRA) Summary: Energy and Climate Provisions (https://bipartisanpolicy.org/blog/inflation-reduction-act-summary-energy-climate-provisions/)
- Summary of the Energy Security and Climate Change Investments in the Inflation Reduction Act of 2022 (https://www.democrats.senate.gov/imo/media/doc/summary_of_the_energy_security_and_climate_change_investments_in_the_inflation_reduction_act_of_2022.pdf)
- Inflation Reduction Act of 2022 (https://www.energy.gov/lpo/inflation-reduction-act-2022)

Policy scope

We consider important policies that can either hinder or help in decarbonization. We limit ourselves, however, to energy and environmental policies, and policies such as siting and permitting that have environmental components and implications. Other I-WEST partners consider labor, economic development, and environmental justice (EJ) policies. We do not consider water policies and air pollution policies outside of carbon dioxide (CO_2) and methane. We define more general fiscal and monetary policies as out of scope, despite their potential relevance.

Policy classification

Since our research teams, policymaker contacts, and other stakeholders are more likely to be experts in a sector's policy area, rather than having expertise across all the policy types in each state, we organize our categorization by policy topics. As seen in the table of contents, the top-level topics are Cross Cutting, Electricity, Industrial (which includes fossil fuels), Fuels and Transportation. Research and development (R&D) policies, tribal policies, and carbon capture, utilization, and storage (CCUS) are classified under Cross Cutting; clean hydrogen (H_2), biofuels, solar, wind, oil, and gas relevant policies are classified under Fuels. A state's transition roadmap covers many topic areas and is classified under Cross Cutting policies.

Approach

To develop the information on the policy landscape we consulted a variety of sources. We attended all state and topical workshops organized by I-WEST partners. This chapter is heavily informed by those workshops. We also conducted interviews with key stakeholders in the states under assessment by I-WEST. These interviewees were identified through the workshops and through interactions with I-WEST partner leads. The Resources for the Future (RFF) research team also gathered written information from a variety of sources, such as government documents, industry and government websites, academic articles, and many other sources. Finally, we consulted RFF materials, especially regarding the federal policy landscape.

Cross-cutting policies

U.S. Climate Alliance membership

To organize decarbonization efforts, several Intermountain West states have developed statewide transition roadmaps and adopted emissions targets. Following the U.S. withdrawal from the 2015 Paris Agreement, governors from Colorado, New Mexico, and Montana joined the U.S. Climate Alliance. The purpose of the alliance is to maintain the objectives of the original Paris Agreement and achieve its greenhouse gas reduction goals through the actions of member states[1]. To organize decarbonization efforts, several Intermountain West states have developed statewide transition roadmaps and adopted emissions targets.

Climate action planning

Colorado is the only Intermountain West state to have passed legislation committing the state to its Greenhouse Gas (GHG) reductions targets[2]. The governors of New Mexico and Montana set their states' targets through executive action.

Towards achieving their goals, Colorado and Montana each developed state climate action plans, which outline policy goals and recommendations for achieving emissions targets. Colorado's plan

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[1] See http://www.usclimatealliance.org/

[2] See *Climate Action Plan to Reduce Pollution* (2019).

suggests a transition away from coal and to renewable electricity while also reducing methane emissions from oil and gas development. Colorado worked with large utilities in the state to develop utility-specific clean energy plans to reduce emissions, retire coal plants, and increase renewables deployment. The plan also makes recommendations to encourage transportation electrification and increased building energy efficiency. The Montana climate plan makes similar recommendations to Colorado's, with particular attention paid to increased energy efficiency and deployment of renewables. Their plan also suggests support for native nations and advocates for additional federal policy.

Table 1. Climate Action Plans and GHG Reduction Targets by State

State	GHG Reduction Target	Climate Action Plan
Arizona	None	n/a
Colorado	26% below 2005 levels by 2025, 50% by 2030, 90% by 2050	Greenhouse Gas Pollution Reduction Roadmap, Jan. 2021[3]
Montana	Net-zero GHG emissions for average annual electric loads by 2035	Montana Climate Solutions Plan, Aug. 2020[4]
New Mexico	45% below 2005 levels by 2030	None
Utah	None	n/a
Wyoming	None	n/a

The Colorado Energy Office also commissioned Energy & Environmental Economics (E3) to produce the report, *Opportunities for Low-Carbon Hydrogen in Colorado: A Roadmap,* which serves as an assessment of hydrogen energy development potential, barriers, and policy recommendations available to the state[5]. Beyond the work of state offices, independent research groups such as E3 are conducting roadmap-related work relevant to transition efforts[6].

Carbon pricing policies

With the exception of the federal methane fee included in the Inflation Reduction Act of 2022, there are no carbon pricing policies at either the federal level or implemented within any of the Intermountain West states. That said, the California Cap-and-Trade Program allows offsets to be utilized from anywhere in the United States, including forest carbon sequestration projects and mine methane capture projects located in the region[7].

[3] See *Colorado Greenhouse Gas Pollution Reduction Roadmap* (2021).
[4] See *Montana Climate Solutions Plan* (2020) .
[5] See Lintmeijer et al. (2021).
[6] See Mahone et al. (2020).
[7] See https://ww2.arb.ca.gov/our-work/programs/compliance-offset-program/offset-project-operators

Policies supporting carbon capture, utilization and storage

The recent legislation – Infrastructure, Investment and Jobs Act (IIJA) -- expands the Carbon Capture Technology program to include pipeline infrastructure with an additional $100 million over the next five years. This investment is to be administered by the National Energy Technology Laboratory (NETL), which awards funding to selected research, development, and demonstration (RDD) projects. These funds are not for RDD itself but would facilitate market growth.

Tax incentives for CCUS

The federal government offers several incentives for the deployment of CCUS equipment beginning construction before 2026, including for use in enhanced oil recovery (EOR). The most prominent of these is known as "45Q," which was recently expanded and raised in value after the signing of the IRA. For equipment entering service before February 9, 2018, the credit is worth $23.82 (in 2020 dollars) per metric ton (mt) of stored CO_2 and $11.91/mt for CO_2 used for EOR purposes. For equipment entering service later, the credit increases by 2026 to $50/mt and $35/mt for non-EOR and EOR uses, respectively. Other qualified uses of CO_2 are also eligible for the EOR rate (Jones and Sherlock 2021). The IRA increased these tax incentives to up to $85/ton CO_2 captured and stored.

The DOE Loan Program Office offers loan guarantees to deploy eligible CCUS projects, along with other projects that utilize fossil fuels but significantly reduce emissions of greenhouse gases or other pollutants (DOE Loan Program Office 2021a). The IRA recently allocated $11.7 billion to support activities by the Loan Programs Office. In addition, the U.S. Department of Agriculture's Rural Utilities Service could potentially be a future source of funding or low-cost lending for IOUs, co-ops, and Native nations seeking to deploy CCUS projects, although we could not find examples of tribes participating in this program[8].

At the state level, relatively few financial incentives currently exist to speed deployment of CCUS, with the exception of incentives for EOR deployment, which we discuss in the following section.

[8] See https://www.hoeven.senate.gov/news/news-releases/hoeven-carbon-capture-is-coal-creeks-next-chapter

Table 2. State tax incentives for CCUS deployment (excluding EOR)	
State	**Description**
Arizona	None identified.
Colorado	None identified.
Montana	For state and local property tax purposes, CO_2 pipelines are assessed at a lower rate than other pipelines; CO_2 storage equipment is assessed at the same reduced rate as "conventional" pollution control equipment.
New Mexico	Provides a tax incentive for gasification and CCS equipment at integrated gasification (e.g., coal gasification) combined cycle power plants. The value of the credit may increase if the employer adds new workers.
Utah	None identified.
Wyoming	None identified.

Sources: Montana Department of Revenue (2021), New Mexico Statutes Annotated § 7-9J.

For some states, CCUS equipment may become eligible for certain tax incentives if new laws or regulations come into effect at the state or federal level in the months and years ahead. For example, Arizona offers an income tax credit for pollution control equipment, but only for equipment that is used to comply with federal or state regulations specific to that pollutant (see Arizona revised statutes §43-1081; https://www.azleg.gov/viewdocument/?docName=https://www.azleg.gov/ars/43/01081.htm). It is possible that CO_2 would be considered a "pollutant" for these purposes, making CCUS property eligible for the tax credit.

Tax incentives for EOR

The federal government provides two tax incentives to encourage the deployment of enhanced oil recovery (EOR), which is a form of tertiary oil recovery. The most significant of these policies is the 45Q tax credit described above. The second is a tax credit (26 USC §43) eligible to operators using EOR when the price of crude oil falls below a certain threshold, which in 2020 was roughly $50 per barrel (Sherlock, 2021).

Many state governments also offer tax incentives for EOR and other tertiary recovery technologies. Table 3 summarizes those policies.

Table 3. State tax incentives for EOR	
State	**Description**
Arizona	None identified
Colorado	None identified
Montana	Montana's severance tax structure is complex, but in general, Incremental oil and natural gas produced using EOR is taxed at a lower rate than primary and secondary production.
New Mexico	Incremental oil production using EOR is taxed at a lower rate when benchmark national crude oil prices fall below a certain threshold ($28/barrel).
Utah	Incremental oil production from enhanced recovery is taxed at half of the standard severance tax rate.
Wyoming	Sales of CO_2 used for EOR are exempt from state sales tax. Severance taxes paid on CO_2 production that is subsequently used for EOR are credited against severance taxes on oil produced using that CO_2.

Sources: Montana §15-36-304; New Mexico §7-29A; Utah §59-5-102(9); Wyoming §39-16-105(a)(viii)(A), §39-16-105(a)(viii)(F), §39-14-205(d).

Class VI primacy

Montana and Wyoming are the only states in the I-WEST assessment to have applied to the U.S. EPA for class VI well primacy, with Wyoming receiving it in 2020. Having Class VI well primacy means that the Wyoming state government, rather than the U.S. EPA, has the authority to regulate and enforce activities associated with wells used for CO_2 storage.

Pore space

Pore space, which is the part of soil where air or water can flow through, is a geological feature of land that is relevant for carbon storage. Ownership of the pore space is therefore an important consideration for the region.

Generally, U.S. property rights hold that the person who owns the surface land has ownership of the space below, although the owner could choose to sell those rights to another entity. This being said, state legislatures, particularly those with CCS development, are starting to establish more explicit ownership criteria for the pore space. In Montana and Wyoming, the pore space is defined as private property, and is owned by the surface owner. In Wyoming, the surface owner can split the surface estate from the pore space, although they are bundled together by default[9].

[9] Pore Space Ownership and Use in the Carbon Capture Industry | Newburn Law, P.C., https://s3-us-west-2.amazonaws.com/dgslaw/uploads/Wyoming-Statute-Pore-Space.pdf?mtime=20210720141256&focal=none https://leg.mt.gov/bills/mca/title_0820/chapter_0110/part_0010/section_0800/0820-0110-0010-0800.html

Unitization

Unitization refers to state-level rules that assemble multiple tracts of the subsurface into a drillable area to maximize recovery of oil and gas resources. In Montana's unitization statute, unitization can proceed upon a hearing which must be petitioned by 60% of the affected leaseholders with "just and reasonable" terms[10]. In Montana, 70% of the parties paying costs to unitization must approve for unitization to proceed. In Wyoming, those who own at least 80% of the pore space must sign a unitization plan for it to become effective[11].

State liability transfer

Liability transfer refers to which party will be responsible for CO_2 leakage from storage sites for the indefinite future. Montana's 2009 law[12] potentially provides a completion certificate 25 years after CO_2 injection ends, at which point, the storage operator's liability is reduced. However, even after obtaining a certificate of completion, storage operators in Montana are required to provide bonding or some other surety for an additional 25 years as an off-ramp to liability. Wyoming's recent law[13] addressing CCS liability allows storage operators to apply for a certificate of completion 20 years after CO_2 injection has ceased. If granted, this certificate transfers liability for leakage back to the state.

Policies supporting direct air capture

Direct Air Capture (DAC) of CO_2 currently faces high up-front costs, but offers immense potential for long-term benefits, making policies that encourage its deployment important. Currently, most policy levers for DAC are at the federal level, including the 45Q tax credit which was expanded to include DAC projects in 2018 and raised much more in the IRA. Although the original tax credit was designed for point-source carbon capture, which is a more mature technology than DAC, which captures CO_2 from ambient air, the new higher tax credit is expected to stimulate DAC projects.

In addition to expansions of the 45Q credit, some researchers have argued that deployment mandates or incentives could be an effective path forward for DAC deployment (A policy roadmap for negative emissions using direct air capture (https://www.nature.com/articles/s41467-021-22347-1.pdf)). One example of a deployment incentive that supports DAC is the CA Low Carbon Fuel

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[10] Montana Code Ann. § 82-11-201
[11] WY Stat § 35-11-316 (2018)
[12] 82-11-183. Certificate of completion -- department of environmental quality participation -- transfer of liability, MCA (mt.gov)
[13] Bill Detail (wyoleg.gov)

Standard (LCFS), which has included credits for DAC since 2018. If the Intermountain West states move forward with a LCFS, including DAC in the credit system could bolster deployment.

Research, development, and demonstration funding

R&D expenditures

According to the 2021 *Survey of State Government Research and Development* conducted by the National Science Foundation (NSF), the Intermountain West states have drastically different research and development expenditures in the areas of energy, environment, and natural resources[14]. The survey measures the amount of R&D activity that was performed and funded by state governments. Colorado funds the largest amount of R&D in energy at $3.4 million, plus $11.6 million in environment and natural resources R&D throughout FY2020. Montana and Utah also spend a relatively high amount on environment and natural resources R&D, with $7.8 million and $5.6 million, respectively, in FY2020. Wyoming is the only other state in the region other than Colorado to put more than $1 million into energy funding, with $1.7 million allocated in FY2020.

Table 4. State R&D expenditures in FY2020

(Thousand $)	Arizona	Colorado	Montana	New Mexico	Utah	Wyoming
Energy	$0	$3,400	$0	$200	$500	$1,700
Environment and natural resources	$1,800	$11,600	$7,800	$2,100	$5,600	$2,000

Source: National Center for Science and Engineering Statistics, 2021, Survey of State Government Research and Development, FY 2020.

Infrastructure Investment and Jobs Act

In 2021, the Infrastructure Investment and Jobs Act (IIJA) was signed into law sending $1.2 trillion of public investment to upgrade roads, bridges, electric grids, and much more between 2022 and 2026. Of most relevance here, the package reserves $31 billion for RDD in clean energy technologies, mostly to be administered as competitive grants by DOE. The funds cover RDD in green hydrogen and carbon capture, advanced batteries, advanced nuclear, and DAC technologies. The IIJA also creates the DOE Office of Clean Energy Demonstrations (OCED) to be in charge of the management of demonstration projects. OCED will conduct project management and oversight of all the demonstration projects noted above and more, representing $22 billion of investment in demonstration projects. This federal landmark bill creates a wealth of clean energy development

[14] https://www.nsf.gov/statistics/srvystaterd/#tabs-1

opportunities for the Intermountain West region. The IRA put much more money into decarbonization innovation. Interested readers should consult sources cited in the introduction for details.

Carbon capture, utilization, and storage

A key piece of the IIJA focuses on CCUS technologies. First, the IIJA expands several DOE programs with $300 million targeted to the Carbon Utilization program to include the development of standards and certifications to support commercialization of carbon oxide products. Along with the standardization of carbon oxide products, this program also awards grants to local authorities to use or procure products derived from carbon capture oxides. By focusing on the commercialization of carbon capture outputs, this piece of the legislation can be understood as a demand-pull instrument (i.e., helping to create market demand).

The IIJA allocates $2.5 billion to create a commercialization program for the development of large-scale carbon sequestration projects and associated transport infrastructure. The funding covers the feasibility, site characterization, permitting, and construction stages of project development and is to be overseen by the DOE's Fossil Energy and Carbon Management program. The Secretary then selects applications at any stage of a project's development on a competitive basis (but the DOE has not yet specified the form of the funding).

Finally, the IIJA grants $3.5 billion for carbon capture demonstration and pilot programs administered through OCED. Along with funding for CCUS, the IIJA also provides $2.1 billion for the Carbon Dioxide Transportation Infrastructure Finance and Innovation Program in the forms of secured loans, in consultation with the DOE Loan Programs Office, and grants.

Direct air capture

The IIJA establishes the Carbon Removal program and provides it with $3.5 billion for the period of 2022- 2026. This program is to be administered through grants, cooperative agreements or contracts for projects that contribute to the development of four regional DAC hubs. Projects will be selected based on geographic diversity, scalability, jobs, cost, and other considerations to advance carbon dioxide removal.

The legislation also appropriates new funding for DAC Technology Prize Competitions. DOE is allocated $100 million for commercial technologies and $15 million for pre-commercial technologies for the year 2022. The goal of these competitions is to promote innovative and diverse approaches to DAC.

Green hydrogen

Funding for green hydrogen (a method for producing decarbonized hydrogen by splitting water using renewable or nuclear power) constitutes another key part of the IIJA with $9.5 billion for different programs in the sector. The bill expands the scope of the DOE's hydrogen R&D program, focusing on the demonstration and commercialization of clean hydrogen production, processing, delivery, and end-use application technologies. Additionally, the bill establishes four new RDD programs including: (1) four or more regional clean hydrogen hubs (this element receives the bulk of the funding at $8 billion), (2) development of a national strategy and roadmap to facilitate a clean hydrogen economy, (3) a clean hydrogen manufacturing and recycling program, and (4) a demonstration, commercialization, and deployment program to decrease the cost of clean hydrogen production from electrolyzers. Eligible entities will receive grants on a competitive basis from the DOE. The IRA includes a major tax credit program for "clean" hydrogen production.

Energy storage

A total of $10 million is allocated to demonstration projects for energy storage of intermittent renewable electricity. Two other energy storage programs, namely the (1) Energy Storage Demonstration Projects and Pilot Grant Program and (2) Long-Duration Demonstration Initiative and Joint Program, are receiving $355 million and $150 million of funding respectively. The IRA also addresses energy storage.

Advanced nuclear

The Advanced Reactor Demonstration Program, which facilitates industrial demonstration partnerships of advanced nuclear reactors, receives $3 billion for the period 2022-2026.

Batteries

One section of the bill focuses on battery manufacturing. It establishes the Battery Material Processing Grant and the Battery Manufacturing and Recycling Grant Programs to be overseen by the DOE's Office of Fossil Energy. Both grant programs are each allocated $3 billion over the next five years. Other RDD grant programs also receive $125 million to develop the battery recycling value chain. In addition, the IIJA supports the DOE's ongoing Lithium-ion Battery Recycling Prize with an additional $10 million to carry out a third phase of the program. These programs are open to both private and public entities. Both battery grant programs are expected to prioritize entities that represent consortia or industry partnerships. The development of these new energy technologies is highly relevant to the transition towards a cleaner and more flexible energy grid, which will directly impact the carbon emissions embodied in cement and steel manufactured in the U.S. and in other hard to abate sectors.

Pumped storage

The Long Duration Energy Storage for Everyone, Everywhere Initiative is being administered by OCED to support energy storage demonstration, validation, and piloting with $505 million in competitive grants funded in the IIJA[15].

Demonstrations and pilot projects

The IIJA allocated $21 billion to OCED for energy transition demonstration and pilot programs. This includes, as partly noted above, $10 billion for carbon capture and DAC, $8 billion for clean hydrogen, $3.5 million in grants for large carbon capture pilots and demonstrations, $1 billion for rural and remote energy demonstrations, and $500 million for the transition of mining lands to clean energy[16].

Grid

The IIJA provides $5 billion from FY22-26 towards the demonstration of transmission, storage, and distribution infrastructure innovations that improve regional grid resilience.

Bioenergy

The DOE's Bioenergy Technologies Office (BETO) began the AlgaePrize competition in January 2022 to spur research into lower cost algal biofuels production[17].

Loan guarantees

The DOE Loan Programs Office currently administers two relevant loan guarantee programs to RDD in the Intermountain West region: the Title 17 Innovative Clean Energy Loan Guarantee Program and the Tribal Energy Loan Guarantee Program, both of which were authorized by the 2005 Energy Policy Act.

[15] https://www.energy.gov/articles/biden-administration-launches-bipartisan-infrastructure-laws-505-million-initiative-boost
[16] https://www.energy.gov/sites/default/files/2021-12/FECM%20Infrastructure%20Factsheet.pdf
[17] https://www.energy.gov/eere/bioenergy/algaeprize-competition

The Title 17 Loan Guarantee Program intends to bridge the funding gap between pilot projects and wide-scale commercialization by investing in early-stage deployment, a stage where energy projects tend to lose the support of investors. The initial commercial deployment of energy technology can be limited by the uncertainty between pilots/demonstrations, and large-scale commercialization, which often impacts a project developer's ability to secure long-term debt financing to build out the project. Figure 1 illustrates the struggles of this timeline and clarifies the role of the Title 17 program.

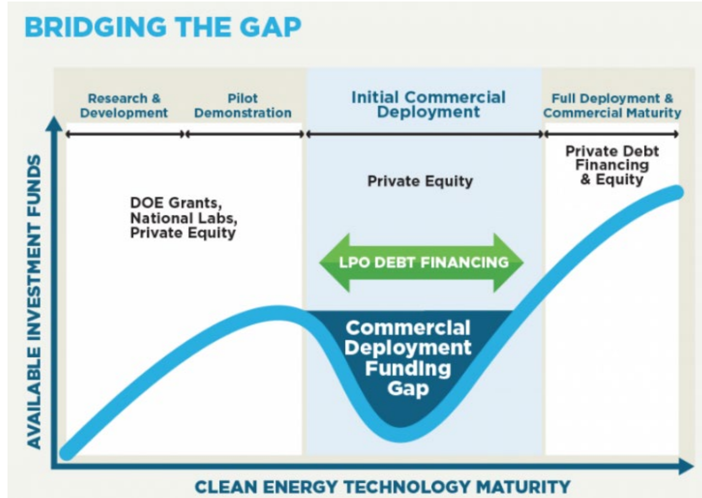

Figure 1: DOE Loan Programs Office Schematic
Image: Source, DOE. TITLE XVII | Department of Energy (https://www.energy.gov/lpo/title-xvii)

Title 17 has provided more than $25 billion in loan guarantees to a broad portfolio of projects including four in the Intermountain West region (Agua Caliente Solar Project in Arizona, Alamosa Solar Project in Colorado, Mesquite 1 Solar Project in Arizona, and Solana Solar Project in Arizona). Title 17 is an opportunity for all-of-the-above clean energy deployment from solar to energy efficiency projects, to advanced fossil fuels. The evidence on the program's cost-effectiveness, however, is quite limited (http://www.sciencedirect.com/science/article/pii/S0140988319300751).

The Tribal Energy Loan Guarantee Program is a partial loan guarantee program that can secure up to $2 billion in loans to support economic opportunities for Native nations through energy development. In this program, DOE can guarantee up to 90% of the unpaid principal and interest on any loan made to a federally recognized tribal corporation for energy development. Different from the Title 17 program which focuses on clean energy development, the Tribal Energy Loan Guarantee Program can be used to support nearly any energy development including fossil production and mining. The goal of the program is to improve tribal access to capital, flexible custom financing, and project expertise. However, we are not aware of any loans that have been issued to date through this program.

Distinct issues

Because of their sovereign status, and because of their trustee relationship with the U.S. federal government, tribes have a distinct set of opportunities and challenges in the energy transition, with wide variation across tribes in the Intermountain West. Some tribes have a long history of energy development. Many other tribes in the region have little or no history of energy development.

This section discusses several issues of importance for Native nations in the region. However, it is not intended to be comprehensive, and significant research gaps remain in understanding how policies can support tribes in the energy transition.

Energy governance

Energy has played a substantial role in economic development for a substantial number of Native nations in the Intermountain West. Historically, this development has primarily consisted of mining for coal, uranium, oil, and natural gas; and in a small number of cases, electric power generation. Oil and gas development is the most common energy production activity across regional tribes, with at least 200 wells drilled since 1950 on eight reservations: Blackfeet, Crow, Fort Peck, Jicarilla-Apache, Navajo, Southern Ute, Uintah and Ouray Ute, and Wind River. Figure 2 illustrates the number of oil and gas wells drilled on each reservation from 1950 through 2020 (note that these data exclude off-reservation Trust lands).

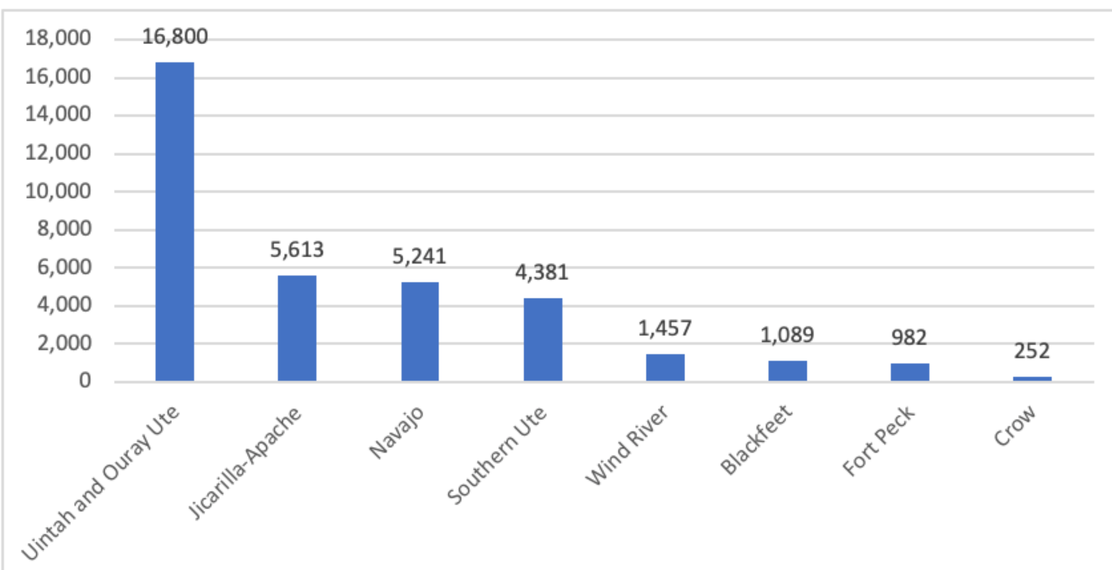

Figure 2: Oil and gas wells drilled on reservations in the Intermountain West between 1950 and 2020. Data source: Enverus.

Multiple factors have led to a complex relationship between the federal government and regional tribes regarding natural resource governance (Smith and Frehner, 2010; Office of Inspector General, U.S. Department of Interior, 2017).

The complexity of arranging intra- and inter-governmental coordination between Native nations and multiple federal agencies responsible for fulfilling trust obligations has created challenges. For example, policies related to natural resource development often require close coordination between tribal authorities and multiple federal agencies within the Department of Interior (DOI), including the Bureau of Indian Affairs (BIA), Bureau of Land Management (BLM), Office of Natural Resource Revenue (ONRR), Office of Surface Mining Reclamation and Enforcement (OSMRE), and others (Grogan et al., 2011). This complex regulatory environment has been cited as a factor that impedes economic development more broadly across Native nations (e.g., Akee and Jorgensen, 2014).

In essence, any major energy activity (e.g., signing an oil and gas lease, siting electricity transmission lines) on tribal lands needs to be approved directly by the Secretary of the Department of Interior. Recognizing this challenge, Congress enacted the Indian Tribal Energy Development and Self-Determination Act of 2005, which established Tribal Energy Resource Agreements (TERAs). TERAs established a process through which tribes take administrative and regulatory control over energy projects and enter into leases and business agreements with operators. However, a 2015 GAO report found that tribes were unable to take advantage of TERAs due to "uncertainty regarding the regulations, a complex application process, and concerns regarding the costs to tribes of assuming federal functions," and no tribe completed a TERA until March 2022, when a related agreement between the DOI and the Red Lake Band of Chippewa Indians (northern Minnesota) established the first Tribal Energy Development Organization (BIA, 2022).

The DOI has made efforts to streamline the bureaucratic hurdles to energy development by, for example, establishing "one-stop shops" that house regional offices for multiple federal agencies. However, these efforts have not prevented slow processing times and mismanagement in some cases (Grogan et al., 2011; Office of Inspector General, US Department of Interior, 2017).

In addition to coordination challenges, tribal energy development may be impeded by inadequate consultation with tribes on specific energy projects. For example, Susskind et al. (2022) describe three cases in California where tribes opposed renewable energy development due, in part, to inadequate consultation and engagement with BLM and state/local officials. In all three cases, projects did not go forward in part because of this opposition. The Biden Administration has laid out detailed guidance to agencies with the goal of improving coordination, consultation, and integration of treaty rights into federal policymaking (US Department of Interior, 2021), though the effects of such efforts remain to be seen.

Congress has taken other measures that have sought to better recognize the sovereignty of Native nations (Grogan et al., 2011), and recent Executive branch regulations on leasing and right-of-way issues have done the same (Mills, 2021). The U.S. Department of Energy operates numerous programs designed to support tribal energy development through capacity building and direct financial support for projects, which can help Native nations identify promising opportunities for future clean energy development, reduce the burdens of high energy costs, and increase access to modern energy services (Office of Indian Energy Policy and Programs, 2022).

Some tribes, such as the Southern Ute Indian Tribe, are partnering with private sector investors to deploy novel technologies that utilize the Tribes' natural gas resources for zero-carbon power generation (Southern Ute Growth Fund and 8 Rivers Capital, 2021). For other tribes, such as the Navajo, shuttering of coal mines and coal-fired power stations have created substantial economic challenges that will require attention from policymakers (AP, 2021).

Environmental justice and remediation

Energy development for some Native nations in the region has resulted in long-term public health and pollution problems. These include, for example, increased mortality rates for Navajo uranium miners (Roscoe et al., 1995); groundwater pollution on the Navajo reservation associated with poorly regulated uranium mining (Hoover et al., 2017); and a large oilfield wastewater plume on the Fort Peck Reservation (Thamke and Smith, 2014).

Reservations also host legacy fossil energy infrastructure. For example, reservations in the region are home to more than 1,600 abandoned mines, although remediation at most of these sites has been completed as of late 2021 (OSMRE, 2021). Orphaned oil and gas wells can also be found on reservations, though data are quite limited. Numerous recent analyses have demonstrated that federal regulations do not adequately protect against the risk that oil and gas wells on federal and tribal lands could become "orphaned," posing environmental risk for host communities and financial risk for taxpayers (GAO, 2019; Raimi et al., 2021).

A recent analysis of data from oilfield data provider Enverus identified a considerable number of oil and gas wells on reservations in the region that could become orphaned in the years and decades ahead. Although reporting classifications vary across jurisdictions, the wells of most concern are those listed as "inactive," "shut-in," or "temporarily abandoned," as these wells may never again produce economic quantities of oil or natural gas. Wells listed as "active" were producing at the time data were gathered (December, 2021), but may also be subject to becoming orphaned wells depending on economic conditions and relevant federal and/or tribal regulations. “Plugged and abandoned” wells have been decommissioned, but also require monitoring and may need additional remediation depending on the long-term integrity of the plug.

Table 5. Oil and gas wells by status on reservations in Intermountain West states

	Active	Plugged and abandoned	Inactive	Shut-in	Temporarily abandoned
Blackfeet	350	1,154	251	354	36
Crow	38	203	66	12	2
Fort Peck	84	683	141	62	22
Jicarilla-Apache	2,576	1,744	3,787	5	45
Navajo	567	2,608	1,327	136	30
Southern Ute	3,458	252	51	30	46
Uintah-Ouray	8,991	874	1,757	317	1,101
Wind River	435	57	1	141	85

Data source: Enverus. Data gathered December, 2021. Excludes off-reservation trust lands.

Some Native nations have developed novel policy approaches to deal with the risks posed by some of this infrastructure. For example, the Jicarilla-Apache tribe has adopted a policy that requires operators to decommission wells unless they can prove, to the satisfaction of the Tribe’s oil and gas regulator, that the well is economically viable, and prohibits wells from being temporarily abandoned for more than 30 days (Jicarilla Apache Nation Code Title 18, Chapter 10, §1(A)(1)).

Clean energy deployment

On reservation lands, federal (and state) tax incentives for renewable energy development have not always been accessible because tribes and tribal corporations are not subject to federal income taxes, though tribal members and associated property may be subject to state and local taxes, such as states sales tax for transactions occurring on reservations (Zimmerman and Reames, 2021). A detailed examination of federal and state tax policy for tribes, tribal corporations, tribal members, and associated property is beyond the scope of this analysis. Nonetheless, tribally-owned corporations or other entities with limited or zero tax liability have not been able to take advantage of federal tax credits, or relevant state tax credits that we discuss below (assuming the tax credit was non-transferrable and non-refundable). This has been a significant issue, particularly with regard to federal energy policies, because the most substantial federal energy policies (by spending levels) are subsidies implemented through the tax code such as the PTC, ITC, 45Q carbon capture tax credit, 48C manufacturing tax credit, and others.

A significant change in this policy was included in the Inflation Reduction Act of 2022, which makes Native nations and other entities that do not pay federal income taxes eligible to receive energy-related tax credits through so-called "direct pay." Although it is difficult to estimate the precise effect of this policy change, it clearly improves the economics of many energy projects that may be contemplated by Native nations in the region.

Permitting

Transmission lines

Transmission lines are mostly regulated by each state's public utility commission. Table 6 shows each state's relevant agency and permit required to site a transmission line.

Table 6. State permitting authorities

State	Office of interest	Permit needed
Arizona	Arizona Corporation Commission	Certificate of Environmental Compatibility
Colorado	Colorado Public Utilities Commission	Certificate
Montana	Montana Department of Environmental Quality	Certificate of Compliance
New Mexico	New Mexico Public Regulation Commission	Location Permit
Utah	Utah Public Service Commission	Land Use Permit
Wyoming	Wyoming Industrial Siting Council	Industrial Development Information and Siting Act Permit

Of these policies, the most unique is Arizona's Certificate of Environmental Compatibility (CEC). To obtain a CEC, a project must demonstrate that it will balance the broad public interest: the need for an adequate, economical, and reliable supply of electric power against the desire to minimize any negative effects on the environment and economy. CEC applications are evaluated by the Arizona Power Plant and Transmission Line Siting Committee by multi-day hearing.

Another unique feature among these policies is that, in Montana, the certification authority resides within the department of environmental quality rather than a corporation commission, perhaps indicating additional weight given to environmental considerations for transmission line siting.

Industrial permitting (New Source Review, NSR)

The Clean Air Act requires that new plants and major modifications of industrial (and power) plants enter the Clean Air Act's New Source Review process, which can be an onerous regulatory process (particularly if the plant is located in an area violating air quality standards). This requirement creates disincentives for plants to invest in modifications that reduce their CO_2 emissions like the construction of carbon capture facilities at power and industrial plants. Adding on those decarbonizing modifications would subject the entire plant to NSR review and possible updating of its emissions control technologies.

Permitting on federal land

Major new facilities on federal lands, developed with federal funding, or subject to federal permitting would be subject to environmental reviews under the National Environmental Policy Act (NEPA). Numerous reforms of NEPA have been implemented to increase its protections and streamline the approval process. In particular, the IIJA contains substantive provisions designed to streamline NEPA environmental reviews for “major projects,” such as those funded by IIJA and those funded under the Fixing America’s Surface Transportation (FAST) Act of 2015. The Council on Environmental Quality (CEQ), which writes NEPA guidance, called for expedited reviews to CO_2 reducing investments, such as CCUS. Outside of the NEPA process, CEQ also called for expediting CO_2 pipeline expansion.

Renewables

For wind energy facilities, the siting and permitting protocols are highly localized and varied across states. Most states in the region take a hybrid approach, requiring state level permits above a certain generation threshold in addition to relevant local permits. Tables 7 and 8 detail the state permits that might be required beyond any local approvals.

Table 7. Wind energy permitting by state		
State	**Authority level**	**Detail**
Arizona	Hybrid State/Local	Arizona siting procedure states that certain wind facilities must obtain siting and zoning approvals at the municipal or county level in addition to obtaining a state Certificate of Environmental Compatibility prior to construction if it generates more than 100 MW.
Colorado	Hybrid State/Local	Local authorities have 120 days to issue a final decision on siting applications for wind energy. Additionally, the public utilities commission must issue a certificate prior to construction.
Montana	Local	There is no state level siting authority for wind energy. Local governments control zoning and land use decisions.
New Mexico	Hybrid State/Local	Local governments regulate wind siting through zoning and land use regulations. Projects generating over 300 MW must be reviewed by the state Public Regulation Commission.
Utah	Local	There is no state level siting authority for wind energy. Local governments control zoning and land use decisions.
Wyoming	Hybrid State/Local	State law requires projects to secure local approval for any energy facility greater than 500kW. Large wind facilities (more than 19 turbines) must obtain a permit from the state industrial siting council.

Source: NCSL State Approaches to Wind Energy Siting, 2020

Table 8. Solar energy permitting by state		
State	**Authority level**	**Siting/permitting details**
Arizona	Local	Permits are distributed at the local level by counties and municipalities. Municipalities and counties are not allowed to require a stamp from a professional engineer unless deemed necessary.
Colorado	Hybrid State/Local	Permits are distributed at the local level by counties and municipalities. There is a statewide cap for permit fees for solar energy.
Montana	Hybrid State/Local	State and local governments are involved in permitting solar.
New Mexico	Local	Permits are distributed at the local level by counties and municipalities. In some cases, a structural analysis from a licensed engineer is required.
Utah	Local	Permits are distributed at the local level by counties and municipalities.
Wyoming	Hybrid State/Local	State and local governments are involved in permitting solar.

Source: DSIRE

Pipeline siting regulations and permitting

CO_2 pipelines

Oversight of CO_2 pipelines has been rejected by Federal Energy Regulatory Commission (FERC), and the U.S. Government Accountability Office has determined that oversight lies under the DOT's Surface Transportation Board (STB). Although STB is responsible for oversight, this power is often delegated to the states. Because of this, CO_2 pipelines are largely overseen by state authorities except for a few scenarios: the pipeline crosses state lines (interstate) or the pipeline crosses federal land. Further, siting CO_2 pipelines has no federal siting authority requirements, and federal agencies have no power of eminent domain for CO_2 pipelines unless on federal land. Thus, while pathways for federal siting authority through the NEPA, ESA, and other federal acts have been explored (Righetti, 2017), authority still falls mainly to state commissions. Although many states have yet to explicitly address the process for siting, there are some policies in place. In New Mexico, for example, any person, firm, or corporation can exercise eminent domain to secure siting for the right of way of a pipeline on both public and private land. This is regulated through the NM Public Regulation Commission Pipeline Safety Bureau and stands out for addressing CO_2 pipelines explicitly[18].

Hydrogen pipelines

In contrast with CO_2, hydrogen can be transported either in blends or exclusively through upgraded existing natural gas pipeline infrastructure. Although there are some technical and safety concerns with blending hydrogen into existing pipelines (and more for repurposing natural gas pipelines for exclusive hydrogen use), the potential for a right-of-way to be already established cuts the siting and permitting time.

Like CO_2 pipelines, there is no federal siting authority for intrastate pipelines to carry hydrogen, and developers must seek approval from the relevant state agencies.

Conversion of oil and gas pipelines to CO_2 or hydrogen pipelines

Converting an existing natural gas or oil pipeline to CO_2 gas service would likely face a number of economic, technical, and safety challenges. For example, CO_2 transport requires high pressure and very low temperatures to be economical, so existing pipelines would need to be retrofitted with "crack arrestors." It also requires many more pumping stations along the route compared with a

[18] See Nordhaus and Pitlick, Energy Law Journal, 2009 for additional specifications

new pipeline built for CO_2 service. Even if an existing pipeline was located, the large number of pumping stations required might not be operationally practical for conversion of a long-distance pipeline.

Currently, the FERC can decide if a natural gas pipeline may be withdrawn from use for shipping natural gas, but once FERC grants a withdrawal from service, its jurisdiction ends, because it has no jurisdiction over carbon pipelines. In contrast, no federal agency regulates whether an oil pipeline may be withdrawn from service.

The U.S. Pipeline and Hazardous Materials Safety Administration (PHMSA) regulates the safety of natural gas, oil and supercritical fluid CO_2 pipelines, but does not regulate the safety of a pipeline when CO_2 (carbon) is pumped through it as a gas, when pipeline pressure is low. Congress directed that PHMSA regulate CO_2 gas pipelines, but PHMSA has failed to issue safety standards for these pipelines. It is likely that state and local governments could not step into this gap to regulate CO_2 gas pipeline safety. Therefore, if a natural gas or oil pipeline is converted to ship CO_2 as a gas, it might not be subject to any federal or state pipeline safety standards. To our knowledge, no state policy, regulation, or safety standard exists on repurposing oil and gas pipelines to transport CO_2.

There are also issues in the conversion of natural gas pipelines to transport hydrogen. The nation's vast natural gas pipeline system could serve as a cost-effective means of shipping hydrogen among a network of regional hydrogen hubs under development. However, the quantities, location, and timing of blended or pure hydrogen that will be needed, have not been assessed and "the dynamics of increasing hydrogen production, transport, and storage as part of future decarbonization efforts are still unclear"[19].

The conversion of natural gas pipelines to carry hydrogen faces a couple of regulatory uncertainties. One example is FERC's regulation of gas quality for blended methane and hydrogen carried in natural gas transmission pipelines during a hydrogen transition. How, and to what extent, FERC could or should establish new hydrogen policies for interstate pipelines under its existing NGA authority, or whether additional legislative authority or direction would be required, may be questions for Congress. Similar concerns about gas quality standards exist among the states with respect to intrastate transmission pipelines and natural gas distribution systems (CRS, 2021). Another example is DOT PHMSA's regulation of hydrogen pipeline safety. The existing pipeline regulations are focused primarily on natural gas, so they may not be adequate to address the

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[19] https://crsreports.congress.gov/product/pdf/R/R46700

potential embrittlement and leakage risks associated with hydrogen transport. Whether PHMSA should develop more hydrogen-specific pipeline safety regulations, and what such regulations could entail, may be an issue for Congress (CRS, 2021).

Hub promotion

Most industrial and energy processes and the transport of energy and CO_2 benefit from scale economies – the bigger the cheaper. They also benefit from network externalities – the co-locating of complementary producing, supplying, using and transporting activities, and, in the case of CO_2, storage opportunities. Such co-location can stimulate innovation, attract top talent, and save distribution costs. Thus, to bring costs of the transition down and to encourage innovation, governments around the world are becoming interested in providing incentives for this agglomeration of economic activity. Specifically, at least four regional clean hydrogen hubs will be funded ($8 billion) with additional funding of four regional direct air capture (DAC) hubs ($3.5 billion). The latter are designated as hubs because they need to have their captured CO_2 stored or otherwise utilized. Projects will be selected based on geographic diversity, scalability, jobs, cost and other considerations to advance just and sustainable carbon dioxide reductions. Unlike DAC, a successful CCUS project needs an industrial or utility source of CO_2. $2.5 billion is allocated to the creation of a commercialization program for the development of large-scale carbon sequestration projects and associated transport infrastructure, plus $3.5 billion for two carbon capture demonstration and pilot programs and $2.1 billion for the Carbon Dioxide Transportation Infrastructure Finance and Innovation Program.

Electricity sector policies

Renewable Portfolio Standards (RPS) Policies

The Intermountain West states take a wide range of approaches to policies that encourage the deployment of low- and zero-emission electricity technologies. Along with variation in the fiscal policies described in the following sections, some states also deploy technology standards known as Renewable Portfolio Standards (RPS), which require in-state utilities to generate a certain proportion of their power using renewable sources such as wind and solar (Table 9). These generate credits known as renewable energy certificates, which are typically tradable.

Table 9. Renewable portfolio standards		
State	**Target**	**Applies to**
Arizona	15% renewables by 2025	Investor-owned utilities (IOUs)
Colorado	100% zero-carbon by 2050	IOUs, municipal electrics (Munis), cooperative utilities (Co-ops)
Montana	15% renewables by 2015	IOUs
New Mexico	80% renewables by 2040 100% zero-carbon by 2045	IOUs, Co-ops
Utah	20% renewables goal* by 2025	IOUs, Munis, Co-ops
Wyoming	None	n/a

*Utah's policy is not a binding target. Source: DSIRE.

Along with these standards, states may offer financial incentives that affect the deployment of clean electricity technologies, including taxes and subsidies. Technology-specific subsidies, such as tax incentives for wind or solar, will tend to speed deployment of these technologies but also limit the ability of governments to raise revenue for public services (notably, in states with binding RPS policies, it is unclear whether such subsidies would truly incentivize new construction or simply reduce costs for project developers). Conversely, technology-specific taxes will tend to inhibit deployment but have the benefit of raising new revenue to support government services.

Alongside these state policies, federal fiscal policy also shapes investment decisions, and in some cases overlaps with state policies. The following section provides an overview of major federal fiscal policies, then compares fiscal policies for each state with regards to electricity generation, transmission, distribution, storage, and consumption.

Tax incentives for renewable electricity generation

At the federal level, renewables are eligible for a variety of policies that reduce tax liability. These have been led by the renewable electricity production tax credit (PTC), which has primarily benefited wind energy; and the energy investment tax credit (ITC) which has primarily benefited solar. Other major provisions include income tax credits for holders of clean renewable energy bonds (CREBS), and accelerated depreciation provisions (Newell et al., 2019; Sherlock, 2021). The DOE Loan Program Office (LPO) also offers loan guarantees for qualifying innovative renewable electricity projects (DOE Loan Program Office, 2021).

At the state level, a variety of additional policies affect tax liability for renewable energy (RE) development, which typically incorporates wind, solar, geothermal, and biomass-based technologies (Table 10). These credits may be offered to offset property, sales, income, or other tax liability.

Table 10. Tax incentives available for renewable electricity generation and manufacturing by state	
State	**Description**
Arizona	-25% personal income tax credit for residential solar/wind, up to $1,000. -100% state sales tax exemption for sales of solar equipment and installation for residential/commercial. May be subject to local sales taxes. -Up to $5 million corporate/personal income tax credit for RE projects with on-site consumption used in manufacturing. Minimum 20MW system. -Property tax incentive worth 80 percent of the original value of RE equipment. On-site generation is fully exempt.
Colorado	-RE equipment is exempt from state sales/use tax. May be subject to local sales taxes. -Residential RE (<2MW) is fully exempt from property taxes -Property tax valuation of facilities greater than 2 MW are capped at the valuation for a non-renewable plant of the same generating capacity. Local governments may offer additional incentives. Facilities less than 2 MW are assessed locally. -PACE financing available for commercial RE and EE investments.
Montana	-Residential and commercial RE facilities are eligible for a 100% property tax exemption for 10 years, worth up to $20,000 for single family and $100K for multi-family or nonresidential. -Utility-scale (>1MW) RE facilities are eligible for 10 years of reduced local property tax rates if approved by local government -Small scale (<1MW) RE facilities are eligible for a full exemption from property taxes for 5 years -Property tax abatement of up to 50% for RE manufacturing facilities. -Personal income tax credit worth up to $1,000 per household was available for residential RE, set to expire on 12/31/2021. -Personal or corporate income tax credit of 35% for investments of $5,000 or more in manufacturing RE equipment -Personal income tax credit of up to $1,500 for installation of residential geothermal heat pump or geothermal direct use
New Mexico	-Sales and installation of RE equipment are fully exempt from the state gross receipts tax (the state has no sales tax), up to $60 million. -RE and EV equipment manufacturers are eligible for a gross receipts tax credit of up to 5% of their qualified expenditures -Biomass/biofuels equipment and materials (including feedstock?) are exempt from paying state use taxes -Personal and corporate tax credit available for producers of biomass from a dairy or feedlot used for electricity generation or biofuels production. Worth $5/wet ton, max of $5 million statewide. Expired at the end of 2019. -Local governments are authorized to deploy PACE financing for commercial and residential RE (and energy efficiency) investments. -Residential rooftop solar is fully exempt from local property tax
Utah	-100% sales tax credit for purchases of “alternative” electricity generation equipment. Includes renewables, nuclear, and unconventional fossil resources. Minimum 2MW. -75% corporate tax credit on incremental revenue associated with renewable power generation, minimum 2MW. -Residential and commercial RE systems eligible for income tax credit, but program is phasing down and set to expire at the end of 2021. -PACE financing available for commercial RE and EE investments.
Wyoming	-Local governments are authorized to deploy PACE financing for residential RE and EE investments. -No other incentives identified.

Data sources: DSIRE; Uebelhor et al., 2021. Includes biomass, geothermal, solar, and wind.

Wyoming currently levies an excise tax of $1.00 per megawatt-hour of electricity generated from wind turbines after three years of operation (WY Statutes § 39-22).

Energy storage policy

As states ramp up reliance on intermittent renewables such as solar and wind, large-scale battery storage can help provide load balancing, peaking, or other services.

Federal policies to support energy storage largely focused on support for early-stage research and development. However, the IIJA authorized roughly $500 million to support energy storage demonstration projects through two DOE programs established in 2020 (Section 41001 of DeFazio, 2021).

States have also begun implementing policies, typically through the utility regulation process, to support the deployment and use of energy storage, as described in Table 11.

Table 11. State policies supporting energy storage

State	Policy
Arizona	Arizona Corporation Commission (ACC) directed utility Arizona Public Service to develop a program to use residential sited energy storage for demand response and load management. ACC institutes differential on-peak and off-peak ratcheted rates, incentivizing storage technologies to reduce energy bills. ACC votes to install energy storage with capacity of 5% of peak 2020 demand by 2035.
Colorado	Colorado consumers can install, interconnect, and use energy storage systems on their property without restrictions, regulations, or fees. Colorado Public Utilities Commission requires utilities to include energy storage in their resource planning process. Colorado Public Utilities Commission has been directed to establish mechanisms for utilities to procure energy storage in their resource planning processes.
Montana	Allows storage devices to be a part of net metering.
New Mexico	New Mexico Public Regulation Commission requires utilities to include energy storage in their resource planning.
Utah	Public Service Commission has been authorized to approve an energy storage demonstration project.
Wyoming	No policies identified.

Data source: Pacific Northwest National Laboratory, Energy Storage Policy Database, 2021

Policies such as procurement targets (which exist in Colorado, California, and a few other states) are stronger incentives than other policies noted in the table above. Arizona and Colorado are leading the way with a combined 1,021.5 MW of energy storage installed, according to the Energy Storage Policy Database from Pacific Northwest National Laboratory[20]. This still pales in comparison to California's 4,147 MW system which is supported by a mandate within the state's RPS to install energy storage systems.

Tax incentives for nuclear energy

The federal government has offered a PTC for new nuclear generation in recent years, but no eligible facilities have entered into service to receive the credit to date. In addition, savings for the decommissioning of nuclear plants are subject to special tax treatment (Newell, Pizer, and Raimi, 2019; Sherlock 2021). The Department of Energy's Loan Program Office has supported nuclear projects in previous years, and currently offers $10.9 billion in authority for loan guarantees for innovative nuclear projects (DOE Loan Program Office 2021a).

The IIJA provided some additional federal policy support for nuclear, including a provision to support the production of hydrogen from nuclear facilities (Section 40314 of DeFazio, 2021); financing and technical assistance for deployment of new nuclear technologies (Section 40321 of DeFazio, 2021); and up to $6 billion worth of tax credits for existing nuclear generators that are at risk of closure due to economic factors (Section 40323 of DeFazio, 2021).

Currently, only one nuclear reactor operates in the region: the Palo Verde plant, a 4-gigawatt (GW) plant in Maricopa County, Arizona. The plant's website states that it is the largest single taxpayer in the state of Arizona, contributing more than $50 million annually (Palo Verde Generating Station 2021). However, we were not able to independently verify this claim despite lengthy searches of records from the Maricopa County Assessor's and Treasurer's office, along with email inquiries to those offices. Records posted online by these offices indicate that the parcels upon which the plant is located have paid $0 in property taxes in recent years. However, the plant's owner may be making payments-in-lieu-of-taxes to the relevant local governments or may have some other arrangement for tax payment.

In Wyoming, legislation enacted in 2020 authorizes the state to grant permits for the construction of small nuclear reactors (SMRs) at sites where coal- or natural gas-fired power plants currently operate. The legislation also imposes a state excise tax of $5.00 per megawatt hour of net

[20] https://energystorage.pnnl.gov/regulatoryactivities.asp

electricity generation (i.e., excluding electricity used on-site) from commercial-scale SMRs, but excludes test- or pilot-scale plants (WY Statutes § 39-23).

Industrial/commercial sector policies

Many policies that would serve to reduce greenhouse gas emissions from industrial operations have been discussed in preceding sections, including the sections on CCUS, DAC, RD&D and electricity decarbonization. Below is a description of additional policies aimed directly at decarbonizing industrial operations in Intermountain West states, as well as some additional discussion of policies mentioned above.

Performance standards

The Clean Air Act (CAA) includes a number of regulations that address industrial emissions or operations. Currently, none of these are specifically designed to address GHGs. But we discuss CAA-related issues here because attempts to reduce conventional air pollutant emissions can have an ancillary effect on GHGs by increasing industrial efficiency and fuel-switching. For example, the CAA includes various limits on criteria air pollutants and hazardous air pollutants, which can impact process emissions and emissions from combustion in industrial operations. The CAA also includes specific limits on the amount of sulfur dioxide (SO_2) that can be emitted from industrial facilities nationwide (annual limit of 5.6 million tons), as well as emissions standards for specific technologies, including industrial boilers and stationary combustion diesel engines[21] [22].

According to the U.S. EPA, the agency does have the authority to set CO_2 performance standards for industrial sectors, but other than rulemaking for reducing methane emissions (a powerful greenhouse gas), they haven't yet written GHG-based performance standards for industry (other than electricity generation). Many climate advocates are urging them to do so. Likewise, no states are engaged yet in this type of rulemaking.

The CAA also requires states to adopt enforceable plans (State Implementation Plans) to meet and maintain air quality standards; these plans must also control emissions that might drift downwind into other states. State Implementation Plans are required for each area designated as a nonattainment area (an area that has not met EPA National Ambient Air Quality Standards). Below

[21] The CAA requires industrial boilers and process heaters to meet certain emissions limits or comply with a regular period of equipment maintenance, and it requires that stationary combustion diesel engines meet specified nonroad diesel emissions standards.
[22] Clean Air Act Requirements and History | US EPA

is a table (Table 12) detailing the number of nonattainment areas throughout the region, many of which are home to industrial operations whose CO_2 emissions could be affected by conventional pollution reduction requirements.

Table 12. CAA nonattainment areas by state	
State	**Number of nonattainment areas designated**
Arizona	17
Colorado	2
Montana	7
New Mexico	2
Utah	7
Wyoming	1
Regional total	36

Source: SPeCS for SIPs Public Dashboard 1 (epa.gov) https://edap.epa.gov/public/extensions/S4S_Public_Dashboard_1/S4S_Public_Dashboard_1.html

In addition to emissions standards, the federal government issues energy efficiency standards—largely implemented by the Department of Energy—for technology and equipment utilized by industrial firms. Increased energy efficiency directly reduces CO_2 emissions to the extent fossil fuel use is reduced, either directly or indirectly through reducing electricity consumption.

Energy efficient standards cover a wide variety of standard energy technologies—from lighting to heat pumps and air conditioning—as well as more specialized technologies used in industrial operations such as boilers, electric motors and water pumps. There are currently 26 energy efficiency standards filed as commercial or industrial through the DOE, not including those standards which are cross-cutting, such as lighting. Each product follows a four-phase process, whereby existing standards are reviewed and new standards are developed[23].

Tax incentives and credits

CCUS tax credit

As mentioned above, in 2018, Congress passed section 45Q of the Internal Revenue Code authorizing a tax credit of up to $50/ton of CO_2 and other carbon oxides removed and permanently stored for approved projects. The IRA raised this credit to $85/ton. This credit could provide needed stimulus to install carbon capture technologies at industrial facilities, such as SMR-hydrogen production plants, particularly where storage sites are close to the carbon capture plants, or where

[23] Standards and Test Procedures | Department of Energy (https://www.energy.gov/eere/buildings/standards-and-test-procedures)

CO_2 pipelines connect the source to a sink or use. However, unless a variety of legal and economic questions can be answered, particularly concerning CO_2 storage, 45Q may have only limited reach in the Intermountain West states; the higher credit amount works in the opposite direction, however. Wyoming and Montana may be leading the charge, with these states having legislation in place to address pore space ownership (Megan Cleveland, 2017).

Energy investment tax credit (ITC)

As discussed above, the Section 48 ITC is a major policy incentivizing solar energy deployment in the electricity sector. It also supports emissions reductions in broader industrial operations, for example by incentivizing investment in combined heat and power (CHP), waste energy recovery, fuel cells, and renewable energy generation at industrial facilities. Under the Section 48 ITC, CHP qualifies for a 10% credit, while waste energy recovery, fuel cells, and renewable energy generation qualify for a 30% credit[24].

Modified Accelerated Cost Recovery System (MACRS)

MACRS is a tax benefit that allows firms to accelerate depreciation (which is a deductible business expense), so as to deduct higher amounts earlier in an asset's lifecycle as a way to reduce tax burden and incentivize investment. For industrial stakeholders, MACRS establishes a set of time periods ranging from 3-50 years over which the property may be depreciated. Especially relevant to industry, fuel cells, microturbines, CHP, solar-electric and solar thermal technologies are defined as five-year properties while biomass properties are defined as seven-year properties[25]. As these technologies can last much longer, the ability of firms to accelerate their depreciation deductions is an important tax benefit. Technology eligibility for the MACRS is defined by eligibility for the Energy Investment Tax Credit. The MACRS is a smaller program compared to the ITC, only estimated to cost $0.3 billion from 2020-2024 (*Estimates of Federal Tax Expenditures for Fiscal Years 2020-2024*, 2020).

Advanced manufacturing tax credit

The section 48C advanced manufacturing tax credit[26] provides a 30% investment tax credit for investments in new or existing manufacturing facilities for the production of clean energy technologies. The credit applies to equipment and facilities that manufacture a variety of clean

[24] https://crsreports.congress.gov/product/pdf/R/R46865
[25] https://www.epa.gov/chp/database-chp-policies-and-incentives-dchpp#ModifiedAcceleratedCostRecoverySystemMACRS
[26] 26 USC 48C

energy related technologies, including renewable energy generation (such as wind, solar, and geothermal technologies), electric grid, energy storage, electric vehicle, CCUS, energy conservation, and other technologies.

The tax credit allocated all $2.3 billion in credits through two application rounds which ended in 2013[27]. However, the IRA included an additional $10 billion for 48C. Further, IRA included a direct-pay option, which would put cash in the hands of manufacturers, rather than tax credits[28]. This provision would give manufacturers with low tax liability the ability to claim the full value of the 48C incentive without finding high tax liability partners through tax equity markets (which often reduces the value of the incentive for the intended recipient—clean energy manufacturers—due to tax equity transaction costs).

Energy Efficiency Incentives

The federal Energy Policy Act of 2005 established the Energy Efficient Commercial Buildings Tax Deduction (179D), which applies to the industrial sector (as a component of the commercial sector). 179D offers a tax deduction of $1.80 per square foot for the owners of new or existing buildings that install technology to reduce total building energy and power cost by 50% or more compared to a building energy performance benchmark determined by the most recent ASHRAE 90.1 standard. The tax deduction also offers $0.60 per square foot to owners of buildings where technologies like lighting, heating, and cooling systems meet target levels that would reasonably contribute to the building's saving of 50% if additional systems were installed[29].

The ENERGY STAR program, a voluntary performance standard to promote energy efficiency best known for household appliances, can also grant certificates to industrial plants meeting an EPA determined energy performance rating[30]. As DOE minimum efficiency standards are updated, the requirements to become ENERGY STAR certified are also adjusted. Plants must be in the top 25th percentile of all plants in energy efficiency to achieve ENERGY STAR certification. In the Intermountain West, there are 12 certified plants including facilities for commercial bread and roll-baking, cement manufacturing, and nitrogenous fertilizer production. Although the program is voluntary, industrial plants looking to be included in Buy Clean or green procurement initiatives

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[27] Biden Administration's proposals would expand and enhance qualifying advanced energy manufacturing credit (ey.com)
[28] Inflation Reduction Act Offers Significant Tax Incentives Targeting Energy Transition and Renewables | White & Case LLP (whitecase.com)
[29] DSIRE (dsireusa.org)
[30] ENERGY STAR plant certification | ENERGY STAR https://www.energystar.gov/industrial_plants/earn-recognition/plant-certification

have an incentive to participate, or at least disclose their ENERGY STAR score as a signal of their low CO_2 emissions.

The DOE Loan Guarantee Program has an energy-efficiency angle, too. The program awards loan guarantees to commercial projects that adopt energy efficient technologies.

At the state and municipal level, one strategy for advancing commercial and industrial building energy efficiency is to adopt and enforce the International Energy Conservation Code (IECC). For example, Colorado requires local governments to adopt and enforce the IECC[31], and many Arizona local jurisdictions have adopted it as well[32]. Table 13 highlights some examples (not an exhaustive list) of state government incentives for energy efficient commercial and industrial buildings.

Table 13. Examples of energy efficiency programs for commercial and industrial buildings by state

State	Policy
Arizona	Property tax exemption is available for energy efficient building components.
Colorado	Offers several programs to finance energy efficient commercial properties and Property Assessed Clean Energy (PACE) financing,
Montana	Offers tax credits and deductions for energy efficiency investments.
New Mexico	Offers a sustainable building tax credit, bonds for energy efficiency investments, and PACE financing.
Utah	Offers a commercial PACE program.
Wyoming	Offers one loan program and several grant programs for energy efficiency.

Source: The State Energy Efficiency Scorecard | ACEEE

Additionally, many states require public buildings to be held to an energy efficiency standard, potentially paving the way for future commercial and industrial buildings to be held to the same standard.

As indicated by Table 13, one common state program seen in the Intermountain West is a Property Assessed Clean Energy (PACE) program. The PACE model is a mechanism for financing energy efficiency and renewable energy improvements to private property—both commercial and residential. PACE programs allow the property owner to finance the upfront cost of energy efficiency improvements and pay back the costs over time through voluntary tax assessment on the property[33].

[31] CO HB 19-1260
[32] ACEEE_ScrSht20_Arizona.pdf
[33] Property Assessed Clean Energy Programs | Department of Energy https://www.energy.gov/eere/slsc/property-assessed-clean-energy-programs

Direct funding and subsidized finance

DOE Advanced Manufacturing Office (AMO) funding

The AMO aims to drive decarbonization, innovation, and productivity improvements in the U.S. manufacturing sector by focusing on applied RD&D in a variety of technologies and production processes. The 2022 budget imposes a new structure including four new program areas (Materials, Manufacturing Innovations, Energy Systems, and Manufacturing Enterprise).

Materials: the materials subprogram focuses on developing new materials with improved sustainability and energy performance properties. This goal is pursued by investments and demonstration activities supported by the AMO to help technologies scale-up and to accelerate adoption and deployment. Funding for the materials subprogram under AMO includes competitive selection of R&D projects at national labs, universities, and companies, and the continuation of consortiums to develop new energy-related materials.

Manufacturing Innovations: this subprogram focuses on advancing new manufacturing technologies and processes, and on improving energy efficiency, with the goal of decarbonizing the manufacturing process. This goal is also supported by RD&D programs, including funding for the continuation of the Clean Energy Manufacturing Innovation (CEMI) Institute, competitive selection and support of projects focused on decarbonization, and competitive selection and support of projects focused on modelling, simulation, and data analysis.

Energy systems: this subprogram focuses on advancing systems for energy conversion, utilization, storage, and management within industry. This subprogram specifically targets combined heat and power (CHP) and resiliency systems. The program operates by providing technical assistance to support RD&D and collaboration with the DOE Hydrogen and Fuel Cell Technologies Office (HFTO) on a funding opportunity focused on electrolyzer manufacturing.

Manufacturing enterprises: this subprogram focuses on value chain adaptability, responsiveness, and resilience during disruption, change, and opportunity. The program supports technical assistance and stakeholder engagement through competitive selection of projects focused on topics like energy and water efficiency, waste reduction, decarbonization, workforce development, and smart manufacturing. The program supports competitive funding, a workforce training program, technical assistance, and educational resource development[34].

[34] FY 2022 Budget Request Vol 3.1 (energy.gov)

Through these four subprograms, the AMO provides funding and support through a variety of channels for a variety of programs ranging from RD&D to job training and educational resource development. AMO specifically focuses on technical areas with high potential for impact.

USDA Business & Industry Loan Guarantee Program and tax-exempt bonds

In addition to the DOE Loan Guarantee Program discussed above, the recently established USDA Business & Industry (B&I) Loan Guarantee Program provides loan guarantees to support the availability of low-cost capital for decarbonization investments at industrial operations located in rural areas. Borrowers can be cooperative organizations, corporations, partnerships, federally recognized tribal groups, for-profit and non-profit organizations so long as the area is eligible as rural[35].

Other federal policies that subsidize finance in ways that could be relevant for industrial decarbonization include tax exempt Private Activity Bonds [36] (issued by state and local governments and exempt from federal taxes), the tax credit bonds listed above in Section 3, the U.S. EPA's Clean Water State Revolving Loan Fund, U.S. Treasury's CDFI Fund and in some cases the various financing programs offered by the Small Business Administration.

Green procurement

As a means of stimulating demand for green (low carbon) products to bring prices down through economies of scale and innovation, governments around the world are creating green procurement programs that include provisions for carbon-intensive commodities produced by the industrial sector, such as steel, cement, and paper. The Biden administration issued an Executive Order directing federal agencies to develop the tools and protocols to implement a green procurement program for commodities routinely purchased and supported by the federal government—including those used in the construction of roads, bridges, and buildings. The term "supported by" is very important, as it would imply that $49 billion a year distributed by the federal government to states under the Federal Highway Trust Fund could come with requirements that the states incorporate the same program in their bidding procedures for highway construction paid for, in part, with federal money.

[35] Database of CHP Policies and Incentives (dCHPP) | US EPA
[36] RL31457 (congress.gov)

The General Services Administration is also implementing embodied carbon requirements in its procurement programs for cement and concrete products. Hence, all public infrastructure projects, including those funded under the IIJA, will be held to GWP thresholds based on product-specific EPDs. These carbon content requirements for federal procurement of cement and concrete products, aligned with the new White House Buy Clean Policy[37], are the first to apply nationwide. The IRA has funded the extra effort and cost of these Buy Clean efforts.

State green procurement programs, such as the Buy Clean California Act[38], could also be an important factor in industrial decarbonization. Buy Clean California implements embodied carbon limits for a selection of building materials (steel products, flat glass, and mineral wood board insulation)[39], which must not exceed the Global Warming Potential (GWP) threshold set by the Procurement Division of the Department of General Services, when procured in public construction projects. The required GWPs for eligible materials were set using industry-wide Environmental Product Declarations (EPDs).

On the east coast, the New York State Green Procurement and Agency Sustainability Program has included low carbon concrete specifications since April 2022. Under this policy, the State requires concrete manufacturers to provide batch-specific EPDs when available, and to supply products complying with a specified cement-to-concrete ratio and a specified share of Supplementary Cementious Materials in the final mix. In addition, contractors have to reduce their use of cement overall by using blended aggregates.

Technical assistance

Identifying the most effective and economical approaches for reducing industrial emissions can be complicated, and federal programs exist to assist firms navigating this process. For example, DOE's Advanced Manufacturing Office (AMO) has housed programs (e.g. R&D Consortia) to pair firms with university-based student-led industrial assessment centers. DOE also develops software to help companies plan energy efficiency and other facility upgrades, including the Manufacturing Energy Assessment Software for Utility Reduction (MEASUR) and 50001 Ready[40].

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[37] https://www.whitehouse.gov/briefing-room/statements-releases/2022/02/15/fact-sheet-biden-harris-administration-advances-cleaner-industrial-sector-to-reduce-emissions-and-reinvigorate-american-manufacturing/#:~:text=Launching%20%E2%80%9CBuy%20Clean%E2%80%9D%20Procurement&text=As%20directed%20by%20the%20President's,stage%20of%20the%20manufacturing%20process.
[38] https://www.dgs.ca.gov/-/media/Divisions/DGS/LegReports/Accessible-Reports/2022/BCCA-Legislative-Report_final.pdf?la=en&hash=C970382B9DC8530385F0F0FFCD1928D2B7533B99
[39] A 2021 amendment, currently on hold, would include concrete as well.
[40] https://www.aceee.org/sites/default/files/pdfs/ie2001.pdf

Fuels policy

Tax incentives

Hydrogen

The IRA created a new program to provide tax credits for the production of "clean" hydrogen (giving stimulus to carbon capture and storage applied to standard hydrogen production facilities (blue hydrogen) and hydrogen produced with electrolysis or other new technologies (green hydrogen)), the tax credit would be larger the lower the CO_2 emissions per unit of hydrogen produced. The lowest hanging fruits for fuel "switching" are (1) replacing grey with blue hydrogen and using the blue hydrogen as current hydrogen is now used (e.g., fertilizer manufacturing), and (2) combining blue or green hydrogen with natural gas for distribution to electric utilities (up to a 20% mixture (10% by Btus)), and perhaps marine transport and even truck transport.

Bioenergy

Fostering the development of bioenergy has been seen as a potential path to decarbonizing multiple sectors of the economy. From biofuels in the transportation sector to biobased displacement of chemical production in the industrial sector, bioenergy presents an opportunity for progress in operations which are otherwise difficult to decarbonize.

Procurement of bioenergy is often included as an option when satisfying renewable portfolio standards. All Intermountain West states except Wyoming with a current or past RPS allow for bioenergy to count towards the renewables share (Table 14).

Table 14. State tax policies supporting bioenergy

State	Policy
Arizona	Reduced tax burden for utility-scale biomass equipment
Colorado	Reduced property tax burden for renewable energy property Local tax exemptions for renewable energy systems
Montana	Property tax exemptions for biomass and biogas generation Property tax abatement for bioenergy
New Mexico	Renewable energy Production Tax Credit Tax deduction for biomass feedstock and production equipment Energy equipment manufacturing tax credit
Utah	Tax credit for biomass energy PTC for biomass generation Tax credit for renewable and commercial biomass energy systems
Wyoming	No policies identified

Arizona offers a reduced tax footprint of 20% of "taxable original cost" for utility scale renewable energy equipment which includes biomass[41].

The state of Colorado has included biogas requirements for gas utility decarbonization within its GHG Pollution Reduction Roadmap. The Colorado roadmap suggests considering a Biogas Portfolio Standard, which would require gas utilities to satisfy a greenhouse gas intensity standard. The roadmap also mentions utility biogas incentives for the waste industry as a near-term action towards decarbonization. A number of Colorado localities offer property, sales, and use tax exemptions for bioenergy generators[42]. Colorado also assesses renewable energy property at a reduced value for state property tax burden[43].

Montana offers property tax exemptions for biomass and biogas through both the Generation Facility Corporate Tax Exemption and the Renewable Energy System Exemption[44, 45]. Bioenergy facilities in Montana are also offered property tax abatement up to 50% for up to 19 years of construction and operation[46].

New Mexico offers the Renewable Energy Production Tax Credit worth $0.01 per kWh which is applicable to biomass. The state also provides a deduction of compensating tax for biomass feedstocks and production equipment[47]. The Alternative Energy Product Manufacturers Tax Credit can be used for energy equipment manufacturers, including renewable bioenergy, with a value of 5% of qualified expenditures[48]. New Mexico also has an agricultural biomass income tax credit which offers a $5 per ton of biomass tax credit for dairy or feedlot owners that supply feedstock to biomass generators[49].

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41 https://www.azleg.gov/viewdocument/?docName=https%3A%2F%2Fwww.azleg.gov%2Fars%2F42%2F14155.htm

42 https://programs.dsireusa.org/system/program/co/biomass

43 https://cdola.colorado.gov/renewable-energy

44 https://leg.mt.gov/bills/mca/title_0150/chapter_0060/part_0020/section_0240/0150-0060-0020-0240.html

45 https://leg.mt.gov/bills/mca/title_0150/chapter_0060/part_0020/section_0250/0150-0060-0020-0250.html

46 https://leg.mt.gov/bills/mca/title_0150/chapter_0240/part_0310/section_0110/0150-0240-0310-0110.html

47 https://nmonesource.com/nmos/nmsa/en/item/4340/index.do#!fragment/zoupio-_Toc100337805/BQCwhgziBcwMYgK4DsDWszIQewE4BUBTADwBdoAvbRABwEtsBaAfX2zgEYAGLgZl4DsADi4BWAJQAaZNlKEIARUSFcAT2gByDZIiEwuBEpXqtOvQZABlPKQBC6gEoBRADJOAagEEAcgGEnkqRgAEbQpOzi4kA

48 https://law.justia.com/codes/new-mexico/2013/chapter-7/article-9j/

49 https://nmonesource.com/nmos/nmsa/en/item/4340/index.do#!fragment/zoupio-_Toc100336950/BQCwhgziBcwMYgK4DsDWszIQewE4BUBTADwBdoAvbRABwEtsBaAfX2zgEYAGLgZl4BsATgCsXAJQAaZNlKEIARUSFcAT2gByDZIiEwuBEpXqtOvQZABlPKQBC6gEoBRADJOAagEEAcgGEnkqRgAEbQpOzi4kA

Utah's Alternative Energy Development Incentive offers a credit to cover 75% of "new eligible state revenues" from biomass projects for 20 years[50]. Utah also has a PTC worth $0.0035 per kWh for biomass generation for the first 48 months of project operation[51]. The Renewable Energy Systems Tax Credit also offers a variable tax credit for residential and commercial renewable energy systems, including biomass, though the residential credit expires in 2023[52].

The federal government has several active projects promoting the adoption of bioenergy (Table 15). USDA runs the Biorefinery, Renewable Chemical, and Biobased Product Manufacturing Assistance Program, providing loan guarantees for retrofitting, construction, or development of advanced biofuels, renewable chemicals, and bioproducts[53]. USDA also operates the Repowering Assistance Biorefinery Program which offers financial incentives for converting fossil fuel generators to a biomass[54].

Table 15. USDA bioenergy investment by state

State	Total investment ($Million)
Arizona	129.3
Colorado	14.2
Montana	16.0
New Mexico	55.6
Utah	51.7
Wyoming	3.9

Note: Bioenergy includes renewable biomass and anaerobic digester[55].

The USDA provides information on investment expenditures by state for programs assisting bioenergy development. Of the states under assessment by I-WEST, Arizona has received the most in bioenergy investment funds. The majority of USDA bioenergy investment in both Arizona and New Mexico was towards anaerobic digestion development. Utah, which has also seen sizeable investment from USDA, has had its investment go towards renewable biomass.

[50] https://energy.utah.gov/tax-credits/aedi/
[51] https://energy.utah.gov/tax-credits/renewable-energy-systems-tax-credit/utility/production-tax-credit/
[52] https://energy.utah.gov/tax-credits/renewable-energy-systems-tax-credit/
[53] https://www.rd.usda.gov/programs-services/energy-programs/biorefinery-renewable-chemical-and-biobased-product-manufacturing-assistance-program
[54] https://www.rd.usda.gov/directives/4288-repowering-assistance-payments-eligible-biorefineries
[55] https://www.wctsservices.usda.gov/energy/maps/investment

Biofuels

Wyoming was the third largest state producer of biofuels in 2021, with a capacity of 8 million barrels per day (mb/d). Colorado currently has three fuel ethanol plants with combined capacity of 9 mb/d, while Arizona has one plant with 4 mb/d in capacity[56].

Montana provides a $0.20 per gallon subsidy for ethanol production, contingent on a percentage of the input products being sourced from Montana[57]. The state also exempts property tax for ethanol production facilities during construction plus 10 years afterwards[58]. Montana offers a $0.02 per gallon fuel tax refund for distributors of biodiesel completely sourced from Montana[59]. The "Clean and Green" Property Tax Incentive may also offer a lower tax rate of 3% of market value for biomass, biogas, and biofuel generation and production facilities[60]. These facilities are also offered property tax abatement up to 50% for up to 19 years of construction and operation[61].

New Mexico offers a deduction of biomass feedstocks and production equipment used for biofuel production towards the compensating tax[62]. New Mexico also offers a Biodiesel Blending Facility Tax Credit with value up to 30% for the purchase and installation cost of 2% or higher biodiesel blending equipment[63].

In 2021, a group of federal agencies led by the DOE, DOT, and USDA started the Sustainable Aviation Fuel Grand Challenge as a MOU towards increasing the sustainability and production of sustainable aviation fuels. The challenge has the goal of reaching 3 billion gallons of sustainable aviation fuels by 2030, and 35 billion gallons per year—the estimated total U.S. aviation fuel demand—by 2050[64].

The DOE Bioenergy Technologies Office (BETO) and NREL created the Waste-to-Energy Technical Assistance for Local Governments (WTE) program in 2021, with the city and county of

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[56] https://www.eia.gov/petroleum/ethanolcapacity/
[57] https://leg.mt.gov/bills/mca/title_0150/chapter_0700/part_0050/section_0220/0150-0700-0050-0220.html
[58] https://leg.mt.gov/bills/mca/title_0150/chapter_0060/part_0020/section_0200/0150-0060-0020-0200.html
[59] https://leg.mt.gov/bills/mca/title_0150/chapter_0700/part_0040/section_0330/0150-0700-0040-0330.html
[60] https://deq.mt.gov/energy/resources#CleanGreen
[61] https://leg.mt.gov/bills/mca/title_0150/chapter_0240/part_0310/section_0110/0150-0240-0310-0110.html
[62] https://nmonesource.com/nmos/nmsa/en/item/4340/index.do#!fragment/zoupio-_Toc100337805/BQCwhgziBcwMYgK4DsDWszIQewE4BUBTADwBdoAvbRABwEtsBaAfX2zgEYAGLgZl4DsADi4BWAJQAaZNlKEIARUSFcAT2gByDZIiEwuBEpXqtOvQZABlPKQBC6gEoBRADJOAagEEAcgGEnkqRgAEbQpOzi4kA
[63] https://nmonesource.com/nmos/nmsa/en/item/4340/index.do#!fragment/zoupio-_Toc100337755/BQCwhgziBcwMYgK4DsDWszIQewE4BUBTADwBdoAvbRABwEtsBaAfX2zgEYAGLgZl4DsAgKzCAIABpk2UoQgBFRIVwBPaAHJ1EiITC4Ei5Ws3bd+kAGU8pAEJqASgFEAMo4BqAQQByAYUcTSMAAjaFJ2MTEgA
[64] https://www.energy.gov/eere/bioenergy/sustainable-aviation-fuel-grand-challenge

Denver, Colorado being the first recipient in the Intermountain West region. The WTE program provides assistance and planning services for biowaste project implementation. USDA manages the Advanced Biofuel Payment Program aimed at boosting biofuel production[65]. This USDA program is a purchasing program for, with payment amounts subject to the program's annual budget. USDA also operates the Higher Blends Infrastructure Incentive Program which provides grants to businesses for biodiesel distribution infrastructure, such as upgraded fuel dispensers or storage systems[66].

Beyond direct project assistance, numerous experts and stakeholders have noted the importance of community education and engagement to ensure community acceptance of new technologies and industry.

The Build Back Better legislation would extend incentives for biodiesel, renewable diesel and alternative fuels through 2026, as well as establish a sustainable aviation fuel tax credit.

Development opportunity assessment

The Wyoming Pipeline Corridor Initiative is working to expand rights of way over additional CO_2 pipelines across federal lands.

Pricing externalities

An important piece of the policy puzzle for fossil fuels from a decarbonization point of view is that most externalities are unpriced by the federal government and most states (Coady et al., 2019).

Subsidies to oil and gas

At the federal level, oil and gas extraction is subsidized through the tax code in a variety of ways. Some of these incentives are related to CCUS and EOR, which we discuss above. Other incentives are more broadly applicable, and include (1) amortization of costs associated with exploration for new resources, estimated to result in forgone revenues of $500 million from FY20-FY24; (2) tax exemptions for publicly-traded energy firms that are classified as partnerships, estimated to result in foregone revenues of $1.8 billion from FY20-FY24; (3) expensing of intangible drilling costs and other costs, estimated to result in foregone revenues of $2.3 billion from FY20-FY24; and (4) the allowance of percentage (instead of cost) depletion, estimated to result in foregone revenues of $2.9 billion from FY20-FY24 (*Estimates of Federal Tax Expenditures for Fiscal Years 2020-2024*,

[65] https://www.rd.usda.gov/programs-services/energy-programs/advanced-biofuel-payment-program
[66] https://www.rd.usda.gov/hbiip

2020). Analyses of these policies have found that they do relatively little to boost oil and gas production (Aldy, 2021; Metcalf, 2017; Murray et al., 2014). For example, the first 18 months of oil and gas produced from a new horizontally drilled well in Montana is subject to a severance tax rate of 0.5%, after which it pays a 9% rate. Given the fact that horizontally drilled wells are most productive in their first months and years of production, this incentive results in considerable foregone revenue for the state (Montana Code Annotated §15-36-304).

Subsidies to coal

Certain types of coal production are subsidized at the federal level. The most significant policies are the “refined coal” tax credit (just expired) and a credit worth $2.00 per ton (in 2005 dollars) for coal produced by “Indian Tribes” or from land held in trust for a tribe by the federal government (26 USC §45). From FY20 through FY24, this latter subsidy was projected to result in $200 million in foregone tax revenues. Construction of new integrated gasification combined cycle systems and other advanced coal technologies have been eligible for investment tax credits worth 15 to 30 percent of the investment (26 USC §48A and §48B). From FY20-FY24, this subsidy was projected to result in $1.2 billion in foregone tax revenues. Another substantial subsidy taxes income from certain coal sales at the 20% capital gains tax rate, rather than the higher ordinary income tax rate (26 USC §631(c)). This provision is estimated to result in $1.6 billion in foregone federal revenues from FY2020 through FY2029. Finally, many coal-fired power plants are able to amortize their investments in certain pollution control equipment, resulting in foregone revenues of $2.1 billion from FY20-FY24 (Sherlock, 2021).

Although little empirical analysis is available to assess the environmental or economic effects of these policies, one recent analysis raises concern. It estimates that the “refined coal” tax credit achieves roughly half of its intended air pollution reduction benefits, and that the social costs of the policy are more than seven times the benefits (Prest and Krupnick, 2020).

Declining fossil fuel revenues

Although fossil fuels are subsidized at the federal and state levels, they also play a major role in funding public services in most Intermountain West states. Coal, oil, and natural gas extraction, transportation, processing, and use each contribute substantially to local, state, tribal, and federal coffers. Revenues are generated through a variety of mechanisms, led by excise taxes on petroleum product (e.g., gasoline and diesel) consumption, severance taxes on fossil fuel extraction, leasing revenue from production on public lands, and property taxes on extraction, transportation, refining, and power plant property (Raimi et al., 2022).

As decarbonization reduces the level of fossil fuel production and consumption across the economy, public revenues from these sources are likely to decline as well, potentially posing fiscal risk for dependent localities, states, and Native nations. The table below (Table 16) provides three metrics to assess the scale of revenue from fossil fuels in the states. It averages annual data from 2015 through 2020, and includes (1) aggregate state and local revenue from fossil fuels, (2) per capita state and local revenue from fossil fuels, and (3) state and local revenue from fossil fuels as a share of total own-source income (i.e., excluding federal transfers).

Table 16. Average annual state revenues from fossil fuels, 2015-2020

State	Aggregate revenue ($millions)	Per capita revenue	Share of own-source revenue	Main sources
Arizona	$844	$117	1.7%	Petroleum products
Colorado	$2,000	$356	4.1%	Oil, gas, petroleum products
Montana	$644	$613	7.9%	Oil, gas, petroleum products
New Mexico	$2,726	$1,303	15.1%	Oil, gas, petroleum products
Utah	$807	$260	3.1%	Oil, gas, petroleum products
Wyoming	$4,264	$7,339	58.6%	Oil, gas, coal

Source: Raimi et al. (2022)

At roughly 59%of own-source revenues, Wyoming is by far the most dependent state on fossil fuels to provide government services in the region and, in fact, the nation as a whole (Raimi et al., 2022). However, New Mexico is also highly dependent as a state, and certain regions of Colorado, Montana, and Utah where fossil fuel extraction is concentrated are also very dependent on fossil fuels to provide critical local services, particularly education.

Decommissioning mines and wells

In the coal sector, major concerns exist around reclaiming abandoned mines and the impoundments that store coal combustion residuals (sometimes referred to as “coal ash”). The Intermountain West is home to a large number of abandoned mines, including coal mines. Safely decommissioning these sites has the potential to provide near-term employment and support longer-term economic development by reducing exposure to pollution in surrounding communities (Raimi, 2020).

Table 17 identifies the number of abandoned mines in the region and their associated costs. “Unfunded costs” refer to expected reclamation costs that are not currently funded, while “funded” and “completed” costs refer to reclamation needs that are either funded or completed, respectively.

Table 17. State and tribal abandoned mine inventories and costs ($millions)				
State/Tribe	**Abandoned mines**	**Unfunded costs**	**Funded costs**	**Completed costs**
Arizona	1	$-	$-	$-
Colorado	1,589	$74	$1	$69
Crow	166	$-	$2	$10
Fort Peck	15	$-	$2	$2
Hopi	49	$2	$-	$4
Montana	2,111	$225	$1	$103
Navajo	1,281	$1	$3	$34
New Mexico	458	$42	$2	$33
Utah	591	$8	$1	$33
Wyoming	3,574	$104	$202	$750

Data source: OSMRE (2021), Data accessed 4/19/2022.

The table highlights the relatively large number of abandoned mines and liabilities in Montana, Wyoming, Colorado, and New Mexico. The IIJA authorized $11.3 billion in federal spending to reclaim abandoned mines across the United States (Section 40701 of DeFazio, 2021).

In the oil and gas sector, state policies have failed to fully incentivize operators to decommission wells at the end of their useful lives. State governments require oil and gas well operators to provide some form of financial assurance (e.g., a surety bond) that can be used to decommission that company's wells if the company goes bankrupt. States also offer so-called "blanket" bonds that provide financial assurance for every well operated by a given company in that state. In the Intermountain West, maximum blanket bond levels range from $50,000 to $250,000 (Table 18).

Table 18. Unplugged orphaned oil and gas wells by state		
State	**Documented unplugged orphaned wells**	**Maximum blanket bond**
Arizona	0	$250,000
Colorado	409	$100,000
Montana	221	$50,000
New Mexico	652	$250,000
Utah	72	$60,000
Wyoming	1,323	$100,000

Source: U.S. Geological Survey, 2022

These blanket bonds are inadequate to cover decommissioning costs for operators that own more than one or two wells. One recent empirical analysis estimates that, on average, decommissioning an oil and gas well costs roughly $76,000, with a small number of wells exceeding $1 million (Raimi et al., 2021). Although some states charge a small annual fee to all oil and gas companies to help cover the costs of decommissioning so-called “orphaned” wells (those whose owners have gone bankrupt), the backlog of such wells has increased over time.

In the IIJA, Congress authorized roughly $4.7 billion to support orphaned well decommissioning and related activities across the country (Section 40601 of DeFazio, 2021). This investment, if decommissioning costs were roughly $76,000 per well, would only cover roughly 60,000 wells. Nationwide, the current, and potential future, number of orphaned wells is at least an order of magnitude higher (Kang et al., 2021), suggesting that reform to state and federal financial assurance requirements are needed to prevent taxpayers from footing tens to hundreds of billions in future decommissioning costs.

Other

Although not directly tied to decarbonization, it is useful to know how the six states compare in the comprehensiveness and stringency of their oil and gas regulations. Indirectly, regulations on abandoned wells affect methane emissions and other regulatory areas also affect those emissions and CO_2. Krupnick and Richardson (2013) compared regulatory performance for shale gas for all states but Arizona in the region. Their findings include (Figure 3): Colorado and New Mexico regulate more or the 25 elements considered than Wyoming, Utah, and Montana, in that order, with the national average being higher than Utah and Montana.

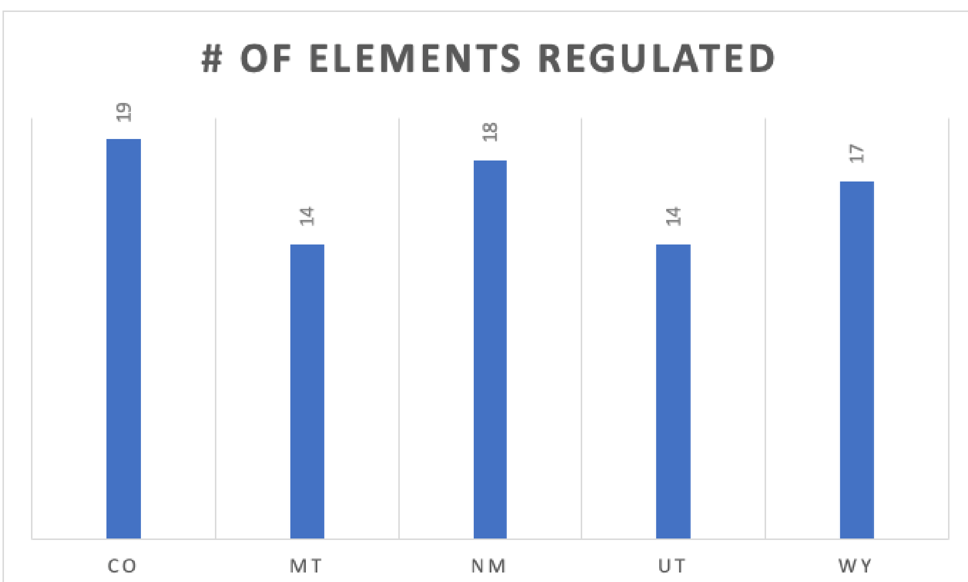

Figure 3: Number of elements considered in regulation.

Of the 25 elements, 13 can be measured quantitatively and compared. Of these, Colorado regulates 12, Wyoming 8, New Mexico 7, Utah 6, and Montana 5.

Of the elements regulated quantitatively, Montana is most stringent, followed by Utah, then New Mexico, Colorado, and Wyoming. In terms of qualitative elements (Figure 4), Krupnick and Richardson also rated the states on stringency. Colorado was first, followed by New Mexico, Wyoming, Montana and Utah.

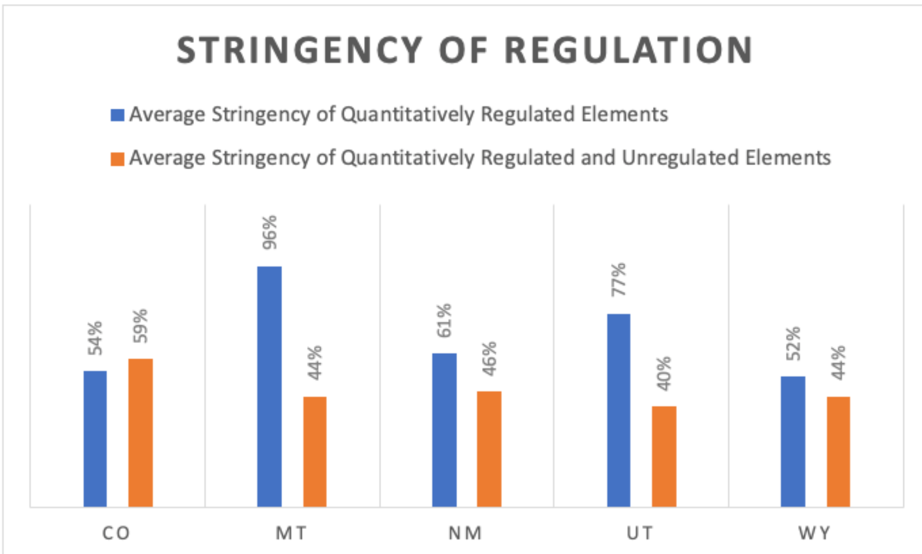

Figure 4: Stringency of regulation.

In addition to these summary measures, they examined and compared particular regulations. One relevant to methane leaks is casing and cement depth. Figure 5 shows that the states within the region take very different approaches.

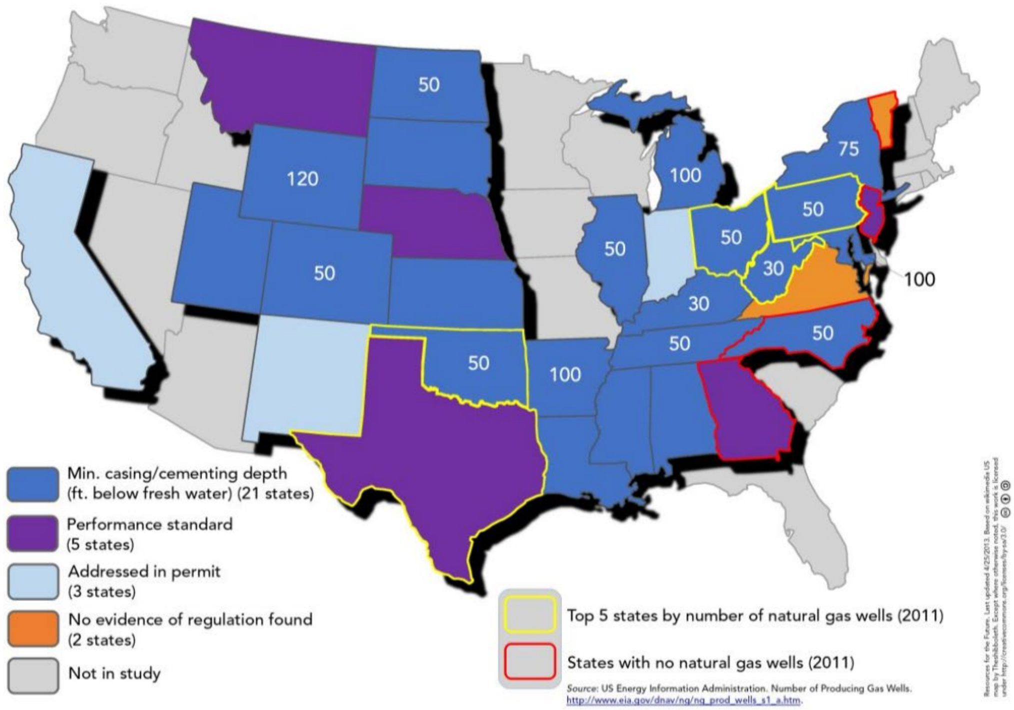

Figure 5: Casing and Cementing Depth Regulations (from Krupnick and Richardson, 2013).

Regulations related to flaring are summarized in Figure 6.

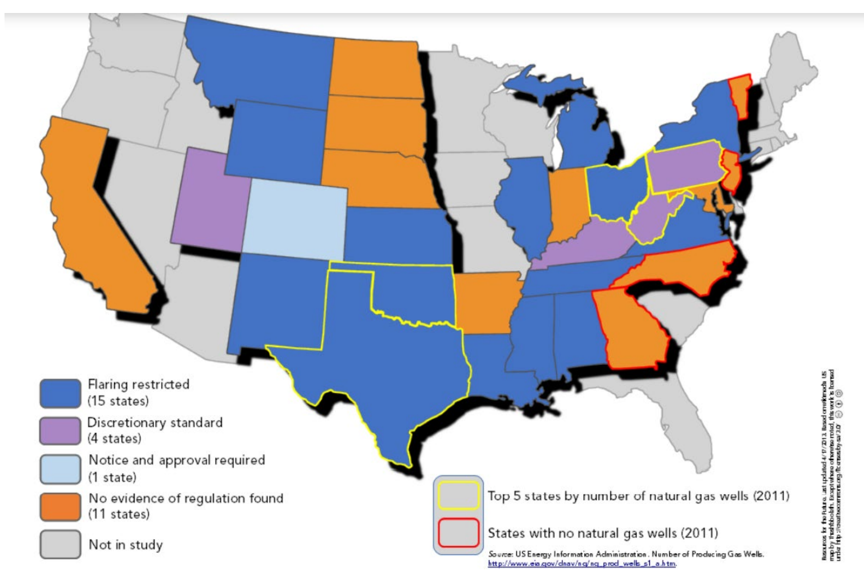

Figure 6: Flaring regulations (from Krupnick and Richardson, 2013).

Figure 7 shows severance tax rates. Higher rates are presumably more beneficial to the economy in creating more tax revenues per mcf produced and may be somewhat of a disincentive to production. Notably, the figure does not show local property taxes, which vary widely across states and which interact with state-level severance tax policies, sometimes reducing the effective rate of the severance tax (as in Colorado). Figure 7 is illustrative of the heterogeneity of approaches.

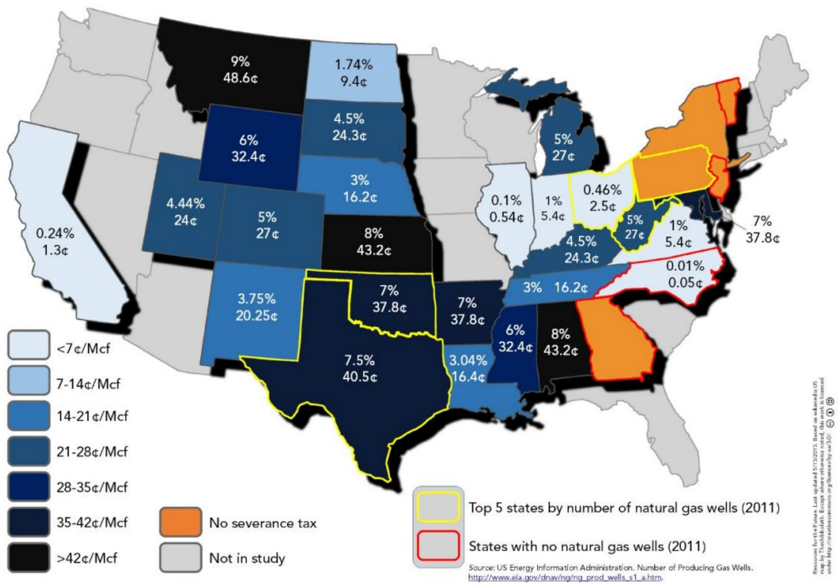

Figure 7: Severance taxes at $5.40/Mcf gas price (from Krupnick and Richardson, 2013).

Transportation sector policies

There are a variety of policies that affect energy use and emissions in the transportation sector, some intentionally (e.g., federal GHG standards for vehicles) and others incidentally (e.g., the federal gas tax). Some focus on fuels, others on vehicles, and still others target infrastructure. All these policies affect the type and volume of fuels being consumed in the region (and therefore CO_2 emissions), and therefore also the types of infrastructure developed to serve demand--some of which is shared with other sectors, such as industrial and commercial operations. The following section organizes transportation policies into four categories: vehicle standards, vehicle purchase incentives, fuel standards and subsidies, and vehicle fueling infrastructure (including electric vehicle charging).

Vehicle standards

Following the Supreme Court ruling in *Massachusetts vs EPA,* it was determined that the Clean Air Act (CAA) requires the U.S. Environmental Protection Agency (EPA) to regulate greenhouse gas (GHG) emissions from transportation ("mobile sources"). This has led to standards for both light-duty vehicles (LDV) and medium and heavy-duty vehicles (MHDV). Federal LDV GHG emissions standards are combined with the Corporate Average Fuel Economy (CAFE) standards established by the Energy Policy and Conservation Act of 1975 and administered by the National Highway Traffic Safety Administration (NHTSA). Similar standards have more recently been established for MHDVs. These standards have driven a gradual improvement in the fuel efficiency and carbon intensity of vehicles.

In addition to requiring EPA to promulgate national standards for vehicles, the CAA authorizes California to seek a waiver from federal preemption (otherwise established in the CAA) over state standards—which effectively allows California to set its own standards, as long as they are at least as stringent as federal standards. Furthermore, Section 177 of the CAA allows other states to adopt California's standards instead of the federal standards. In 2012, the California Air Resources Board adopted its Advanced Clean Cars Program (ACCP), which established light-duty vehicle emissions standards (pursuant to the CAA waiver) for model years 2015-2025. In addition to emissions standards, the ACCP established a zero-emissions vehicle (ZEV) mandate—requiring that a certain percentage of new light-duty vehicle sales be electric vehicles (EVs), hydrogen fuel vehicles or plug-in hybrid vehicles[67]. At the time of drafting this report, Colorado has joined this program, and New Mexico is in the process of joining[68]. California is now working on a second regulation—Advanced Clean Cars 2, which will set more stringent targets for model years 2026-2035.

Additionally, in 2021 California adopted a similar program for medium- and heavy-duty vehicles, called Advanced Clean Trucks (ACT), which sets ZEV targets for manufacturers of Class 2b-8 vehicles[69]. Similar to the ACCP, other states can choose to adopt the California standards. Furthermore, the ACT is intended to be paired with a policy still under development at the time of writing called Advanced Clean Fleets (ACF), which would regulate fleet owners with the goal of

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[67] https://ww2.arb.ca.gov/our-work/programs/advanced-clean-cars-program/about

[68] https://ww2.arb.ca.gov/resources/documents/states-have-adopted-californias-vehicle-standards-under-section-177-federal; https://www.edf.org/media/epa-moves-restore-states-unlawfully-withdrawn-ability-set-clean-car-standards

[69] By 2035, ZEV sales would need to be 55% of Class 2b – 3 truck sales, 75% of Class 4 – 8 straight truck sales, and 40% of truck tractor sales. For more detail, see: https://ww2.arb.ca.gov/resources/fact-sheets/advanced-clean-trucks-fact-sheet

achieving the ACT targets[70]. At the time of writing, none of the Intermountain West states have adopted the ACT rules to our knowledge.

Vehicle purchase incentives

In addition to mandates like the ACCP ZEV program, there are a number of federal and state market mechanisms designed to incentivize the adoption of low-carbon vehicles (Table 19). At the federal level, the Internal Revenue Code Section 30D[71] tax credit (maximum of $7,500 pr vehicle) for electric passenger vehicles and the 30B[72] tax credit for “alternative motor vehicles” (includes hydrogen and compressed natural gas (CNG) vehicles) are examples of federal tax policy designed to incentivize the adoption of clean fuel vehicles.

There are a variety of similar policies in effect within the region. These policies range from tax credits, exemptions, and deductions, to grants and loans. Arizona also incentivizes alternative fuel vehicles (AFVs) by allowing them to drive in HOV lanes regardless of the number of occupants, and by allowing them to park for free in spaces designated for carpool operators.

Table 19. Vehicle purchase incentives by state

State	Policy summary
Arizona	- Reduced vehicle license tax for an alternative fuel vehicle (AFV) - Use tax exemption for vehicles converted from diesel to alternative fuels - HOV lane and free parking incentives
Colorado	- Income tax credit for the purchase or lease of LDV and MHDV EVs, plug-in hybrid electric vehicles (PHEVs), and AFVs - Grants to scrap & replace pre-2009 MHDVs, with EVs or renewable natural gas vehicles - Grants for local government to purchase electric vehicles
Montana	- Grants for MHDV electric and alternative fuel transit buses - Income tax credit for converting conventional fuel vehicles to use alternative fuels
New Mexico	- Grants for converting MHDVs to run on alternative fuels, and for new electric MHDVs - Revolving loan fund for local government AFV purchases
Utah	- Income tax credit for the purchase of AFV MHDVs - Grants for businesses to convert conventional fuel vehicles to AFVs
Wyoming	N/A

Source: North Carolina Clean Energy Technology Center, 2021

[70] https://ww2.arb.ca.gov/resources/fact-sheets/advanced-clean-fleets-regulation-summary
[71] https://uscode.house.gov/view.xhtml?hl=false&edition=prelim&req=granuleid%3AUSC-prelim-title26-section30D&num=0&saved=%7CKHRpdGxlOjI2IHNlY3Rpb246MzBDIGVkaXRpb246cHJlbGltKQ%3D%3D%7C%7C%7C0%7Cfalse%7Cprelim
[72] https://uscode.house.gov/view.xhtml?hl=false&edition=prelim&req=granuleid%3AUSC-prelim-title26-section30B&num=0&saved=%7CKHRpdGxlOjI2IHNlY3Rpb246MzBDIGVkaXRpb246cHJlbGltKQ%3D%3D%7C%7C%7C0%7Cfalse%7Cprelim

Fuel standards and subsidies

The federal Renewable Fuel Standard (RFS)[73], established by the Energy Policy Act of 2005 (which amended the Clean Air Act to include the RFS[74]) and later modified by the Energy Independence and Security Act of 2007, is an example of a regulatory policy aimed not at vehicles but at increased adoption of low carbon fuels, such as biodiesel and ethanol. The RFS requires fuel blenders to incorporate a certain amount (determined annually by EPA as the Renewable Volume Obligation or RVO) of renewable fuels[75] into their petroleum-based gasoline and diesel products, with a goal of incorporating 36 billion gallons of total renewable fuels by 2022[76]. Compliance is demonstrated by how many renewable fuel credits (referred to as Renewable Identification Numbers or RINs) a given firm acquires in a given year. Firms can acquire RINs when they purchase fuels, or they can purchase RINs directly in a credit market.

The federal government also utilizes the tax code to incentivize a shift to low carbon fuels. For example, a biodiesel tax credit of $1.00 per gallon may be claimed by fuel blenders for adding biodiesel or renewable diesel to diesel fuel, including heating oil.

Three states (Bracmort, 2021) in the nation have programs similar to the RFS: the California Low Carbon Fuel Standard, the Oregon Clean Fuels Program, and the Washington Clean Fuel Standard[77]. All of these policies mandate increased adoption of low carbon fuels. While Colorado and New Mexico have both considered similar policies[78], at the time of writing none of the Intermountain West states have implemented such a policy. Nonetheless, the federal policies as well as the west coast state policies all together create a demand for biofuel production in the region, even if some of that production is consumed elsewhere.

[73] See 40 CFR Subpart M
[74] See 42 U.S. Code § 7545(o)
[75] The RFS defines renewable fuels as: biomass-based diesel, cellulosic biofuel, advanced biofuel, and total renewable fuel.
[76] https://www.epa.gov/renewable-fuel-standard-program/overview-renewable-fuel-standard
[77] https://ww2.arb.ca.gov/our-work/programs/low-carbon-fuel-standard, https://www.oregon.gov/deq/ghgp/cfp/Pages/default.aspx, https://ecology.wa.gov/Air-Climate/Climate-change/Reducing-greenhouse-gases/Clean-Fuel-Standard
[78] https://drive.google.com/file/d/11zczj8ieUzNbxMvlob9HJCctyzJGVYF3/view; https://www.nmlegis.gov/Sessions/21%20Regular/bills/senate/SB0011.pdf

Vehicle fueling infrastructure

The federal 30C[79] Alternative Fuel Vehicle Refueling Property Credit provides a tax credit up to 30 percent of the cost of certain fueling infrastructure associated with low-carbon transportation, including EV charging stations, as well as hydrogen and CNG fueling stations.

The federal government also advances clean transportation infrastructure through the distribution of funds via grants and by directing funds to states. For example, the Bipartisan Infrastructure Law, which passed in late 2021, directs $7.5 billion to projects aimed at EV charging infrastructure expansion. Another $5 billion goes directly to states through formula funding, and the remaining $2.5 billion is allocated to competitive grants[80]. In addition, long-standing policies such as the Federal-Aid Highways Program (FAHP) and the Federal Public Transportation Program (FPTP) have directed federal dollars to transportation projects, some of which could play a role in decarbonizing transportation. For example, in addition to generally supporting public transportation (an important strategy for reducing vehicle-miles traveled), the FPTP includes the Low or No Emission Vehicle Program, which provides funds (roughly $1 billion annually) through competitive grantmaking for the purchase of facilities that service low-emissions vehicles, such as electric vehicle charging stations (Mallett, 2022). And, while the FAHP largely funds the construction of highways, it also includes a program focused on reducing emissions from transportation—the Congestion Mitigation and Air Quality Improvement Program, which was allocated an average of $2.4 billion annually in recent years (Kirk, 2021).

The Intermountain West states are all part of REV West, a consortium of eight states (including the six encompassed in I-WEST, plus Idaho and Nevada) working to develop an "Intermountain West EV Corridor," including coordination on the siting of EV charging stations, fundraising, establishing voluntary minimum standards for charging stations and more[81].

In addition, as indicated in Table 20, several of the Intermountain West states have individual policies to promote the development of EV charging and AFV fueling infrastructure, in addition to incentives and other programs offered by electric utilities.

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79 https://uscode.house.gov/view.xhtml?req=(title:26%20section:30C%20edition:prelim)
80 https://www.whitehouse.gov/briefing-room/statements-releases/2021/12/13/fact-sheet-the-biden-harris-electric-vehicle-charging-action-plan/
81 https://www.naseo.org/issues/transportation/rev-west

Table 20. EV and AFV infrastructure incentives by state	
State	**Policies**
Arizona	N/A
Colorado	- Grants for fueling and charging infrastructure - Natural gas fueling station air quality permit exemption - Technical assistance / coaching on EV infrastructure development
Montana	N/A
New Mexico	- Grants for fueling and charging infrastructure
Utah	- Grants for EV charging infrastructure
Wyoming	N/A

Source: DSIRE

Future policy

In this section, we move our focus towards future policy needs and away from describing the current policy landscape. We present some ways of framing the topic first and then present a set of bullets describing future policy options by topic area. In this effort, we have drawn on—most importantly—topics, ideas and recommendations coming out of the I-WEST Policy Workshop, as well as interviews we conducted, reports we read, including state roadmaps, workshops held by others on the I-WEST team, and our own expertise as economists and policy analysts.

Framing future policy needs

There are two basic ways of thinking about future policies: (i) as a roadmap and (ii) as a menu. For the former, a set of policies is presented as an integrated whole with tradeoffs and potential inconsistencies among them already worked out. A menu approach, in contrast, presents a range of policies, making no claims of consistency or choosing the best policy combinations given the tradeoffs. Described in this way, (ii) is a preliminary step towards the desired goal for a roadmap. In this report, we "walk before we run" and take the approach of (ii).

In this spirit, there are several themes that underlie policy choices:

States start from very different places on energy and climate policies, so some have farther to go than others.

Each state has its own unique history of fossil fuel development and laws supporting and shaping that development. The degree of tribal, state, and local revenue dependence on this sector is one important outcome that is shaped in part by policy at all levels of government. Likewise, each state government projects a unique attitude towards climate change and policies to support the transition away from fossil fuels. These attitudes are manifest, for instance, in creation of transition roadmaps by some states. Populations have attitudes that, in some states, predominantly small government and tout that they are “open for business,” while other states favor a larger government role and seek to significantly shape industry behavior.

Policies addressing sectors, technologies, and fuels will be needed. Take advantage of federal policies; leverage federal and non-regional governments; find industry first movers.

Irrespective of a state’s history, attitudes, political orientation, and existing policy landscape, policies covering the major sectors (transportation, residential/commercial buildings, hard to decarbonize industry, the fossil fuel sectors), addressing cross-sectoral technologies (such as CCUS) and key “new” fuels (such as blue/green hydrogen and biofuels) will be needed to speed the transition and make it cost-effective. Fossil fuel dependent states and tribes may naturally turn to policies favoring blue hydrogen and CCUS more generally, because these approaches permit a thriving natural gas sector. States and tribes with a high degree of dependence on oil extraction may focus on reducing upstream emissions (e.g., methane) from extraction and pursuing net-zero carbon oil through the combination of direct air capture and enhanced oil recovery.

Of course, when considering future policies, states and tribes are not on their own. They may have considerable help from voluntary actions by the private sector, public-private partnerships, and the federal government. Private sector leadership, pushed by their employees, stockholders, lenders, and rating agencies, is increasingly setting ambitious GHG reduction targets, developing company and Association-level decarbonization roadmaps, and planning (and in some cases already building) major decarbonization projects. In the region, some 60 projects are listed in this category. Granted, some of these projects have also been pushed by state and federal financial help (see below). In any event, states would do well to partner with industry leaders across a variety of dimensions, including public-private partnerships on pilot projects and policies to encourage voluntary behavior (e.g., favorable tax treatment, zoning exceptions, and expedited permitting).

Considering the federal aid, there are a raft of policy carrots and sticks administered by the federal government that have been detailed in the policy landscape section of this chapter. The leveraging we have in mind could take several forms, including getting more federal risk bearing guarantees for modular nuclear power plants and CO_2 leakage liabilities from storage wells, as well as helping to enforce and build upon federal regulatory programs, such as the proposed methane rule for existing oil and gas wells.

As for leveraging state government policies, some of the fossil fuel-dependent Intermountain West states and tribes are major exporters of this energy, such as to the West Coast. Given that some of the greatest market opportunities for clean energy generated in Intermountain West states exist in CA, OR, and WA (where strong decarbonization policies do exist, such as renewable portfolio standards and low carbon fuel standards), special attention should be placed on policies and infrastructure development efforts that maximize access to those markets (such as high voltage transmission lines that connect wind resources from Wyoming and Montana, for example, to the Pacific state markets).

Work together to (i) harmonize policies, including those on infrastructure (grid); (ii) be competitive for federal demonstration project funding; (iii) build interdependent roadmaps.

While Intermountain West states and tribes often go their own way on many policy issues, they already work together on many issues, but will have to raise these activities to a new level if the region is to cost-effectively decarbonize. Policy harmonization is needed on regulations for hydrogen and CO_2 pipelines that cross state or tribal borders, for instance. Most important is to end the balkanization of the electric grid, this region along with the southeastern US being the only regions not served by an independent system operator or regional transmission organization. Such operators could lead region-wide planning for smart grids and new transmission lines and help in load balancing as more generation relies on intermittent renewables. Another important concern is economic "leakage" of emissions. Unless states cooperate, tight regulations in one state could end up being offset by industry relocation to other states or by other activities that move geographically to take advantage of cost and regulatory differentials.

We envision a more short-term cooperation among states as well, recognizing that in competing for major federal grant money under the new Infrastructure legislation and earlier legislative initiatives, multi-state proposals that take advantage of each state's comparative advantage will be more competitive than one state going it alone. Already, in response to the $8 billion being made available for hydrogen hub demonstration projects, Wyoming, Colorado, Utah, and Montana have signed an MOU to submit a joint proposal to help secure a hydrogen hub for the region termed WISHH (Western Inter-States Hydrogen Hub).

Ultimately, just as states need to plan their own decarbonizing strategies—as Colorado and New Mexico have done with their roadmaps—the Intermountain West states need to build roadmaps that reflect and address their interdependencies in decarbonizing.

Native nations in the Intermountain West face a distinct set of challenges and opportunities, with wide variation across tribes.

Tribes have experienced many injustices over two centuries, including energy and environmental injustices for tribes in the region. These include health impacts associated with coal and uranium mining, mismanagement of energy leases on tribal trust lands, and a lack of access to modern energy services. For an energy transition to be successful, federal and state officials will need to work closely with their tribal partners, treat them as equals, and seek to address the injustices of the past.

Some tribes, such as the Navajo, Hopi, and Crow, have already experienced substantial economic disruptions due to the downturn of coal mining and coal-fired power generation. These tribes are taking different approaches to the energy transition, in some cases working closely with the federal government to speed the deployment of renewable energy—solar in particular.

However, numerous barriers exist to developing clean energy on and around reservation land. This includes (1) bureaucratic challenges associated with working with multiple federal agencies that slows permitting processes; (2) difficulty accessing federal tax credits for clean energy, CCUS, and other projects; and (3) limited access to existing energy infrastructure (e.g., transmission lines).

Some tribes in region depend heavily on oil and gas production as an economic engine. These include the Southern Ute Indian Tribe, Jicarilla-Apache, Ute Indian Tribe of the Uintah & Ouray Reservation, and the Eastern Shoshone and Northern Arapaho Tribe of the Wind River reservation. These tribes will face important questions about the role that oil and gas production will play in their energy futures. Some, such as the Southern Ute Indian Tribe, are taking innovative approaches to deploying new zero-emissions technologies that can help play an important role in the energy transition.

Community attitudes to transition could determine success, so engagement and tailoring policy interventions to state and local policy conditions are important.

Federal or state efforts to support an energy transition will only be successful if they work closely with community partners and leverage local strengths. Consistent communication between federal, state, and local partners will be essential, and will need to flow in multiple directions, so that federal and state priorities can match local needs and "on the ground" experience.

Developing these relationships will take time and require resources. In some Intermountain West communities, there is a strong local culture of independence and skepticism of federal government interventions. Federal and state policymakers should seek to engage local stakeholders early and often to build trust and incorporate local perspectives to address potential barriers.

Community issues have the potential to accelerate or impede the energy transition. Benefits will include new employment opportunities, tax revenue, and potentially reduced local pollution. But concerns will also arise from siting new infrastructure (e.g., pipelines, CCUS facilities, electricity infrastructure). Policymakers at all levels will need to understand and address these concerns as they arise.

A transition away from fossil fuels could be very disruptive for some communities, particularly those with a heavy reliance on coal, oil, and natural gas activities for local employment and tax revenue. Policymakers will likely need to allocate resources to support workers and communities in transition.

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I-WEST

Phase One Final Report | Detailed Chapter

Economic Impacts

VERSION 2.0 UNIVERSITY OF NEW MEXICO JUNE 2023

About this chapter

The Intermountain West Energy Sustainability & Transitions (I-WEST) initiative is funded by the U.S. Department of Energy to develop a regional technology roadmap to transition six U.S. states to a carbon-neutral energy economy. I-WEST encompasses Arizona, Colorado, Montana, New Mexico, Utah, and Wyoming. Each state is represented in this initiative by a local college, university, or national laboratory. Additional partners from beyond the region were selected for their expertise in applicable fields. In the first phase of I-WEST, the team built the foundation for a regional roadmap that models various energy transition scenarios, including the intersections between technologies, climate, energy policy, economics, and energy, environmental, and social justice. This chapter presents work led by an I-WEST partner on one or more of these focus areas. A summary of the entire I-WEST phase one effort is published online at www.iwest.org.

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Table of Contents

Introduction

The economic impact of energy transition projects in the Intermountain West is a complex subject with spatial and temporal considerations. Since carbon dioxide (CO_2) is a global greenhouse gas, reducing CO_2 emissions has global benefits. However, the economic impacts of initiatives to reduce CO_2 are realized at local, state, or regional levels. Assuming a technology is viable, economic impacts at these levels may include a variety of considerations, including but not limited to jobs impacts, tax revenues, local environmental impacts, resource constraints, or timing of a project. This report focuses on factors that are highly variable at the county level and the potential that each has on economic outcomes.

In this report, economic impacts are divided into five sections. The first section provides an overview of relevant economic factors in the Intermountain West states, with a focus on the county levels. The second presents two case reviews of counties that have a history of energy production and are moving toward transition economies. The third section provides a series of location-specific input-output analyses that illustrate the potential economic impacts of a project on that county. The fourth section focuses specifically on bioenergy, while the fifth and final section discusses the potential impact of heterogeneity on outcomes and the importance of considering heterogeneity in economic outcomes of projects.

Economic conditions

The Intermountain West states and counties are diverse in economic activity, community characteristics, employment, population density, and land ownership. The impact of a transition technology deployed in any of the 220 counties in the region may depend on current energy production; technology deployed; existing infrastructure; economic conditions, including economic diversity, workforce characteristics, or alternative opportunities; and impacts on air, water, and land.

County characteristics

Of the 220 counties in the region, 170 are classified as non-metropolitan areas by the USDA Economic Research Service (ERS), (2020a). As shown in Figure 1, the geographic distribution and number of non-metropolitan counties varies by state, with Montana (MT) and Wyoming (WY) having the largest percentage of counties with small populations.

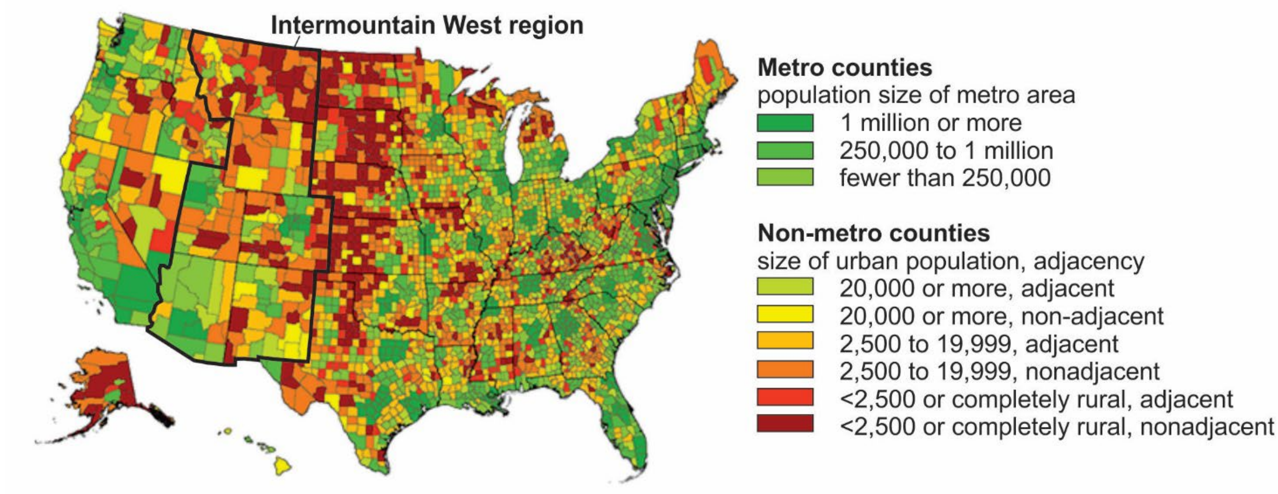

Figure 1: Rural-urban continuum county classification map (modified from USDA, Economic Research Service). Classification codes are from 2013.

State-level economic activity

Economic activity, as evidenced by gross domestic product (GDP), varies across the states, not only in terms of the current level of economic activity, but also the compound annual growth rate from 2015 to 2020 (U.S. Bureau of Economic Analysis (BEA) 2022). Table 1 provides an overview of economic activity in each state in 2015 and 2020. The U.S. economy grew 2.8% over the 2015-2020 period (BEA 2022). The Intermountain West states exhibited varying levels of growth. Arizona (AZ), Colorado (CO), and Utah (UT) saw larger growth over the period than the U.S. as a whole. While Montana (MT) and New Mexico (NM) saw positive growth, growth in these states was lower than the national average. Wyoming (WY) experienced a decline over the 2015-2020 period, which is largely attributed to a decline in numerous industries impacted by the COVID-19 pandemic in 2020 (Wyoming Economic Analysis Division, 2021).

Table 1. Economic activity 2015 and 2020 (data from U.S. Bureau of Economic Analysis)

State	2015 GDP (in millions of current $s)	2020 GDP (in millions of current $s)	Compound Annual Growth Rate (2015 to 2020)
AZ	299,393.3	373,719.0	4.5%
CO	320,721.1	382,584.7	3.6%
MT	46,604.1	51,508.8	2.0%
NM	90,274.3	98,472.1	1.8%
UT	149,153.4	197,561.9	5.8%
WY	38,426.9	36,323.5	-1.1%

County-level economic activity

There are substantial variations in economic activity at the county level. Figure 2a-f show the 2015-2020 compound annual growth rates at the county level (BEA, 2022). All Arizona counties had positive economic growth over the period, with the largest concentration of counties with low growth rates in the non-metropolitan, northeast part of the state. The highest growth rates were in the metropolitan counties.

Colorado saw a variation in growth with many counties experiencing negative growth—up to an 11% decline —while other counties experienced growth as high as 14%, compounded annually. Montana counties had high variations in annual growth rates ranging from over 40% growth to over 40% decline. Most New Mexico counties experienced negative growth over the period. The majority of Utah counties experienced growth, and this state experienced the highest state-level growth rate in the Intermountain West region over the period (as shown in Table 1). Wyoming saw small positive growth in some counties, but large declines in others, resulting in a negative overall state-level annual growth rate.

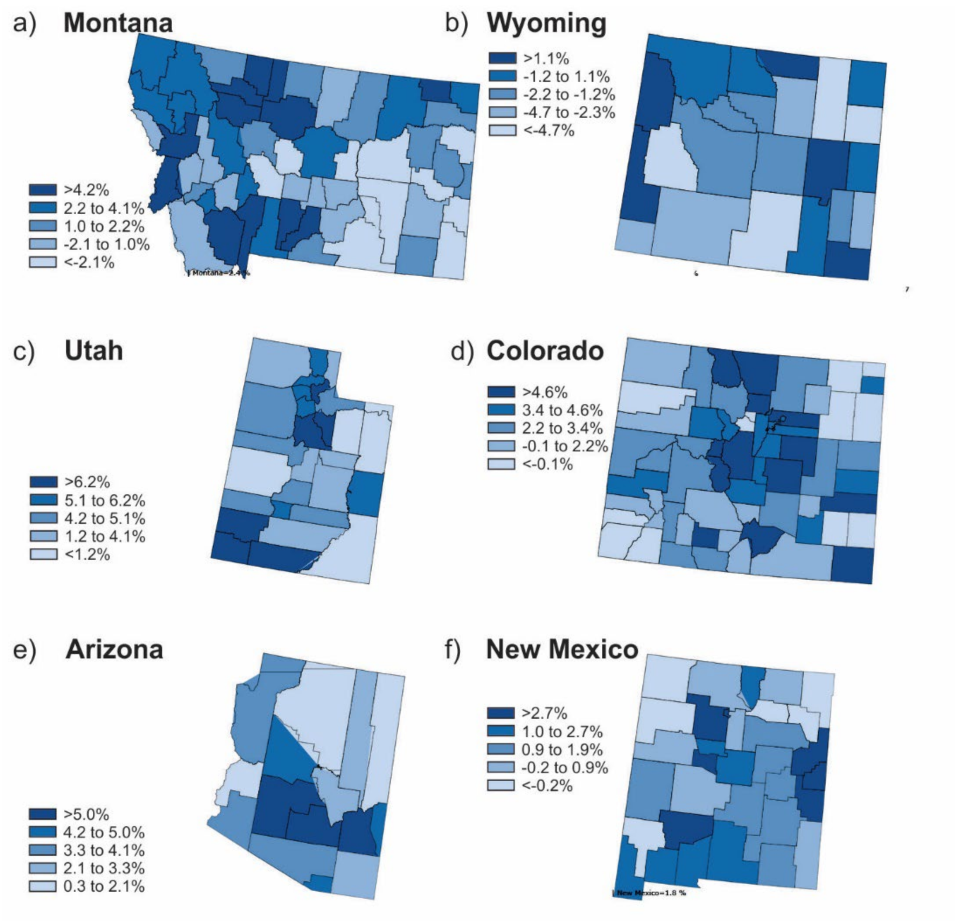

Figure 2. County annual compound growth rates 2015 to 2020, all industries. Source: BEA. a) Montana; b) Wyoming; c) Utah; d) Colorado; e) Arizona; f) New Mexico.

State-level energy economic activity

Specific to energy, of the 220 counties in the Intermountain West, ShaleXP (2022) reports 90 counties were producing oil in January 2022, and 103 produced natural gas in January 2022. The USDA ERS (2020b) reported that during 2011, 104 counties produced oil and 113 produced natural gas. This is a 13.5% decline in oil producing counties and an almost 10% decline in counties producing natural gas.

The U.S. Energy Administration (EIA) (2021a) reports that 19 counties produced coal in 2020, compared to 22 counties in 2015 (EIA 2016). The U.S. Environmental Protection Agency (EPA) reports that 75 counties generated electricity from fossil fuels or biomass in 2020 (EPA 2022), nine of which had operating refineries (EIA 2021b).

These variations can impact economic activity. Table 2 presents activity levels in 2015 and 2020, as well as the compound annual growth rate over the five years for the mining, quarrying, and oil and gas production sectors (referred to as "extractive" from here forward), and utilities sectors (referred to as "utilities" from here forward), respectively. Mining, quarrying, and oil and gas production is the North American Industry Classification System (NAICS) NAICS 21 sector and includes oil and gas extraction (NAICS 211), mining – except oil and gas (NAICS 212), and support activities for mining (NAICS 213). Utilities is the NAICS 22 sector and consists of electric power generation, transmission and distribution (NAICS 2211), natural gas distribution (NAICS 2212), and water, sewage and other systems (NAICS 2213).

Four of the six states saw contractions in economic activity levels for mining, quarrying, and oil and gas production, and three of the four states saw overall positive economic activity during the same period. All six states saw positive growth rates in the utilities sector.

Comparing Tables 1 and 2, the importance of the energy sectors to each state becomes clearer. Table 3 provides the percentage of total GDP contribution for the two sectors for each state in 2015 and 2020. The state with the largest economy, Arizona, has the lowest dependence on the extractive sector (during both years), while the two states with the weakest economic performance between 2015 and 2020, New Mexico and Wyoming, have the highest dependence. Contributions from the utility sector are relatively small in all states.

Table 2. State-specific economic activity 2015-2020. Source: BEA

State	Mining, Quarrying, Oil and Gas Production (Extractive)			Utilities		
	2015 (millions current $s)	2020 (millions current $s)	Compound Annual Growth Rate (%)	2015 (millions current $s)	2020 (millions current $s)	Compound Annual Growth Rate (%)
AZ	3,881.8	4,470.7	2.9	6,385.7	7,401.6	3.0
CO	11,663.1	7,345.4	-8.8	4,055.0	4,784.1	3.4
MT	1,944.3	1,765.9	-1.9	1,096.4	1,163.0	1.2
NM	6,977.4	6,227.1	-2.2	1,616.7	1,813.6	2.3
UT	3,047.5	3,261.2	1.4	2,002.6	2,908.1	7.7
WY	7,023.8	4,614.2	-8.1	1,011.4	1,024.7	0.3

Table 3. Contribution to state GDP by sector. Source: BEA				
State	GDP Contribution by Extractive Sector (%)		GDP Contribution by Utilities Sector (%)	
	2015	2020	2015	2020
AZ	1.3	1.2	2.1	2.0
CO	3.6	1.9	1.3	1.3
MT	4.2	3.4	2.4	2.3
NM	7.7	6.3	1.8	1.8
UT	2.0	1.7	1.3	1.5
WY	18.3	12.7	2.6	2.8

County-level energy economic activity

The importance of energy and utilities to county level economies shows high variation. Figures 3-8 present the county level activity for extraction and utilities for 2020 for the six Intermountain West states, as well as the compound annual growth rate during the 2015 to 2020 period.

In Arizona, the largest extractive activity in 2020 was associated with mining and occurred in counties located in the southern part of the state (Figure 3). The largest compound growth rates occurred in the northwest and southeast, and the largest declines occurred in the northeastern counties, which include traditional coal producing areas. Utility activity was distributed across Arizona, and growth in utility activity mainly occurred in the southern portion of the state. State-wide, both the extractive and utility sectors experienced annual increases between 2015 and 2020.

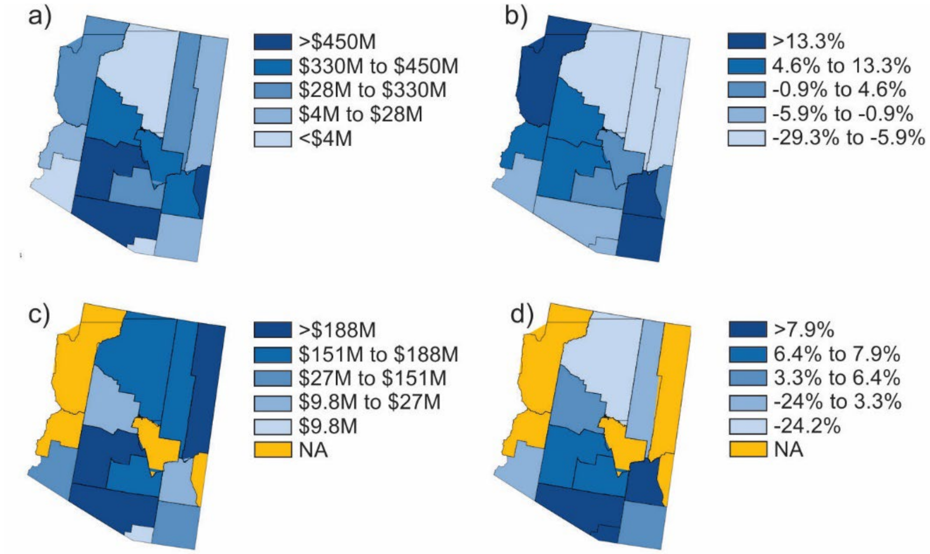

Figure 3. Arizona extraction and utility economic activity by county. Source: BEA. a) 2020 Extraction activity; b) 2015-2020 Extraction industry growth rate; c) Utility activity; d) 2015-2020 Utility industry growth rate.

In Colorado (Figure 4), the largest contributions from extractive industries are in the northwest, southwest, and north central portion of the state; however, the annual growth rate has been largely negative. Specific to utilities, the largest contributions to GDP in 2020 are from the northern half of the state, but the largest growth has been in the southeast quadrant. Both the extractive and utilities sectors may reflect the changing focus on energy extraction and the move toward renewables. While the overall, state-level result is an annual decline in GDP contributions from the extractive sectors, there was an overall annual increase in the contribution from the utilities sector.

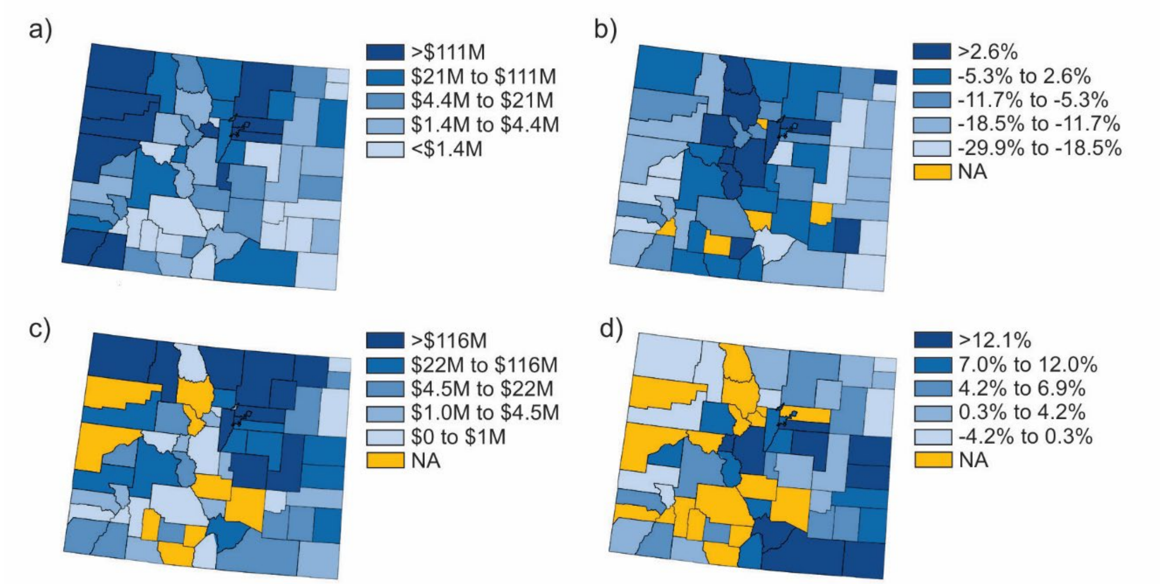

Figure 4. Colorado extraction and utility economic activity by county. Source: BEA. a) 2020 Extraction activity; b) 2015-2020 Extraction industry growth rate; c) Utility activity; d) 2015-2020 Utility industry growth rate.

In Montana (Figure 5), the extractive industries in the southern portion of the state were among the largest contributors to state GDP in 2020. Growth between 2015 and 2020 mainly came from the southwest portion of the state. The overall impact was an annual 1.9% decline in the extractive industries. 2020 GDP contribution from the utilities sector was primarily from the central and northwest sections of the state. The annual growth from the sector is distributed through the state. The overall impact was an annual 1.2% increase in the utilities sector contribution to GDP.

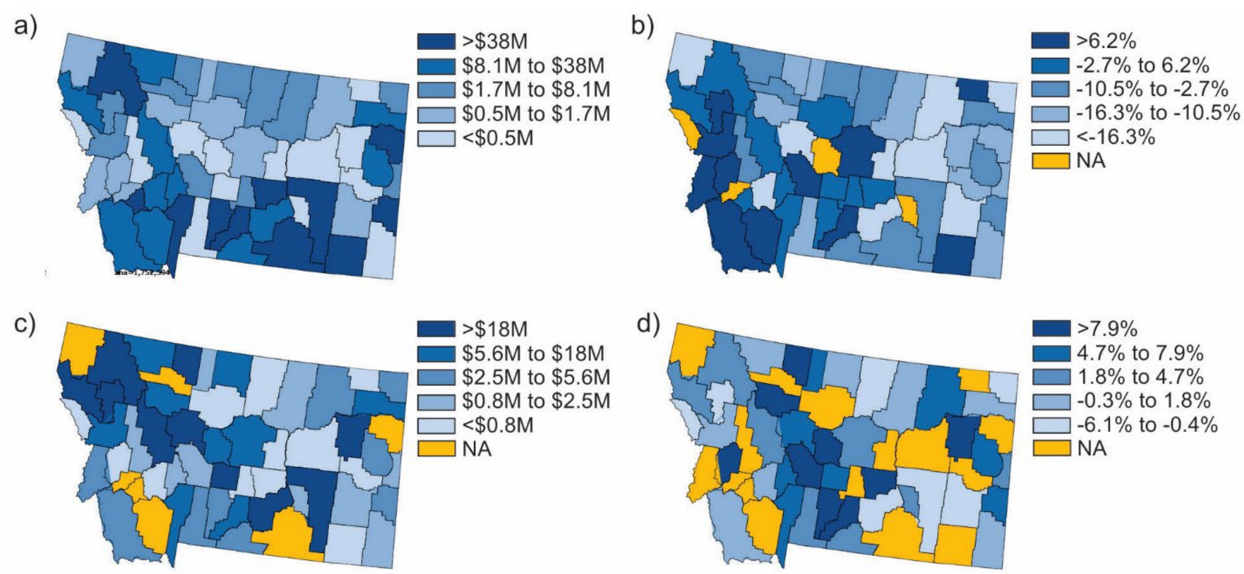

Figure 5. Montana extraction and utility economic activity by county. Source: BEA. a) 2020 Extraction activity; b) 2015-2020 Extraction industry growth rate; c) Utility activity; d) 2015-2020 Utility industry growth rate.

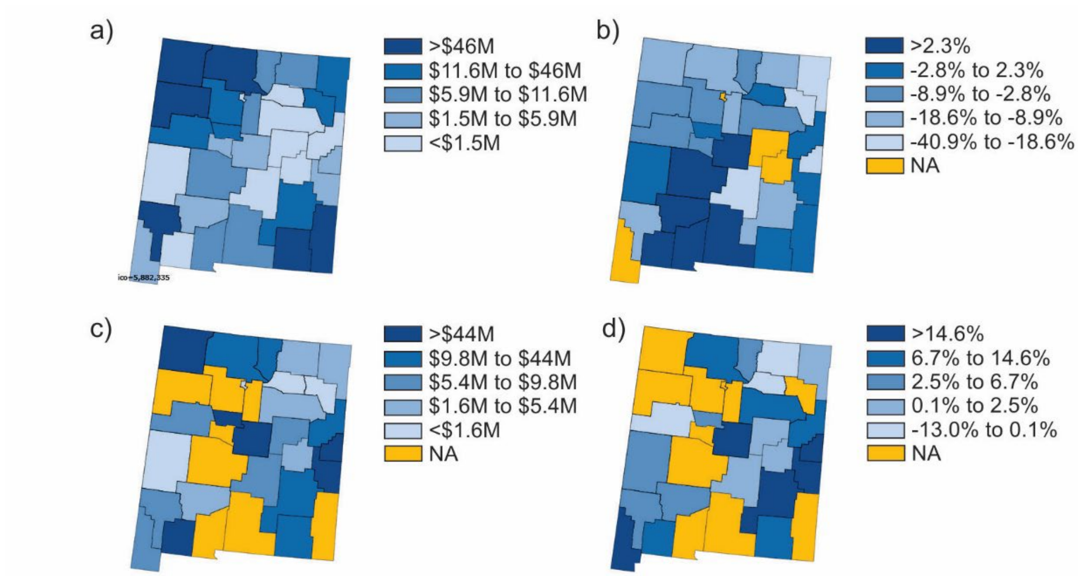

Figure 6. New Mexico extraction and utility economic activity by county. Source: BEA. a) 2020 Extraction activity; b) 2015-2020 Extraction industry growth rate; c) Utility activity; d) 2015-2020 Utility industry growth rate.

New Mexico's largest contributions to the extractive sector GDP are from the northwest and the southeast portions of the state, which coincide with the San Juan Basin natural gas producing area and the Permian Basin, respectively (Figure 6). However, both areas saw negative annual growth rates over the period. Specific to utilities, many counties show no measurable economic activity in 2020. A few counties in the northwest, central, and eastern sections have the largest contributions in 2020. However, the largest annual increases are limited to those same counties in the central and eastern part of the state.

In Utah, the 2020 extraction activity is strongest in the eastern half of the state (Figure 7) with counties in the northeast providing large contributions. However, the rate of annual growth between 2015 and 2020 has been very low or negative for these same counties. Over the same time in the utilities sector, the largest annual growth from 2015 to 2020 is from counties in the northwest and southwest corners of the state.

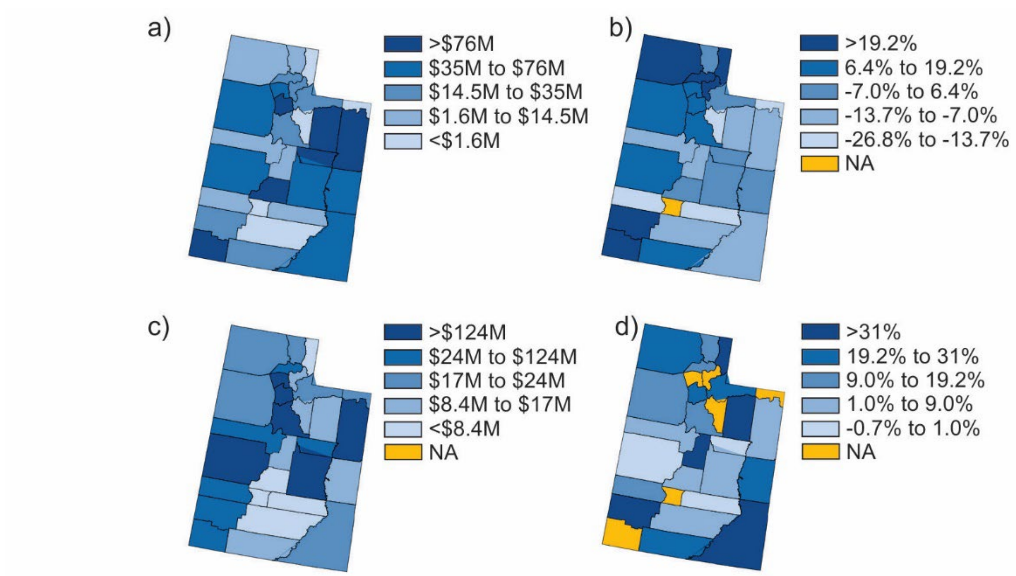

Figure 7. Utah extraction and utility economic activity by county. Source: BEA. a) 2020 Extraction activity; b) 2015-2020 Extraction industry growth rate; c) Utility activity; d) 2015-2020 Utility industry growth rate.

In Wyoming, the largest contributions to the economy from the extraction sector come from five counties (shown in dark blue, Figure 8). However, all five of these counties experienced negative annual growth rates between 2015 and 2020. The strongest annual growth rates come from counties that are among the smallest contributors to GDP in 2020. Most counties show little to no contribution to the utilities sector, with only six counties showing an annual compound growth rate of more than 3.9%. Uinta county in the southwest portion of the state was among the top contributors to 2020 GDP and had one of the highest growth rates over the 2015-2020 period.

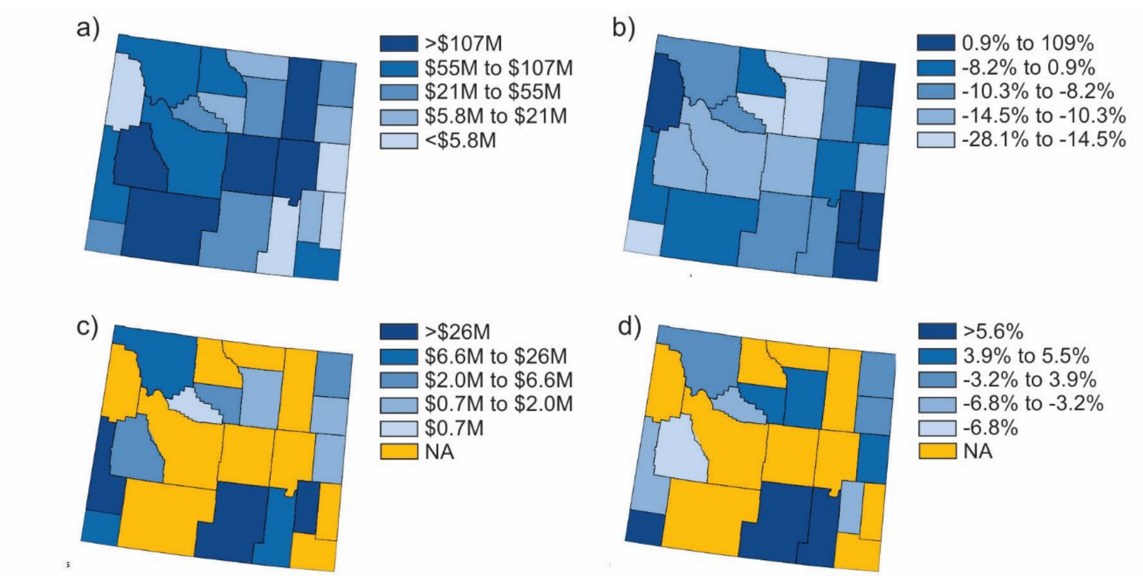

Figure 8. Wyoming extraction and utility economic activity by county. Source: BEA. a) 2020 Extraction activity; b) 2015-2020 Extraction industry growth rate; c) Utility activity; d) 2015-2020 Utility industry growth rate.

The variation in growth rates and contributions across the six Intermountain West states demonstrates how complex the energy industry in the region is, and how complex the deployment of energy-transitions technologies could be moving forward. No two counties face the same set of circumstances.

Many counties currently contributing to energy activities may be suited to technologies that can be added on to existing projects. For example, in Lincoln County, Wyoming, CO_2 as a by-product of natural gas production is separated and then used for enhanced oil recovery. Additional projects are being considered in Wyoming and in San Juan County, New Mexico that would allow coal-fired generation to continue with added carbon capture, utilization, and storage (CCUS) technology.

Counties with little or no current energy production may consider alternative technologies such as hydrogen, or biomass. Technology deployment will depend on the economic suitability of the location for that technology, where suitability is broadly defined to consider the unique characteristics of the location, as well as local goals and objectives.

Jobs

At the local level, job retention and the potential for new jobs are a primary focus for the technology deployment. According to U.S. Bureau of Labor Statistics (BLS) data (BLS 2022), the annual unemployment rate in the U.S. during 2021 was 5.4%. At the same time, the unemployment rate in the Intermountain West region was 4.8%. Figure 9 presents the annual unemployment rate for the U.S., the Intermountain West region, and for each individual state within the region from 2011 through 2021. New Mexico and Arizona consistently have the highest state-level unemployment rate during this period, and Utah has the lowest state-level unemployment rates during most years.

The variation in unemployment rates across counties is as varied as that of the states. Figure 10 presents the average annual unemployment rates for 2022 by county.

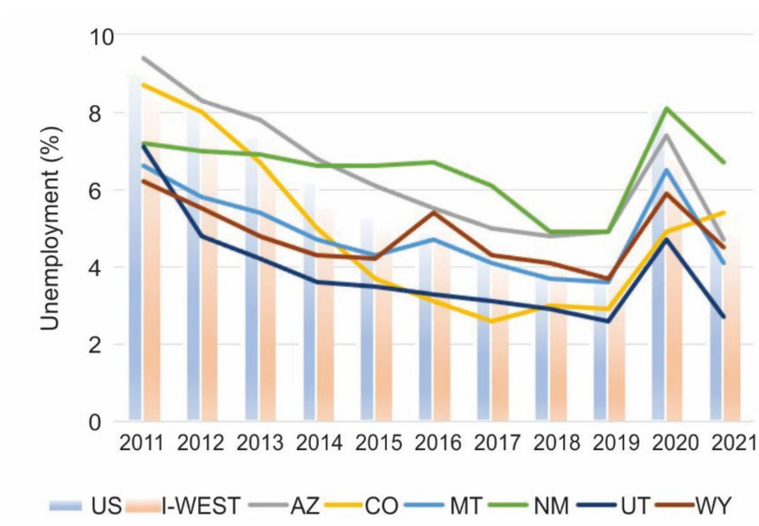

Figure 9. Annual unemployment rates. Source: BLS.

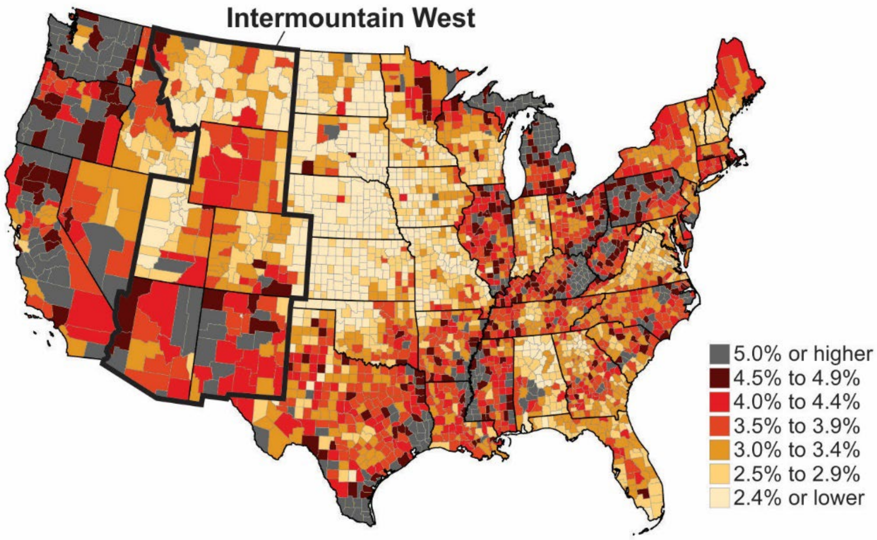

Figure 10. Unemployment rates by county, 2022. Source: BLS.

In April 2022, the monthly unemployment rate across the Intermountain West was 3.57%. During this month, the rate at the level of a single county ranged from 1.5% to 14.5%.

Of the 220 counties in the region, 84 (~38%) had unemployment rates above the regional average. In each county with an unemployment rate above the average, there is at least one factor previously discussed that correlates to that county. Almost all coal-producing counties had an above average unemployment rate. 39% of natural gas producing counties are above the average unemployment rate, as are 38% of the oil producing counties. 65% of the counties with an above average unemployment rate are non-metropolitan counties.

Unemployment is also correlated to workforce availability. Figure 11 shows the workforce numbers for each state from 2017 through 2021. The workforce availability in Arizona and Colorado dwarfs that of the other Intermountain West states.

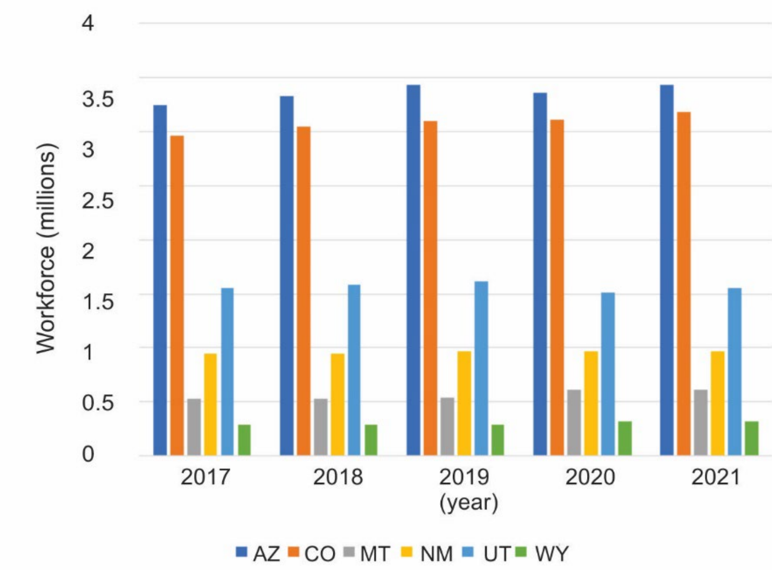

Figure 11. Workforce by state. Source: BLS.

Table 4 provides the annual percentage change in workforce levels for each state. At the state level, comparing the change in workforce to the unemployment level can begin to provide detail concerning factors impacting unemployment levels. For example, in Colorado in 2021, the unemployment rate increased. However, the workforce also increased by 2.2%, suggesting either a potential workforce migration into the state, or workers returning to the workforce, which is an indication that the demand for work outpaced job opportunities.

Table 4. Annual percentage change in workforce. Source: BLS

State	2017	2018	2019	2020	2021
AZ	-0.4%	2.7%	3.1%	-2.0%	1.9%
CO	2.4%	2.9%	1.7%	0.4%	2.2%
MT	1.3%	1.0%	1.6%	12.4%	1.1%
NM	0.5%	0.2%	1.4%	-0.1%	0.8%
UT	3.6%	1.9%	2.2%	-6.4%	2.6%
WY	-2.2%	-0.3%	0.5%	10.3%	-1.0%

Focusing on the county level, in 2021, 30% of Wyoming counties had an annual workforce percentage change less than the state average. Montana had 39% of its counties below the state average, CO had 45% below, NM had 61% below, and UT had 62% below. Thus, there is substantial unevenness in workforce growth across states and counties. Migration between counties and states and/or workers returning to the workforce may be partially responsible, as may have changes in job availability within the location. During 2021 all the states saw an increase in the number of workers employed. Only 5 out of the 108 counties in Colorado, Arizona, and Utah—the states with lowest contributions to GDP from the extractive and utility sectors combined—had a decline in the number employed in each county. Meanwhile, 49 of the 112 counties in New Mexico, Wyoming, and Montana saw declines in employee numbers between 2020 and 2021.

Additional considerations of economic impact

The discussion above provides basic factors of importance to local and regional economic activity, and factors of consideration for energy transition technologies. However, there are additional factors that may be of importance, some of which are discussed below.

Paramount among these factors is availability of key resources, such as water and land. Figure 12 (Leeper et al., 2022) shows the number of weeks each county in the U.S. was in D3 (extreme) drought between 2000 and 2019. Potential impacts of D3, or extreme drought, are location specific, but in general include major crop or pasture loss, widespread water shortages, and water restrictions. Of the Intermountain West states, only Montana and Colorado have counties that experienced less than 50 weeks of drought over the period. Given the location and climate, Arizona and New Mexico have the largest number of counties with the longest periods of drought. Arizona, New Mexico, and Wyoming all have counties that have experienced more than 300 weeks of drought over this time period. This means these counties have experienced six or more years of extreme drought over the 20-year period. At the local or regional level, understanding the availability of water, and the potential impact (if water is a necessary input into a transition technology) is imperative, as is an understanding of the competing demands for water.

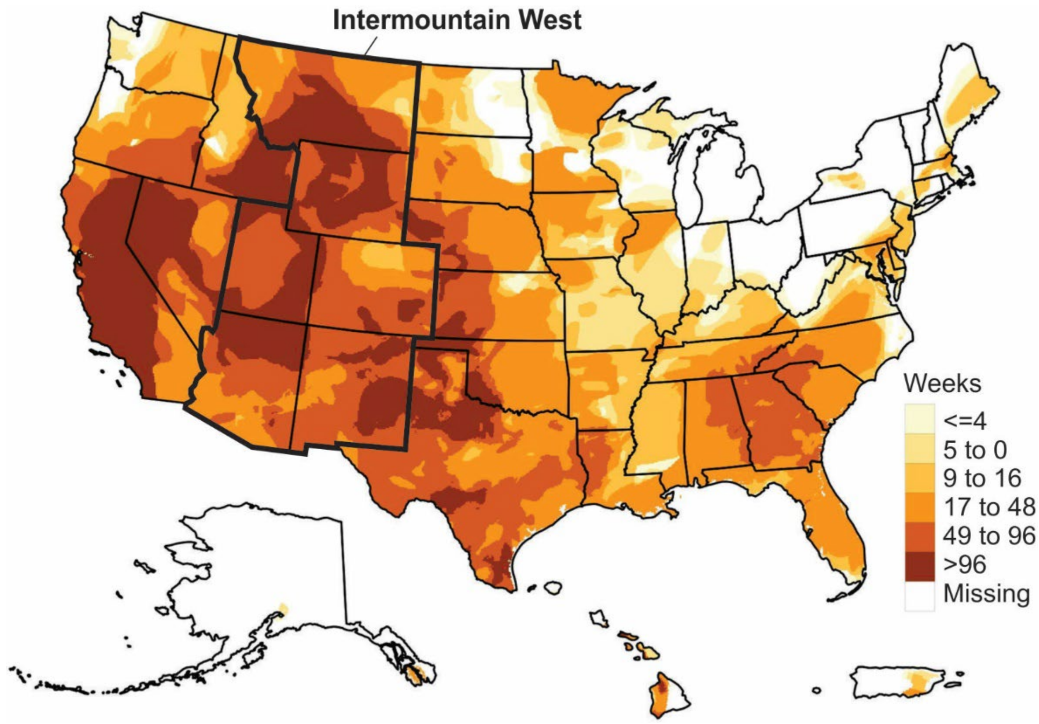

Figure 12. Weeks in D3 (extreme) drought from 2000-2019. From Leeper et al. (2022).

Land ownership in the region is a complex issue, with private, state, federal, and tribal lands interspersed across each state. Figure 13 shows the diverse types of land ownership across the western U.S., which may impact the economic outcome for a community or region. Projects that cross land ownership boundaries may have increased local economic impacts.

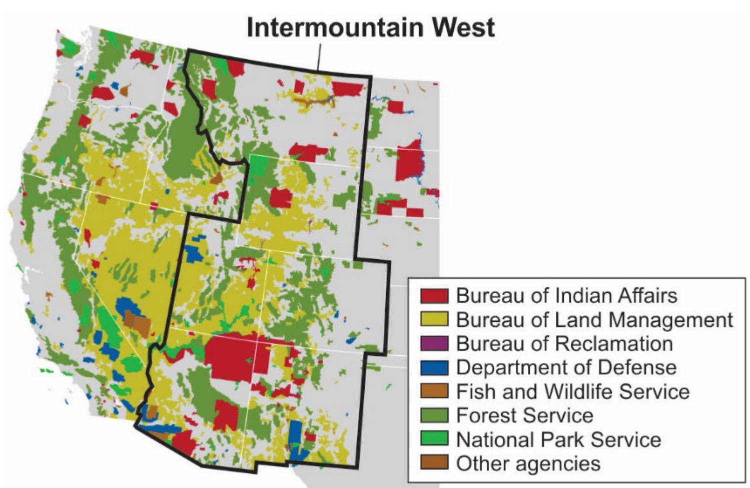

Figure 13. Land ownership in the Intermountain West region. Source: National Atlas of the United States, http://nationalatlas.gov.

The preceding paragraphs present an overview of factors that may influence the economic impact of a project on a region and factors that may affect place-based solutions. The discussion is not exhaustive, nor does it provide an assessment of individual locations. In addition, other factors such as policy and regulations, which are major factors of consideration, are not addressed here due to their complexity and location specificity.

Two overviews

This section provides a brief overview of two counties: San Juan County, New Mexico, and Lincoln County, Wyoming. Both have a long history of energy production and have faced boom-and-bust cycles because of their dependency on energy. While both are moving toward energy transition, the processes and current issues are unique.

San Juan County

San Juan County, located in the northwest corner of New Mexico, has been a major producer of natural gas since the 1920's. Since 2010, production in the county has declined from a high of 571.8 million thousand cubic feet (MCF) to 257.9 million MCF in 2021. Oil peaked at 5.59 million barrels (bbl) in 2019 and then declined to 4.25 million bbl (MineralAnswers.com 2022). A large portion of conventional natural gas reserves have been produced, and substantial interest remains in the Mancos Shale. However, increased production from the San Juan basin will, in part, depend on energy prices, tying a substantial portion of San Juan County's economic activity to boom-and-bust cycles outside the control of the county. For example, while the first commercial well was drilled in the area in the 1920s, the absence of a pipeline to export natural gas resulted in little activity until the 1950s, when a pipeline to the west coast was completed. This led to the county's first "boom" and a population increase from about 3,500 residents in 1950 to 23,000 in 1960 (Romeo, 2021)—an over 20% annual increase for the decade. The 1950s were followed by a series of cycles. In the 1990's the boom was associated with the production of natural gas from coalbed methane (CBM), which was aided by governmental subsidies to encourage development of CBM resources.

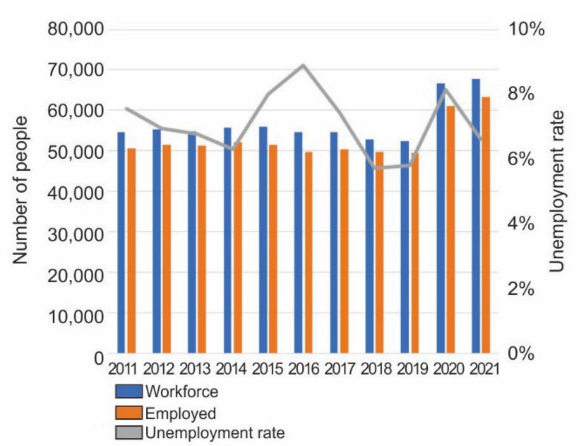

Figure 14. San Juan County, NM workforce and employment 2011-2021. Source: BLS.

Coal production was a later addition, with surface mining starting in the 1960s at the Navajo Mine and in 1973 at the San Juan Mine. Underground mining via a single longwall began in 2000 (Mercier 2010). Coal from the San Juan Mine was used to fuel the San Juan Generating Station, while coal from the Navajo Mine was supplied to the Four Corners Power Plant. Both the Navajo Mine and the Four Corners Generating Station are located in San Juan County on Navajo Nation lands.

Two units of the San Juan Generating Station were closed in December 2017, and the remaining two units are tentatively slated for closure in 2022, resulting in a full retirement of the plant. In addition, the Four Corners Power Plant decommissioned three of its five units, which greatly reduced the demand for coal.

The reliance of San Juan County on the energy industry is evident. In 2018, almost 7,720 San Juan County jobs were in the mining (including oil and natural gas extraction) and utilities sectors (Arrowhead Center, 2020). The jobs in these industries accounted for 15% of all jobs in the county. Change in employment in this sector can have a significant impact on the county's employment and overall economic activity. Figure 14 shows the overall workforce, employment, and the unemployment rates for the county from 2011 through 2021 (data from the BLS, 2022).

The reduced demand for coal, the push towards carbon zero electricity generation, and a location that is somewhat isolated has resulted in San Juan County focusing on broadening their economic base.

A variety of avenues are being considered. For example, in a 2018 report detailing economic opportunities in the Four Corners area, O'Donnell (2018) recommended that the region prioritizes tourism and recreation, solar and scalable storage, mine reclamation, healthcare, and local food systems.

In a second report, O'Donnell (2019) estimates that a 450-megawatt solar photovoltaic plant on the San Juan Generating site could replace lost property tax revenue, support thousands of jobs during construction, and generate over $65 million in additional tax revenue at the state and local level.

An alternative to closing the generating station is the installation of amine-based CO_2 capture technology for use in enhanced oil recovery, which is currently being pursued by Enchant Energy. Estimated jobs impacts are substantial, with Management Information Services, Inc. (2020) estimating this CCUS project would result in 92 times as many operations and maintenance jobs as a solar project. Without an influx of workers into the county, this level of job creation would result in full employment, which may be unrealistic.

County officials, Farmington city officials, Four Corners Economic Development, and Sovereign Nations are working towards a broader economic base, and as one official said, "all options are on the table." Their focus is centered on enhancing existing projects and expanding in new directions, both in energy and non-energy sectors. Specific to energy, the City of Farmington is partnering with Enchant Energy to develop the San Juan Generating Station Carbon Capture Project, and Navajo Transitional Energy Company (NTEC) has invested in Enchant Energy. San Juan Community College is focused on workforce development to broaden the base of workers in the area, to retrain displaced workers, and to provide opportunities to residents to remain in the county. A main focus in this area is to retain jobs, develop new job opportunities, increase economic activity in the county, and provide stability to the economy.

Lincoln County

Lincoln County, located in the southwest corner of Wyoming, has a long history of energy production. The majority of production is in the southern portion of the county in the Kemmerer, Cokeville, and Diamondville regions. Lincoln County has been a coal producing region since the late 1880s. Initially, the railroad was a major factor in the coal industry; the Oregon Short Line Railroad provided transportation and a market for coal for steam engines (Goldby et al., 2015). Coal production from the Kemmerer Mine, the only remaining mine in Lincoln County, generated about 4.1 million short tons in 2018, but production declined to about 2.5 million short tons in 2020 (EIA, 2021a). Coal from the mine is utilized at the Naughton power plant, also located in Lincoln County.

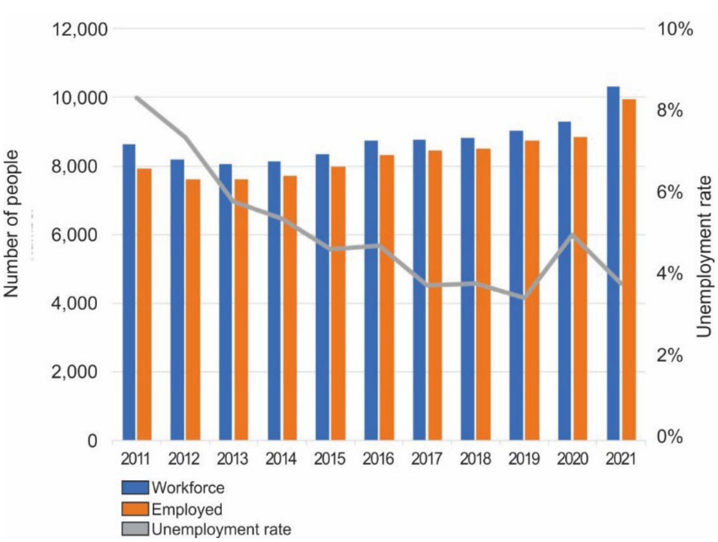

Figure 15. Lincoln County, WY Workforce and Employment (2011-2021). Source: BLS.

The county remains one of the top 10 natural gas producing counties in Wyoming (ShaleXP, 2022), but the county appears to be past peak production for oil and natural gas. Oil production peaked in 1999 at 3.1 million barrels and by 2020 declined almost 75%. Natural gas production peaked in 1994 at 344 million MCF and by 2020 had declined by 70% (MineralAnswers.com, 2022). In addition, the Naughton coal-fired power plant is slated for closure in 2025, which would result in a substantial loss of jobs both at the power plant and the Kemmerer Mine.

At the same time, Lincoln County is home to a number of innovative energy projects, such as the Shute Creek processing facility. High CO_2 and low methane levels in natural gas produced from the La Barge field required a combination of technology and economics to produce the natural gas. Over 30 years ago, technological advances and favorable economic conditions led to the decision to build the facility. The project's economics hinged on high oil prices and the ability to use CO_2 for enhanced oil recovery (EOR). Since its inception, the facility has sold about 50% of the total CO_2 for EOR and vented the remainder (Robertson and Mousavin, 2022). Shute Creek is the largest and third oldest CCUS facility in the world. Owner ExxonMobil initiated plans in late 2021 to expand the plant with a final decision expected in 2022 (Natural Gas World 2021).

The county is expanding its focus on energy; for example, permits for an 80-megawatt solar plant were filed in 2021. Also, in 2021, TerraPower announced Lincoln County as the home of its demonstration Natrium plant, which would be located near the Naughton plant. The technology is described as a cost-competitive sodium fast reactor combined with a molten salt energy storage system. The economic impacts on the county, if realized, would be substantial. This estimated 4 billion dollar project would double the population of Kemmerer during construction and, when operational, would provide about 250 permanent jobs. This project could provide an expanded energy economy in the county.

As shown in Figure 15, the county has a workforce slightly above 10,000 in 2021 and its unemployment rate is among the lowest in Wyoming (data from BLS, 2022). The county-level workforce has steadily increased since 2014, as have employment levels, with the only increase in annual unemployment rates occurring during the pandemic period. However, this county-level assessment does not reflect the reality in southern Lincoln County, where the population has been stagnant or declining since 2010, resulting in a stagnant workforce (The Bank of Star Valley, 2021). Energy prices has been a contributing factor.

Lincoln County's approach to economic development may best be summed up by a letter of support for the TerraPower project from the County Commissioners. The July 21, 2021 memo from the Lincoln County Commissioners (https://svinews.com/lincoln-county-commissioners-echo-support-for-proposed-nuclear-plant/) reads in part:

> *"Lincoln County is no stranger to energy projects. Our citizenry has long worked in energy production…energy is the heart of our county's economy… We have an*

existing workforce that is willing and able to transition to nuclear energy production.

The existing infrastructure would already support the needs this project would bring to Lincoln County."

The two counties highlighted above both have long, proud histories in energy production. The cyclical nature of the energy economy has resulted in both counties seeking paths to broaden their economic base, but both remain focused on energy as a main contributor to their economies. There is, however, a difference in the current apparent success of the counties. Location and accessibility may be contributing factors. Moving forward toward new energy transition energy projects, these local factors may become increasingly relevant.

Economic impacts of energy transitions

As discussed in previous sections, main goals for many regions and counties include developing job opportunities and enhancing local economic outcomes. One difficulty in developing an energy transition roadmap with an economic assessment is that there is a lack of project-specific information. Project, initial capital costs, and jobs created (both during construction and operations) have not been determined for most potential projects, though there are exceptions. In a pre-feasibility study, it was estimated that the Enchant Energy CCUS project in San Juan County, New Mexico will result in 18 permanent O&M (Operations and Maintenance) jobs in the utilities sector. Using IMPLAN modeling tool (https://www.implan.com), we capture the interdependencies between producing and consuming industries. From the established number of permanent O&M jobs and anticipated labor income, direct (expenditures associated with the event), indirect (expenditures associated with business support (supply chain) activities), and induced effects (expenditures from households associated with the event) as a change from the status quo is estimated. With 18 potentially permanent O&M jobs, a preliminary assessment of the total annual impact of the CCUS project on San Juan County would be 203 jobs. In addition, the added labor value is estimated to be $20.7 million (direct, indirect, and induced) and the value added (the difference between value of output and cost of intermediate products) from the addition of the CCUS to the existing plant is estimated to be $79.4 million. While this assessment is based on a number of assumptions (input-output models such as IMPLAN are static models that assume constant returns to scale, no supply constraints, a fixed input structure, and fixed technology structure), it provides a realistic base assessment of the potential impact of a project.

We assess here a series of hypothetical projects across counties in the Intermountain West utilizing IMPLAN. The impact of annual operations for projects consistent with either fossil fuel or renewable energy generation are considered, and the economic impacts are assessed as if the projects were developed in 18 different counties in the region. Each project is treated as the only economic event to isolate the potential impact of the project. In addition, the economic impacts on surrounding area counties are also estimated. The area counties are those that surround the county of interest; in some cases, the counties cross state lines. If a county is not in an I-WEST state, it is not included in the analysis.

A total of 12 scenarios for each county were run (Table 5). The scenarios include a small job impact (five permanent direct jobs added) or a large job impact (20 permanent jobs added). Each job level is assessed under two salary levels based on the Bureau of Labor Statistics estimated average salaries for each state for the average construction and extraction salary and for power plant operators. Finally, each of these scenarios is considered as a fossil fuel, solar, or wind generation project. The impact of initial construction is not included, as this would be site and project specific. Table 5 presents the counties considered, the 2021 labor force, the 2021 unemployment rate, the two salaries used in the scenarios, and the surrounding counties that are included in more regional impact. There are substantial differences across these counties, including differences in the labor force and unemployment rates, as well as variations in salaries across the states and the current energy activity in the counties.

Table 5. Counties assessed by state in IMPLAN analysis					
State	**County**	**Labor force (2021)**	**Unemployment rate (2021)**	**Two average salary models considered**	**Surrounding area**
AZ	Apache	2,441	12.4%	$50,150/ $67,870	Navajo, Greenlee, Graham, Gila, Navajo, San Juan UT, San Juan NM, McKinley, Cibola
	Pinal	480,903	5.0%		Graham, Gila, Maricopa
	Maricopa	8,616	5.1%		Pinal, Gila, Yavapai
CO	La Plata	4,974	4.4%	$54,450/ $96,510	Montezuma, San Juan (CO), Hinsdale, Archuleta, San Juan NM
	Moffatt	463	5.0%		Rio Blanco, Routt, Sweetwater WY, Uinta, Daggett UT
	Pueblo	6,265	4.5%		Huerfano, Las Animas, Otero, Crowley, Lincoln, El Paso, Fremont, Custer
MT	Rosebud	4,330	4.2%	$53,720/ $78,990	Treasure, Big Horn, Powder River, Custer, Garfield, Petroleum, Musselshell
	Stillwater	17,489	3.6%		Carbon, Yellowstone, Golden Valley, Sweet Grass, Park
	Teton	1,904	2.4%		Ponderosa, Chouteau, Cascade, Lewis & Clark, Flathead
NM	Lincoln	27,957	9.6%	$47,830/ $92,680	Chavez, De Baca, Guadalupe, Torrance, Socorro, Sierra
	San Juan	62,732	6.6%		Rio Arriba, Sandoval, McKinley, Apache, AZ, La Plata, Montezuma, CO
	San Miguel	49,527	8.0%		Santa Fe, Mora, Harding, Quay, Guadalupe, Torrance
UT	Emory	7,748	4.9%	$49,650/ $84,330	Carbon, Grand, Wayne, Sanpete, Sevier
	Iron	6,574	4.4%		Piute, Garfield, Kane, Beaver, Washington
	Uintah	36,804	2.9%		Daggett, Grand, Carbon, Duchesne, Moffatt, Rio Blanco
WY	Campbell	5,316	4.4%	$56,260/ $84,800	Crook, Weston, Converse, Sheridan, Johnson, Powder River
	Converse	7,884	3.9%		Campbell, Niobrara, Platte, Albany, Natrona
	Lincoln	49,373	4.0%		Teton, Subletter, Sweetwater, Uinta

Tables 6 through 11 present the scenarios for each county that result in the maximum and minimum impacts for jobs and for value added. Direct, indirect, and induced impacts are presented for the county in which the project is located. Impacts to surrounding counties are either indirect or induced. These numbers are reported in aggregate rather than for individual counties.

There is substantial variation in the impact of the projects across counties. This results from a number of factors, including the current economic activity characteristics of the county and the characteristics of other counties in the area. Job impacts may be larger for indirect than for direct, or the area jobs may be relatively large (or small) compared to the project county. For example, counties with larger populations may be able to accommodate more indirect and induced jobs and not depend on neighboring counties. In other cases, the impact on surrounding counties is substantial as more of the indirect and induced impacts are accrued to the surrounding counties. A major takeaway of these results is the variation in outcomes across counties and across areas, depending on the project specifics—keeping in mind that the models are based on a set of hypothetical characteristics and that a model of an actual proposed project would be project specific. These results also illustrate the potential value of cooperation among counties or locations as there can be economic benefits across a larger region.

Table 6. Arizona economic impacts, IMPLAN analysis. FF is fossil fuel, solar is solar energy, wind is wind energy, low/high is job impact scenario

County	Scenario	Impacts	Jobs	Value added	Area jobs	Area value added
Apache	Solar/20/High	Direct	20	$1,357,400	--	--
		Indirect	40.7	$9,038,186	4.3	$1,092,936
		Induced	8.2	$690,372	2.9	$231,636
	FF/5/Low	Direct	5	$1,227,687	--	--
		Indirect	2.6	$528,879	0.6	$231,567
		Induced	0.9	$71,732	0.4	$30,149
Pinal	FF/20/High	Direct	20	$1,357,400	--	--
		Indirect	21.4	$1,087,795	54.8	$8,406,900
		Induced	4.0	$144,415	27.1	$2,665,514
	Solar/5/Low	Direct	5	$339,350	--	--
		Indirect	5.5	$272,953	7.0	$1,284,298
		Induced	0.9	$35,164	3.9	$395,360
Maricopa	FF/20/High	Direct	20	$1,357,400	--	--
		Indirect	82.7	$13,000,000	1.4	$168,098
		Induced	43.8	$4,310,997	1.0	$92,452
	Solar/5/Low	Direct	5	$1,387,980	--	--
		Indirect	2.9	$726,672	0.02	$3,511
		Induced	2.8	$368,131	0.05	$4,912

Table 7. Colorado economic impacts, IMPLAN analysis. FF is fossil fuel, solar is solar energy, wind is wind energy, low/high is job impact scenario						
County	**Scenario**	**Impacts**	**Jobs**	**Value added**	**Area jobs**	**Area value added**
La Plata	FF/20/High	Direct	20	$1,930,200	--	--
		Indirect	61.5	$8,656,439	16.2	$4,815,280
		Induced	37.8	$3,088,173	9.5	$779,432
	Solar/5/Low	Direct	5	$272,250	--	--
		Indirect	6.3	$915,767	3.4	$660,999
		Induced	3.5	$286,486	1.2	$93,884
Moffatt	Solar/20/High	Direct	20	$1,930,200	--	--
		Indirect	36.7	$7,502,484	8.8	$1,511,878
		Induced	15.3	$1,245,335	4.4	$370,623
	FF/5/Low	Direct	5	$1,034,233	--	--
		Indirect	2.2	$1,143,353	0.8	$159,485
		Induced	1.8	$263,737	0.5	$43,957
Pueblo	FF/20/High	Direct	20	$1930,200	--	--
		Indirect	40.7	$6,996,402	18.1	$3,107,724
		Induced	19.5	$1,611,439	14.1	$1,221,935
	Solar/5/Low	Direct	5	$272,250	--	--
		Indirect	4.6	$780,943	1.4	$227,622
		Induced	2.3	$187,426	1.1	$98,550

Table 8. Montana economic impacts, IMPLAN analysis. FF is fossil fuel, solar is solar energy, wind is wind energy, low/high is job impact scenario						
County	**Scenario**	**Impacts**	**Jobs**	**Value added**	**Area jobs**	**Area value added**
Rosebud	Solar/20/High	Direct	20	$1,579,800	--	--
		Indirect	20.4	$2,765,208	3.2	$466,558
		Induced	5.6	$354,976	1.7	$126,170
	FF/5/Low	Direct	5	$1,267,966	--	--
		Indirect	1.9	$316,999	0.4	$78,501
		Induced	1.0	$66,419	0.2	$18,836
Stillwater	FF/20/High	Direct	20	$1,579,800	--	--
		Indirect	16.9	$1,921,880	23.5	$5,831,366
		Induced	3.5	$282,988	14.7	$1,150,488
	Solar/5/Low	Direct	5	$268,600	--	--
		Indirect	2.9	$323,381	3.0	$782,043
		Induced	0.6	$47,012	1.7	$131,482
Teton	FF/20/High	Direct	20	$1,579,800	--	--
		Indirect	17.6	$2,469,425	11.4	$1,226,021
		Induced	6.8	$470,362	5.6	$405,264
	Solar/5/Low	Direct	5	$268,600	--	--
		Indirect	2.8	$382,031	1.7	$164,736
		Induced	1.0	$72,742	0.8	$59,702

Table 9. New Mexico economic impacts, IMPLAN analysis. FF is fossil fuel, solar is solar energy, wind is wind energy, low/high is job impact scenario						
County	**Scenario**	**Impacts**	**Jobs**	**Value added**	**Area jobs**	**Area value added**
Lincoln	FF/20/High	Direct	20	$1,853,600	--	--
		Indirect	36.9	$4,062,858	3.5	$953,051
		Induced	13.2	$991,308	1.6	$125,616
	Solar/5/Low	Direct	5	$239,150	--	--
		Indirect	4.3	$435,624	0.3	$79,910
		Induced	1.6	$118,880	0.14	$11,419
San Juan	Solar/20/High	Direct	20	$1,853,600	--	--
		Indirect	48.3	$10,622,428	5.1	$970,360
		Induced	23.1	$1,889,121	5.9	$464,871
	FF/5/Low	Direct	5	$849,325	--	--
		Indirect	2.7	$711,103	0.3	$127,128
		Induced	1.9	$154,133	0.5	$80,059
San Miguel	FF/20/High	Direct	20	$1,853,600	--	--
		Indirect	23.3	$2,545,286	4.6	$741,990
		Induced	7.3	$502,703	1.8	$151,235
	Solar/5/Low	Direct	5	$239,150	--	--
		Indirect	3.0	$328,182	0.2	$29,168
		Induced	0.9	$65,110	0.2	$13,691

Table 10. Utah economic impacts, IMPLAN analysis. FF is fossil fuel, solar is solar energy, wind is wind energy, low/high is job impact scenario						
County	**Scenario**	**Impacts**	**Jobs**	**Value added**	**Area jobs**	**Area value added**
Emery	Solar/20/High	Direct	20	$1,686,600	--	--
		Indirect	31.4	$8,473,916	5	$546,408
		Induced	7.5	$603,510	4.4	$296,591
	FF/5/Low	Direct	5	$1,070,450	--	--
		Indirect	1.6	$425,064	0.4	$73,825
		Induced	0.7	$58,598	0.4	$27,022
Iron	FF/20/High	Direct	20	$1,686,600	--	--
		Indirect	50.9	$5,043,234	24.4	$2,829,853
		Induced	18.3	$1,115,910	7.3	$504,736
	Solar/5/Low	Direct	5	$963,207	--	--
		Indirect	1.6	$161,981	0.4	$67,460
		Induced	1.7	$102,525	0.3	$18,682
Uintah	Solar/20/High	Direct	20	$1,686,600	--	--
		Indirect	30	$4,405,740	10.6	$4,067,259
		Induced	10.6	$808,579	5.6	$456,483
	FF/5/Low	Direct	5	$1,248,930	--	--
		Indirect	2.9	$455,113	1.0	$392,256
		Induced	1.6	$120,835	0.6	$51,186

Table 11. Wyoming economic impacts, IMPLAN analysis. FF is fossil fuel, solar is solar energy, wind is wind energy, low/high is job impact scenario						
County	**Scenario**	**Impacts**	**Jobs**	**Value added**	**Area jobs**	**Area value added**
Campbell	Solar/20/High	Direct	20	$16,960,000	--	--
		Indirect	38.2	$7,221,182	3.1	$622,492
		Induced	10.3	$889,052	1.6	$115,361
	FF/5/Low	Direct	5	$883,397	--	--
		Indirect	2.9	$710,795	0.2	$44,071
		Induced	1.2	$104,049	0.1	$11,158
Converse	Wind/20/High	Direct	20	12,000,000	--	--
		Indirect	23.5	$4,725,025	13.4	$3,589,903
		Induced	4.7	$429,310	5.5	$473,340
	FF/5/Low	Direct	5	$894,473	--	--
		Indirect	1.6	$392,510	1.4	$443,952
		Induced	0.6	$50,519	0.7	$56,193
Lincoln	Wind/20/High	Direct	20	$1,696,000	--	--
		Indirect	33.1	$5,224,536	1.7	$360,336
		Induced	9.4	$655,155	1.3	$109,867
	FF/5/Low	Direct	5	$896,085	--	--
		Indirect	2.8	$556,157	0.1	$42,366
		Induced	1.2	$83,954	0.2	$13,451

The impact on jobs in the project county depends on the economic conditions prior to the project event. Table 12 provides the impact on unemployment for the highest impact project in each county. As expected, in all counties, there is a positive impact on the rate of unemployment (using 2021 conditions as the starting point). In two cases, the potential impact of jobs would result in a near zero unemployment rate, suggesting that current workforces would not be able to cover all potential new jobs, resulting in net migration into the county.

Table 12. Jobs impact by county, IMPLAN analysis. FF is fossil fuel, solar is solar energy, wind is wind energy, high is job impact scenario					
State	**County**	**Scenario**	**Labor force (2021)**	**Jobs added**	**Unemployment, prior to and after event**
AZ	Apache	Solar/20/High	2,441	69	12.4% to 9.6%
	Pinal	FF/20/High	480,903	45	5.0% to 5.0%
	Maricopa	FF/20/High	8,616	147	5.1% to 3.4%
CO	La Plata	FF/20/High	4,974	119	4.4% to 2.0%
	Moffatt	Solar/20/High	463	72	5.0% to ~0%
	Pueblo	FF/20/High	6,265	80	4.5% to 3.2%
MT	Rosebud	Solar/20/High	4,330	46	4.2% to 3.1%
	Stillwater	FF/20/High	17,489	40	3.6% to 3.4%
	Teton	FF/20/High	1,904	44	2.4% to 0.1%
NM	Lincoln	FF/20/High	27,957	70	9.6% to 9.3%
	San Juan	Solar/20/High	62,732	91	6.6% to 6.5%
	San Miguel	FF/20/High	49,527	51	8.0% to 7.9%
UT	Emory	Solar/20/High	7,748	59	4.9% to 4.1%
	Iron	FF/20/High	6,574	98	4.4% to 2.9%
	Uintah	Solar/20/High	36,804	61	2.9% to 2.7%
WY	Campbell	Solar/20/High	5,316	69	4.4% to 3.1$%
	Converse	Wind/20/High	7,884	48	3.9% to 3.3%
	Lincoln	Wind/20/High	49,373	63	4.0% to 3.9%

An additional complexity concerning jobs depends on the types of needed jobs in the direct, indirect, and induced categories. General skills jobs are more easily filled than specialized skills jobs, so understanding matching between available workforce skills and needed skills is critical. Table 13 provides an example for Lincoln County, Wyoming and the top five indirect employment areas for the Wind/20/High scenario. While the numbers in this illustration are relatively small, the importance of understanding whether or not the size of the workforce can accommodate a project and whether or not the existing workforce has the necessary skills for the project—and supporting jobs—is an important factor for assessing potential projects. If labor cannot be supplied locally, then an additional concern for a project may be net migration into a community or county.

Table 13. Lincoln County, WY top five indirect job areas	
Employment Area	**Number of Jobs (% of indirect jobs)**
Transportation, truck transportation, and support	4.1 (12.4%)
Electric power transmission and distribution	3.3 (10%)
Other real estate	3.1 (9.4%)
Electric power generation - Fossil fuel	1.9 (5.7%)
Misc. Professional	1.9 (5.7%)

Bioenergy

Bioenergy is unique within the energy transition as it involves the use of forest or waste products. These factors impact project location and magnitude of production, which in turn may point to locations that are substantially different than those for other energy-related projects. An analysis of available and accessible forest residues on a county basis—either from selected harvesting, land use change, or forest management, or from harvesting standing dead trees from drought or fire—provides the basis for a preliminary set of economic indicators for each of the 220 counties in the region to assess potential bio-ethanol production. Figure 16 highlights the top two counties in each, showing harvesting radius against production potential and illustrating substantial variations across the states. The top two counties in Colorado, Washington and Morgan, have significantly larger production potentials, at a larger area, than any of the counties in the other states. The potential economic impact of bioenergy in these counties, or in any other, ultimately depends on the scale and type of operation.

Moving forward, climate change impacts, which may include increased temperatures and changes in precipitation, could affect supplies of biomass that may be available for bioenergy (biofuels or biogas). This includes forest resources in the Intermountain West that are at risk from wildfires.

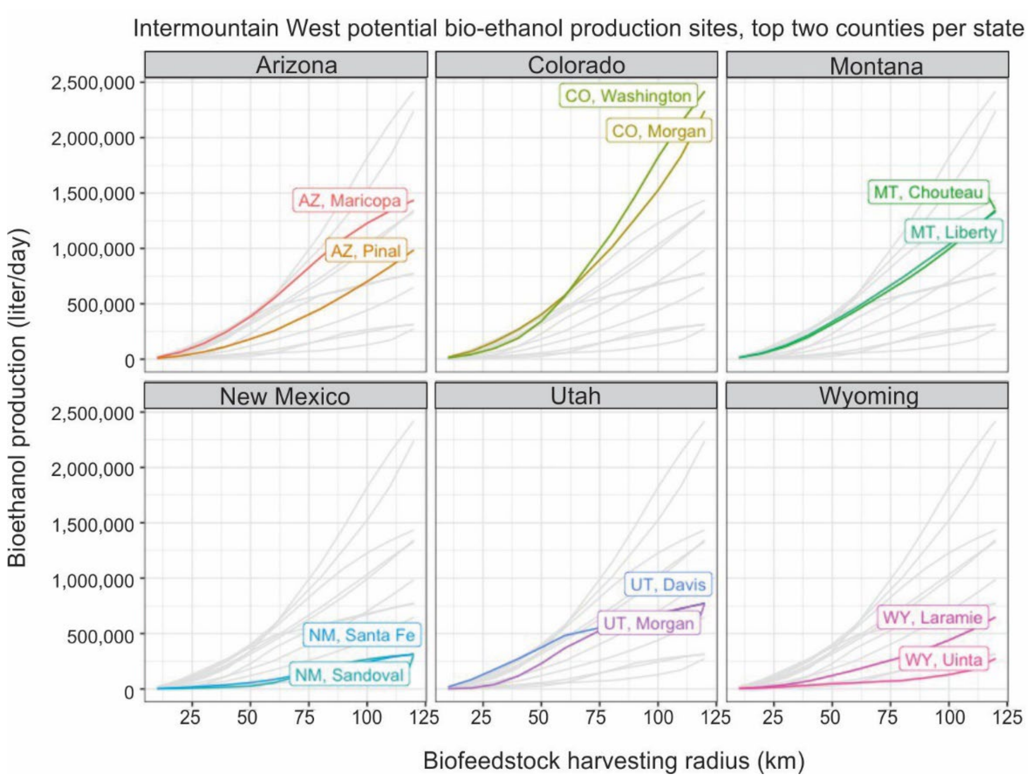

Figure 16. Potential bioethanol production counties. Source: (https://afdc.energy.gov/fuels/ethanol_feedstocks.html)

Heterogeneity

A variety of factors that can impact the economic outcome of a project have been discussed in the preceding sections of this report. Those, however, focus on heterogeneity associated with location, including current economic conditions, water availability, or labor availability. Policy (which I-WEST also considered in its phase-one assessment) can also result in heterogeneity of outcome. An additional aspect of heterogeneity that could impact the outcome of a project is heterogeneity of preferences of residents impacted by a project.

A variety of studies and surveys suggest that, in general, there is support for energy transition technologies. However, the support is not universal and there are some aspects of a technology that may be more important than others to residents.

A study focusing on New Mexico (Chermak and Ehrenfeucht, 2022) finds 20% of survey respondents would not support carbon neutrality, regardless of the cost, while more than 50% say that they *would* support carbon neutrality regardless of the cost. They also find stronger support for technologies with which individuals are more familiar. Respondents were most familiar with renewables and almost 40% of respondents were very supportive of deploying renewables. Support for hydrogen and CCUS was slightly over 20%, depending on the time frame for deployment. Creation of new jobs was consistently an important factor as were health impacts and impacts on individual households through energy costs. These results suggest knowledge or education is an important factor for community support for a project. Further, potentially positive impacts on the individual household were found to be important, as were potentially negative impacts. For example, almost 80% of respondents thought higher energy costs due to transitions would be a very or somewhat important concern. This is also consistent with comments from regional stakeholders at the I-WEST Economics Workshop regarding the potential impact on energy burdens in communities if energy transition projects result in higher costs or energy burdens to households.

The impact on the local economy through job gains or losses was also important, with more than 70% of respondents focusing on jobs as a very important or somewhat important factor in transition projects.

Finally, an individual's knowledge about specific technologies was important in how supportive of specific aspects of a technology they were. For example, those who indicated they had a very strong understanding of hydrogen technology was ~8.5%, which is similar to the percentage of those who had a strong understanding of CCUS. Those two technologies also had substantially lower levels of strong support for deployment in either 5 or 15 years than did renewables, where ~23% of respondents indicated a strong understanding.

Western and Gerace (2021) conducted a survey of Wyoming perspectives from residents in 12 counties focusing on a net zero energy economy. Key findings include 94% of respondents believe energy production is very important now and, in the future, while 43% believe it is important for the state to transition to carbon-neutral energy. Demographic indicators of preferences included political affiliation. Similar to the New Mexico study, understanding or knowledge of a technology (in this case, hydrogen) resulted in stronger support for that technology. Also similar to the NM study, jobs were of high importance.

The above provide results for single states. While each state in the Intermountain West has some representative surveys focusing on various aspects of energy transitions and residential support, the results cannot be easily compared to draw conclusions about support for future projects and the potential impacts that support (or lack thereof) will have on the economic outcome of a project.

Two projects that focus on aspects of energy and/or climate change and include all the states under assessment by I-WEST are Colorado College's annual "State of the Rockies" survey and the "Yale Program on Climate Change Communication" (https://climatecommunication.yale.edu) which includes a mapping of attitudes and preferences towards climate change. The former provides results at a state level, while the latter provides results at the national, state, county, or congressional district level.

As an example, the Yale work includes a question asking if the respondent is worried about climate change. Table 14 provides the county in each state that had the highest and lowest percentage of respondents who were worried.

Table 14. Worried about climate change

State	Highest Response (%)	Lowest Response (%)
AZ	Pima (73%)	Mohave (55%)
CO	Denver (76%)	Kiowa (50%)
MT	Glacier (71%)	Richland, Fallon (49%)
NM	Mora (78%)	Eddy (55%)
UT	Salt Lake (70%)	Emery (47%)
WY	Teton (70%)	Campbell (48%)

A second question asks if the respondent agrees or disagrees with setting strict CO_2 limits on existing coal-fired power-plants. These results are reported in Table 15. In those cases where the same county is found in both tables, those that fall in the highest response rate are relatively more consistent across the two questions. For example, Denver County in Colorado had a 76% response rate for both questions. In general, for the low response rates, the percentage of respondents that agree with setting strict CO_2 limits is lower than the low response rate for being worried about climate change. For example, 43% of respondents in Emery County are worried about climate change, but only 38% of respondents believe there should be strict CO_2 limits set on existing coal-fired power-plants.

Table 15. Setting strict CO_2 limits on existing coal-fired power-plants

State	Highest Response (%)	Lowest Response (%)
AZ	Pima (72%)	Mohave (53%)
CO	Denver, Boulder (76%)	Moffatt (44%)
MT	Glacier (72%)	Rosebud (46%)
NM	Santa Fe, Taos, Mora (78%)	San Juan (49%)
UT	Summit (72%)	Emery (38%)
WY	Teton (73%)	Washakie, Converse (39%)

The 2022 Annual Survey of Voters in the Rocky Mountain West, conducted by Colorado College as part of the "State of the Rockies" poll focused on a number of issues, including the gradual transition to 100% renewable energy over the next 10 to 15 years. Across the Intermountain West, support ranged from 49% (Wyoming) to 69% (Arizona). Compare this to the 2020 poll, which focused on support for requiring states to transition to 100% clean, renewable sources over the next 30 years, where responses from the region ranged from 36% (Wyoming) to 70% (Arizona and Colorado). The questions asked were not identical; there are differences in sample sizes and mode of survey, but the results suggest an increase in support at the state level for a transition to renewables. The 2020 and 2022 state level results are presented in Table 16. The level of support is fairly constant for five of the six states. Wyoming, however, has a 13-point increase over the time period. The caveat to these results is that it is at a state level and may not capture location nuances.

Table 16. State-level support for transitioning to renewable energy

State	2020 (support at any level)	2022 (support at any level)
AZ	70%	69%
CO	70%	68%
MT	55%	59%
NM	63%	63%
UT	60%	61%
WY	36%	49%

These results provide an example of the heterogeneity of opinion and policy preference across and within the region. Moving forward, the structure of a program or of a project may be an important factor in whether or not there is local support for that project.

Conclusions and future directions

The states and counties within the Intermountain West are diverse in their current economic conditions, current reliance on energy in their economy, land ownership, experience with drought, and population density (i.e., metropolitan versus rural). Economic outcomes from projects depend on a variety of factors. As the hypothetical projects suggest, the current conditions and ability of a county to accommodate a project will affect its economic value and impact on jobs. In some cases, job creation occurs mainly within the county, while in other instances, the surrounding counties play an important part in economic activity. These examples also show the potential benefit of regional cooperation for projects.

Economic success of projects may also depend on location characteristics. For example, San Juan County, New Mexico, and Lincoln County, Wyoming, both have a long history of energy production, including boom-and-bust cycles. Energy is still a significant part of these counties' economies and both are pursuing transitions to new energy economies. The success of those transitions may depend on the characteristics of the location, including access to that location. Further, transitions that are not subject to the boom-and-bust economics of fossil fuels could provide stability within communities.

The development of a successful energy transition roadmap will take these factors into account and can provide an improved understanding of the future potential of energy-related projects. Due to the disparate characteristics of the Intermountain West, the interactions among counties, the potential for collaboration among counties, and the social economic impacts of a specific project are not easily estimated; furthermore, comparisons across projects are even more difficult. The development of a holistic modeling tool to assess economic impacts and tradeoffs (market and nonmarket) of projects, and to incorporate factors of importance into those assessments, would provide a mechanism to better understand the impacts and tradeoffs of different energy futures in the Intermountain West. This report provides an initial presentation of factors that would prove relevant within such a modeling tool.

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I-WEST

Phase One Final Report | Detailed Chapter

Workforce Impacts

VERSION 2.0 ARIZONA STATE UNIVERSITY JUNE 2023

About this chapter

The Intermountain West Energy Sustainability & Transitions (I-WEST) initiative is funded by the U.S. Department of Energy to develop a regional technology roadmap to transition six U.S. states to a carbon-neutral energy economy. I-WEST encompasses Arizona, Colorado, Montana, New Mexico, Utah, and Wyoming. Each state is represented in this initiative by a local college, university, or national laboratory. Additional partners from beyond the region were selected for their expertise in applicable fields. In the first phase of I-WEST, the team built the foundation for a regional roadmap that models various energy transition scenarios, including the intersections between technologies, climate, energy policy, economics, and energy, environmental, and social justice. This chapter presents work led by an I-WEST partner on one or more of these focus areas. A summary of the entire I-WEST phase one effort is published online at www.iwest.org.

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Table of Contents

Introduction

"DOE plan(s) on the deployment and demonstration of carbon management and clean energy technologies to support the administration's goals of decarbonizing the electricity sector by 2035 and the economy by 2050." - Department of Energy Office of Fossil Energy and Carbon Management[1]

We are in for a lot of change. As the quote above notes, the U.S. intends to rapidly decarbonize electricity generation, to be followed by the decarbonization of transportation.

This chapter postulates on what the changes in our energy mix will mean for labor over the next 15 years. Let's be clear, this is speculation with some data to support it. The energy transition we are going to experience will be too radical to project with clear foresight. One might think of this chapter as a guide to the possible and one might surmise from this guide that education, training, and research are going to be the hallmarks for labor in the coming decade. The more we focus on those three supports, the more successful the energy transition will be.

Worker evolution in the energy transition and the accompanying jobs[2] will need a concentrated effort to find new opportunities for those and new workers. This chapter considers how the energy transition might introduce new jobs or growth in areas that already exist as well as entirely new sectors.

There is reason for optimism. Consider the two quotes below; change can happen very rapidly. Humans are an adaptive species, we know how to change, and in this case, we will be adept at changing as well.

"There is no reason anyone would want a computer in their home." Ken Olsen, President and founder of Digital Equipment Corp., 1977

"I think there is a world market for maybe five computers." Thomas Watson, President of IBM, 1943

Our nation is about to embark on a journey to carbon neutrality, including a reduction of CO_2 in the atmosphere to pre-2000 levels. As our nation, and others, take these steps, we will focus on three approaches. First, we will reduce the production of CO_2 (and other greenhouse gases) and slowly at

[1] U.S. Department of Energy Office of Fossil Energy and Carbon Management; Request for Information: DE-FOA-0002660
[2] The US Labor Market in 2050; Holzer and LaFarge; Georgetown University. 2018

first, we will capture and “put away” the excess CO_2 that is in the atmosphere and oceans. Second, we will re-create the physical structure of our country. We will make changes to adapt to climate-induced changes such as droughts, fires, flooding, rising seas, and storms. Our transportation will change, our housing will be modified, we will have many new industries. Third, every nation-state is going to seek to fulfill its role to protect its citizens and enhance their well-being. That will be a tough obligation to meet.

Energy may face the biggest changes and the most difficult. We have slowly advanced our physical well-being and longevity through increasing amounts of energy consumption. Sustaining the growth of energy without the burning of fossil carbon is going to be a challenging task to fulfill. Our current world and its culture are going to change, and the coming decades will tell the tale of how successful we were.

Assumptions and outlook

This chapter focuses on the future workforce changes in the Intermountain West region. Efforts at decarbonizing the region are already underway, with all states and communities and companies displaying a certain level of planning and implementation. International momentum is gaining and pressure from civil society is increasing. At the same time, renewables only provide 3% of the regional electricity generation, while the fossil industry employs over a million workers nationally in various tasks related to fuel extraction, electricity generation, and fossil related transportation (**Table 1**). As the path to carbon neutrality continues, there will be new jobs and careers.

The Intermountain West is highly diverse and rapidly developing. It is already experiencing the impacts from the phasing out of coal and the growing pains of a rapid introduction of renewable energy. The region will need to address economic and environmental inequities which are much sharper in this region than in many parts of the US.

The outlook for the region is that fossil carbon will become a less prominent member of the energy mix. This will not be an overnight change and sectors will experience different impacts. Coal mines and plants are closing in the Intermountain West and oil extraction is expected to decline (notwithstanding some spikes in production). While renewables will need to rapidly grow, the need for seasonal and daily backup will keep fossil energy in the generation mix. Batteries will provide some backup and natural gas is likely in the next decade(s) to provide the bulk of the remainder. In brief, the outlook for the region is an expansion of renewables, hardening[3] of the energy infrastructure, expanding electric transmission, building out of electric transportation, the introduction of capture technologies including fabrication and operation, and many new technological innovations that will need to be designed and built.

From this outlook, it is clear the transition to carbon neutrality will have a dramatic impact on the energy workforce in the region. The bad news is significant disruption of the workforce from the decrease in fossil fuel extraction jobs. The good news is that energy related jobs will likely increase, and many of these jobs will be at a high skill level[4]. The new work will require retraining or added training and there will be relocation of workers. Jobs will not only need to be plentiful, but they will also need to be "good" jobs that pay a fair wage, provide social protection, and offer training[5]. The planning will need to identify the conditions to make that happen.

Overall, it is a story of change but with benefits of new well-paying jobs as a big part of that change[6]. The changes will not just be in terms of the types of jobs; the way we work is also likely to change and evolve over the next fifteen years, not only because of continued automation and the rise of artificial intelligence. Industry will need to embrace training as a part of doing business. Existing community college training programs that are tied to industry as partners are examples of how this might be done[7]. There also will be other models created and used as the transition from a fossil-based energy evolves to one that incorporates more renewables.

The coming changes have social justice implications. Rural lands, particularly those in tribal lands in each of the Intermountain West states are losing revenue and jobs from the closure of fossil fuel extraction activities and the closure of fossil carbon electricity generating stations. Areas facing economic distress need dedicated interventions. The advance of new technologies such as Direct Air Capture (DAC) or hydrogen production may create new possibilities. For example, could closed coal power stations be replaced by DAC facilities? A guide on what this energy transition could look like in terms of workforce will be developed in the following sections and appendices.

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[3] Hardening refers to physically changing the infrastructure to make it less susceptible to damage from extreme wind, flooding, or flying debris.
4 Net-Zero America: Potential pathways, infrastructure, and impacts. Larson et al. (2020). Interim report. Available at https://environmenthalfcentury.princeton.edu/sites/g/files/toruqf331/files/2020-12/Princeton_NZA_Interim_Report_15_Dec_2020_FINAL.pdf
[5] "Why equipping workers is the key to energy transition"; Energy Monitor. Phipppa Jones. Sept. 2020
[6] Free market Approaches to Controlling Carbon Dioxide Emissions. Lackner, Wilson, and Ziock. 2000
[7] PVNGS Arizona Training programs

Table 1. US energy employment from the 2020 US Energy and Employment Report by the National Association of State Energy Officials and the Energy Futures Initiatives[8]		
Energy sector	**Employment, # of people**	**% Annual change**
All (4.6% of US population)	6,800,000	1.8%
Fuels	1,148,900	1.9%
Oil	615,500	
Natural Gas	276,000	
Biofuels	775	
Mining	7,000	
Coal Fuels	75,500	
Electricity Generation	896,800	2%
Natural Gas	122,000	8%
Solar	248,000	2.3%
Wind	114,800	3.2%
Coal	79,711	-8%
Transmission and Distribution (T&D)	2,400,000	1.3%
Construction	499,000	4%
T&D	417,600	0%
Energy Efficiency	2,380,000	3%
Motor Vehicles	2,550,000	1%
Alternative Fuels	266,300	-2%
Fuel Economy	494,000	0%

Energy workforce landscape

The states of the Intermountain West region are distinctive compared to the other U.S. states in several ways. They are mountainous, less urban, and do not have access to water transportation. The region has the highest percentage of government-controlled land and the highest percentage of Native American population of any combination of six states in the continental U.S. Economically, the region has relied heavily on agriculture and extraction of resources. Because land is less densely populated, transportation is heavily focused on roadways and individual vehicles.

The Intermountain West states differ in education, diversity of employment, and the reliance on energy as an economic driver. However, energy has played a significant economic role for all six. Four of the states are in the top ten for energy export and all six are in the top 20. The states have extracted and exported coal, copper, oil, uranium, and natural gas. They have also exported electricity to their more urban neighbors. The states have taken different approaches to carbon

[8] 2020 US Energy & Employment Report. NASEO & Energy Futures Initiative. Available at https://static1.squarespace.com/static/5a98cf80ec4eb7c5cd928c61/t/5ee78423c6fcc20e01b83896/1592230956175/USEER+2020+0615.pdf

neutrality and continued reliance on fossil generation. Some anticipate continued reliance on fossil generation and transportation while others have policies that move away from fossil energy.

Direct employment by the energy sector across the Intermountain West is estimated to total over 500,000 workers (**Table 2**) representing a significant share of the national energy workforce. A typical profile of the workforce can be exemplified by the state of Utah. According to the Kem C. Gardner Policy Institute's Economic Impacts of Utah's Energy Industry Report, in 2017, Utah's energy industry directly and indirectly supported 3.8% of the state's employment, 4.2% of its earnings, and 5.7% of its gross domestic product[9]. According to the 2020 U.S. Energy and Employment Report (USEER)[10] Utah has 31,468 energy workers. The other states resemble this picture. Energy and its related industries are a major employer and pay relatively well.

Table 2. Direct employment in the energy sector by category
Data from the Employment by State 2020 report produced by the National Association of State Energy Officials and the Energy Futures Initiatives.[11]

Employment Category	AZ	UT	NM	CO	MT	WY	Total
Fuels	2,095	11,885	25,123	38,708	5,506	22,191	105,508
Electricity Generation	24,080	11,853	5,321	25,397	1,376	1,526	69,553
T&D	20,776	7,730	13,668	28,480	8,648	9,556	88,858
Energy Efficiency	44,782	32,483	6,099	36,092	8,838	7,568	135,862
Motor Vehicles	31,949	23,266	7,882	32,321	6,226	3,215	104,859

At-risk workforce in the coming energy transition may include those employed in coal mining, coal plant operation and maintenance, fossil energy plant construction, and internal combustion engine maintenance. The workforce relying on natural gas may eventually become at-risk. These at-risk workers are mostly located in rural areas and in tribal communities, adding to challenges arising from historical injustices. For example, in many of the states, tribal nations are faced with the burden of fossil reduction more than the rest of the population. Tribal lands are mineral- and resource rich and many fossil power plants are/were located there. This means that tribal communities hold the bulk of the on-site jobs for both coal extraction and coal plant operation and consequently will be at the front line in terms of job loss.

[9] Kem C. Gardner Policy Institute, Economic Impacts of Utah's Energy Industry, 2017
[10] 2020 U.S. Energy and Employment Report - Utah
[11] Energy Employment by State – 2020. NASEO and Energy Futures Initiative. Available at https://static1.squarespace.com/static/5a98cf80ec4eb7c5cd928c61/t/5e78198f28dc473dd3225f04/1584929183186/USEER-Energy-Employment-by-State-2020.pdf

Disruptions with reasons for optimism

The transition will disrupt fossil fuel related jobs and will dislocate workers and communities. Communities in rural areas and on tribal lands will be at the forefront of that change. Yet, the transition is also an opportunity. As a region with recent historical experience in transitioning to become a net-energy exporter with highly trained workers to do so, the Intermountain West states are well positioned to lead the charge in this new transition. Growth in employment in clean energy will likely balance the losses, and most likely will exceed them. Targeted approaches must intentionally focus training and employment generation in distressed communities that have disproportionately lost (or will lose) jobs. The synergies of fossil fuel operation repurposing with new technologies like DAC will create new opportunities for employment.

Historical trends

The disruption of the fossil energy related workforce has already begun. For example, in Arizona, the fossil generation plants are closing, and all coal mines are now closed. The Navajo Generating Station has closed, terminating employment for 433 people, the Kayenta mine closed and with it went 265 positions, and the Four Corners and Cholla plants have been assigned closure dates. Other Intermountain West states are experiencing similar closures and terminations.

Since the early 1980s, coal mining employment has decreased to a third of its former level (**Figure 1**). In the period from 2000-2012, employment levelled before reducing to 40,000 workers nationwide. These trends have local impacts that are masked by regional statistics[12]. In Wyoming for example, the number of people employed in coal mining has risen over the last 20 years, from 4,285 in 2001 to 4,781 in 2020. However, it declined significantly since reaching its peak of 7,054 employees in 2009 (**Figure 2**). This decline has not had an adverse impact on overall employment in Wyoming. The unemployment rate in Wyoming has been steeply declining since reaching a peak of 8.1% in May of 2020. As of October 2021, it was down to 4.1% which is lower than the pre-pandemic level of 4.8% in February 2020.

[12] Workforce Template for Response. *University of Wyoming School of Energy Resources.* Dec. 17, 2021

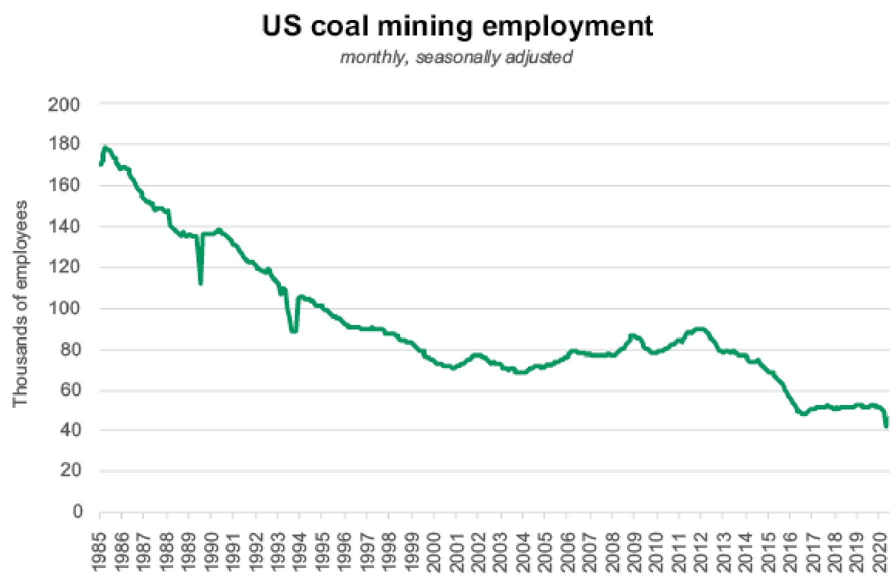

Figure 1. Workers employed in coal mining throughout the United States.[13].

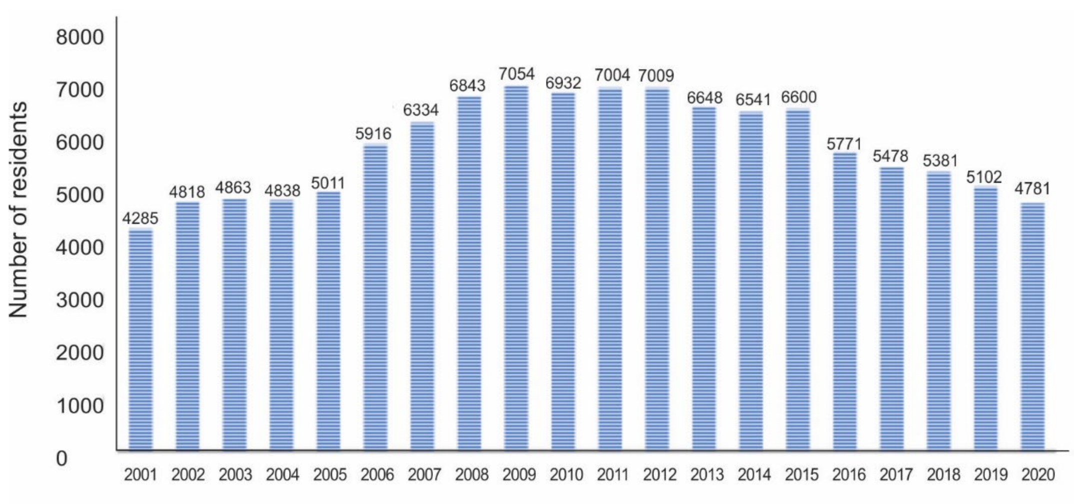

Figure 2. Number of Wyoming residents employed in coal mining 2001-2020[13].

Case study: Utah

In Utah, employment trends are positive. Utah's unemployment rate was 2.2%, while the national unemployment rate was 4.6% (**Table 3**). Utah's job growth rate was 3.7% while the U.S. 's was -2.2%. However, like other Intermountain West states, fossil generation is declining. Utah is part of

[13] EIA Coal Mining Jobs Since 1985; Bureau of Labor Statistics

PacifiCorp's six-state territory, and PacifiCorp's system-wide Integrated Resource Plan in Utah indicated the planned portfolio may include accelerated coal retirements, no new fossil-fueled resources, continued growth in energy efficiency programs, new transmission investments, and incremental renewable energy and storage resources. The USEER report estimates traditional fossil fuel power generation jobs in Utah at 3,304 in 2020, which was down 3%. Utah's 2021 Employment Summary for October 2021 indicated the mining and natural resources sector lost 1,200 jobs in the last two years. However, COVID-19 may have impacted job numbers during that time.

Table 3. Unemployment rates for October 2021 compared to the U.S. national average of 4.6%
Data from U.S. Bureau of Labor Statistics

State	Rank	Rate %
Utah	2	2.2
Montana	8	3.1
Wyoming	21	4.1
Arizona	31	5.2
Colorado	34	5.4
New Mexico	47	6.5

Relocation and training

As with previous energy transitions, workers, companies, and industries that navigate the present elegantly may endure while others may struggle. Wyoming, New Mexico, and other Intermountain West states already have some transition programs in place, but many workers self-train or move to other positions that require similar skills. Examples might include natural gas pipeline workers shifting to hydrogen and CO_2 pipelines, or oil and gas drillers switching to water, geothermal, and sequestration wells. These examples are in areas which will have future work nearby.

Growth is expected in the number of jobs in sectors such as transmission, engineering, and dispatching. Coal mines train general skills which can be transferred to other heavy equipment operations. Some oil and gas workers will be able to move into new renewable capture and decarbonized energy jobs, but not all workers have a clear path through the transition. These workers may be able to find their own way, but state training matching market trends could be a significant help. There will also be entirely new occupations such as fabrication and installation of EV chargers, and manufacturing of carbon products from captured carbon.

One example of forward thinking is the "Wyoming Innovation Network," a partnership among the University of Wyoming and Wyoming's community colleges to address new forms of employment and related issues. At the local level, there are initiatives working to preserve jobs in the fossil industries while preparing for the day when those workers could perhaps be employed in new industries such as carbon-to-products. An example of success is the recently announced Natrium nuclear power plant, which will be built in Kemmerer, Wyoming. This new plant reflects success by Wyoming in attracting new energy industries that hold promise for both preserving existing jobs and creating new ones.

The changes and adaptation also impact workers indirectly employed in the energy sector. The commonly used equation that every power plant job translates into ten jobs off-site provides a conceptual guide to the impact of job loss[14]. Closure of extraction operations and generation plants means many other folks within the community are disadvantaged and all lose revenue including commercial, retail, local government, and service professionals. The local doctor and hospital lose revenue and patients, retail stores close, government and schools lay off, local contractors and service providers lose work, and the entire community shrinks in both funds and population. These changes are felt even more when the communities are remote or isolated – which is the case with most mines and power plants.

Community losses are less direct and harder to both quantify and reverse. Additionally, the logistics of dealing with community loss is more complex. While not ideal, there is an assumption in industrial transitions that some portion of the harmed workforce will relocate. In contrast, communities seldom resettle. They may fail, but there are really only two alternatives, which are to 1) bring in another source of employment and revenue or 2) abandon/denigrate the location. States will need to focus funding and plans for new development of employment centers in these locations. Training is going to need to be open to a wide swath of the community and not segregate between ex-energy employees and the local retail worker – they will all need a path forward.

States and communities are starting to consider what the new jobs are going to be and how the current and emerging workforce can be trained/educated to fulfill these new roles. The future jobs and revenue rests on how accurately states and local governments predict what new work might be developed in their locale and how quickly they can train their workforce to serve in these new roles. Which states will develop the educational and research centers that attract the winners in the battery, DAC, alternative fuels, electric charging, and certification of sequestration industries?

[14] The “10 to 1” rule may or may not be accurate, but it is commonly used in power plant siting hearings.

Projected job changes for the next 5 to 15 years

On the one hand, jobs in fossil-based industries are projected to continue to decline. The Arizona coal mines have closed, and the last coal power plant will soon close. The situation is similar in Wyoming, with the largest electric utility, Rocky Mountain Power, intending to retire its coal plants in the state in the years ahead. The stated goal in their 2021 Integrated Resource Plan (IRP) is a 74% reduction in greenhouse gas emission below 2005 levels by 2030. To meet this goal, they are scheduled to retire 14 of their coal-fired power plants across several states by 2030, and a total of 19 by 2040. Though they converted one unit at a coal-fired power plant to natural gas and are considering a similar conversion of two more units at a separate plant in Wyoming, they are not otherwise choosing to invest in future natural gas construction. Rocky Mountain Power is planning to continue to invest heavily in renewable energy technologies in the state (i.e., wind, solar, grid-scale storage) that should lead to new jobs in these new energy industries[15]. For states like Wyoming with very high shares of the population employed in fossil fuel industries, it is possible that energy-related employment may decrease as a share of the total employment[16].

In Utah, the situation is similar. The majority of Utah coal, 64% in 2018, was used in-state. In the past, Utah was a significant net exporter of coal, but out-of-state domestic demand has decreased from a high of 16 million tons in 2001 down to only 1.9 million tons in 2018 as coal has dropped out of favor as a fuel for electric and industrial needs. Utah's foreign exports peaked in the mid-1990s at about 5 million tons, then dropped to near zero in the mid-2000s. However, the foreign export market has seen a resurgence in the past few years, increasing to 3.1 million tons in 2018[17].

The long-term decline in demand for coal, and anticipated decline in other fossil fuels, if not arrested through carbon capture and storage, will produce knock-on effects in energy generation, transmission, and distribution. The many associated industries such as heavy machinery servicing, environmental reclamation, and all commercial activities which multiply the value of each fossil energy job, will be impacted.

The Intermountain West states are working toward deploying renewables and have targeted other potential growth areas related to the energy transition. Wyoming has seen limited growth in solar PV (solar photovoltaic) generation. The only commercial operation in the state is Sweetwater Solar, installed by 174 Power Global. However, Wyoming has seen significant investment in wind energy generation. This is not only due to the greater average wind speeds in the state, but also the

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[15] PacifiCorp; Energy integrated-resource-plan
[16] Net-Zero America: Potential pathways, infrastructure, and impacts. Larson et al. (2020)
[17] Utah's Energy Landscape 5th Edition, Utah Geological Survey

tendency of these winds to blow at dusk and early night, allowing electricity from them to serve peak demand in the Rocky Mountains and west coast. The federal production tax credit for wind has also played a role. Formal electric vehicle infrastructure is limited to larger cities supportive of EV such as Jackson, Cheyenne, and Riverton, but private charging at home and incidental locations means electric vehicles can be found almost anywhere in Wyoming. The trend towards EVs in towns is increasing, but almost all rural areas such as ranches or utilities are dominated by gasoline vehicles. Public transportation follows EV trends, being overall rare, but present in Wyoming towns[18].

In 2018, Utah ranked 26th in the nation in percent of total net electric generation from renewable resources (11.2%) and Utah is one of only seven states where electricity is generated from geothermal resources. Utah's renewable electric generation is dominated by 914 MW of newly installed utility-scale solar farms (50%), followed by hydroelectric (21%), wind (18%), and geothermal (10%) power. Renewable energy sources now account for 11% of Utah's total electricity generation. The total capacity of net-metered PV solar installations (i.e., roof-top solar) in Utah has increased exponentially in the past few years, from a total of 3.4 MW in 2010 to 273 MW in 2018, 78% of which was in the residential sector[19].

Significant potential new transmission investments are underway in Utah, including PacifiCorp's Gateway South project, which filed for a Certificate of Public Convenience and Necessity at the Utah Public Service Commission in September 2021[20], and the TransWest Express project, which recently concluded its open solicitation process[21]. Utah's wind generation produced about 15% of Utah's renewable electricity in 2020. Utah has five wind farms operating with about 390 megawatts of generating capacity. The state's two largest wind farms send power to southern California. Commercial wind power potential is found in the Wasatch and Uinta Mountain ranges in Utah's north-central region and on the mesas in western Utah[22].

During the 2020 session, the Utah Legislature passed H.B.396[23] which directed the Utah Public Service Commission to authorize Rocky Mountain Power to recover a $50 million investment in an electric vehicle charging infrastructure program. Rocky Mountain Power filed its proposed program with the Utah Public Service Commission in August 2021[24]. The Utah Legislature also passed

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[18] Workforce summary by Wyoming
[19] Utah's Energy Landscape 5th Edition, Utah Geological Survey
[20] Utah Public Service Commission Docket No. 21-035-55
[21] TWE Project Open Solicitation
[22] U.S. Energy Information Administration – Utah State Profile and Energy Estimates
[23] H.B. 396 Electric Vehicle Charging Infrastructure Amendments
[24] Utah Public Service Commission Docket No. 20-035-34

H.B.259[25], directing the Utah Department of Transportation to lead the creation of a state-wide electric vehicle charging network plan, which was released later that year[26]. The state of Utah is well positioned to serve as a hub for emerging clean industries. The University of Utah Energy and Geoscience Institute has provided extensive characterization of geological formations and carbon sequestration opportunities across the state of Utah.

This balance between destruction and creation of employment will be at play in all Intermountain West states, each starting from a different share of employment in fossil fuel industries. Overall, despite significant job losses in the fossil fuel sector, the increase in activity in other energy sectors may result in either no overall change in employment numbers or see an increase in the next 5 to 15 years[27], although locally the impact will be felt differently.

Repurposing creates opportunities

Repurposing abandoned fossil fuel operations for new technologies will bring opportunities to create new and keep existing employment. For example, abandoned strip mines and coal plants might be repurposed for DAC, solar farms or wind. Electrical and pipeline infrastructure can be repurposed for renewable energy. This will vary with location. For example, in the Four Corners Region most of these sites would naturally lend themselves to redevelopment with solar energy and in some cases wind energy as well. Combining solar with DAC could develop synthetic liquid fuel. Abandoned oil fields are prime for carbon sequestration. With DAC, old coal mines, retrofitted with renewable energy facilities, would lend themselves to the production of synthetic fuel and the production of synthetic chemicals that can be used to displace petrochemicals. Many synergies have yet to be imagined but it is clear that new technologies are creating opportunities. Repurposing and transformation will bring new workforce avenues.

Future energy workforce needs

Based on the postulated changes and an in-depth analysis of the various energy related activities (**Appendix 1**), we may start to define future workforce needs recognizing that the disruption of

[25] H.B. 259 Electric Vehicle Charging Network
[26] State of Utah Electric Vehicle Master Plan, Second Edition 2020
[27] Net-Zero America: Potential pathways, infrastructure, and impacts. Larson et al. (2020)

workforce by the energy transition will operate alongside other forces including automation and artificial intelligence (AI). To smoothen the disruption, funding, training, education, and policy are primordial needs. New fields of studies, interdisciplinary work, and transformed education centers will be required to support the new workforce. Planning at various levels will be crucial (**Appendix 2**). Communities at the frontlines of the energy transition should be prioritized for training that leads to high-wage, high-demand jobs in clean energy. All communities will need to add new academic subjects and craft training will need to prepare workers for entirely new roles with new skill sets.

Overview

The Intermountain West region ought to continue to have plentiful energy related work, assuming forward-looking planning. The loss of extraction and closure of power plants will remove well-paid jobs. The challenge for the region is to replace that work with new or expanded high-skill jobs in the new low-carbon energy industries. Part of the challenge will be adapting to a change in energy production and use, analogous to the invention of the steam engine. Some of the energy mix changes do not demand the same high-level skillset, and thus they pay less. Other new energy jobs will demand a high skill set and as such pay well. The work to maintain a solar plant does not require the same level of worker skills as a coal plant nor does a solar farm employ as many workers per megawatt[28]. Fortunately, solar is not the only new technology that will be employing workers as we transition to the new low carbon future.

The Intermountain West states will need to be aggressive to achieve high employment in the new jobs coming out of the transition. Some areas of work such as manufacturing are less common in the region than other areas of the country. Other work such as the construction of pipelines and transmission lines are large employers in the region, due to the vast expanse of territory that pipe and wire need to cross, yet they do not offer the same large-scale in-place employment as manufacturing. As many of the new technologies are going to require manufacturing facilities that are new and different from any prior factories, the region may want to compete for those fabrication facilities and jobs. Tesla assembly in Nevada and the Kore Power battery plant in Arizona are examples of large new factories developed in non-traditional manufacturing locations[29]. Other examples in the region are the new EV manufacturing facilities for Lucid, Nikola, and ElectraMeccanica[30].

[28] Parson Brinkerhoff jobs analysis
[29] Kore Power Selects Arizona Site. AZ Governor's Office. July 2021
[30] Arizona could become an EV manufacturing hub. Associated Press. May 2021

As technologies emerge and move from demonstration to commercial level production, the region will need to choose which opportunities to pursue. The region has done well with some of the new technologies, such as the growing amount of PV solar, EV (electric vehicle) manufacturing, and advanced battery technologies. By attracting more facilities in these industries and enticing other industries to locate in the region, job losses are less likely to result in extended raises in unemployment. The Intermountain West states will need to develop ways to maximize employment in the areas they are strong, grow the areas that are less robust, and continue to grow and exploit the employment opportunities in the new technologies.

The region will need to form one or more forums to evaluate technologies and estimate which might be pursued for future manufacturing.

In **Appendix 1**, a list of potential fields of employment is discussed in detail. The Appendix reviews areas of existing work that could be expanded and new technologies that are just being realized. While the list is not exhaustive, it is extensive. What the Intermountain West states need to consider is how they can become involved in the new fields such as battery chemistry, EV software, new poly manufacturing and DAC. Also, the states need to build on existing jobs such as pipeline and wire infrastructure.

Future energy worker needs ought to be viewed broadly. As an example, the installation of electric wiring and rails for mass transit could be viewed as a likely place to expand skilled workforce, based on skills that exist and would need only modest additional training. Building more efficient structures will employ workers dependent on skills that are already in place. Fabrication, assembly, and operation of carbon capture devices will need new skills and training, as will the associated chemistry for DAC sorbents.

The states and organizations that view what is coming most broadly and with a positive outlook will be in the best position to deliver high skill jobs to their workforce. Automation and AI are going to be more and more relied on to gain energy efficiency and to avoid harmful emissions. States will need to educate the disciplines that will work in these fields. From primary through graduate school, states will need to focus on this and other fields anticipating the growth in the marketplace for skills and educating to fill the coming need.

A new field of study just for CO_2 management will also need to emerge. This new discipline will employ engineers, chemists, designers, mechanics, operators, and managers who understand this field. Just as we created a field of study called aerospace, we need to create a new area of study focused on the removal, sequestration, and use of CO_2.

When we look at the needs for energy work in the future we tend to train and educate for energy generation related jobs such as wind and solar. We need to look at a much broader landscape that will include a larger, more complex mix of work to meet the needs of the energy transition. This appears to be a new industry that will demand high skill levels for the coming work. San Juan College in NM, Arizona State University, the University of Wyoming and a few others are beginning to form schools and research centers that will lead to educating these new disciplines.

Funding

In response to the deterioration of infrastructure across the nation, the Infrastructure Investment and Jobs Act (IIJA or the Infrastructure Bill) would provide for $1.2 trillion in spending, $550 billion of which would be new federal spending to be allocated over the next five years (**Table 4**). The investments would significantly reshape the future of work in the U.S., significantly increasing employment in clean energy, capture and other related areas (**Figure 3**).

Table 4. Funds break-down in the Infrastructure Investment and Jobs Act[31]

Sector		Allocated funds ($B)
Transit		
	Public	39
	Railways	66
	Electric vehicles	7.5
	Electric buses	7.5
Electric Power		
	Power grids	73
Resilience and climate change		
	DAC	3.5
	Other	50

The new legislation provides many opportunities for work, and we need to educate our workforce to secure them. As this funding is on-going, when actual application will unfold is still unknown. There is some prognosis as to how the future work will be allocated. Anticipating what is coming, states that wish to secure fabrication and other employment will need to quickly roll out education and training programs. States and regions will need to analyze what type of education and training

[31] At a glance: what's in the Infrastructure Bill? Ernest and Young. Available at: https://www.ey.com/en_us/infrastructure-investment-and-jobs-act

should be pursued and begin putting those programs in place. It is abundantly obvious that states must work on education and training so that they can avail themselves of this work.

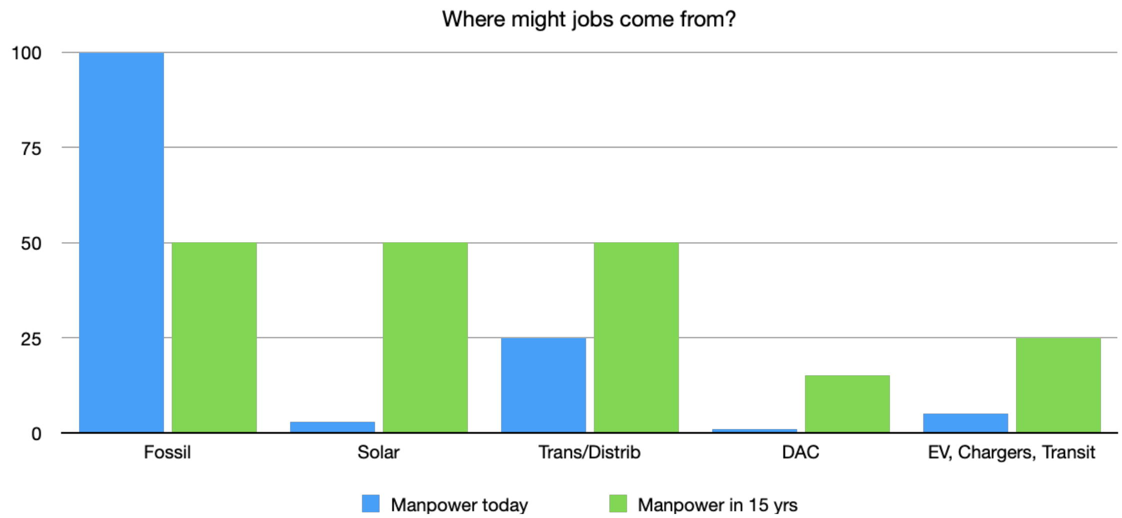

Figure 3. Projection of energy related jobs that could result from the Infrastructure Bill[32].

Education and training

Education may be the most critical factor in the transition of the workforce to new employment opportunities. The better the primary and secondary education the more likely the individual will learn a new skill set[33]. Some of the Intermountain West states have a strong or acceptable educational base. In others, such as Arizona and New Mexico, the education landscape is not encouraging (**Table 5**). Following good foundational education training programs, colleges and universities can build the specific education/training curriculums that will build the future workforce. Training and education to fill the new jobs that will be appearing to enable the energy transition will depend on a workforce educated to succeed in these new occupations.

Educating new workers that will be entering the job market requires educational opportunities that lean toward new opportunities. Workers need training to pivot to new opportunities. Training will involve many skill sets and educational disciplines. A few areas to consider include design, engineering, construction, assembly and installation, social impact roles, quality and safety, operations and maintenance, electric line work (transmission and distribution), concentration and purification of CO_2, DAC sorbent design/fabrication/application, management, legal, supply chain

[32] CNCE analysis
[33] Union Station Job Training and Hiring Analysis (TECO), 2001

and transportation, grid dispatching, land management, water reclamation, teaching, and training. States need to commit to build different yet compatible programs to prepare the different age levels and experience levels for new and existing work. There will be a significant range of new work with an equally significant range of educational needs. Programs with specificity should be created now with the expectation that these jobs are coming online quickly.

Potential workers in the education system now and the future need to be advised of the coming opportunities. Additionally, educational programs must be developed to suit those new careers. Consider a new educational discipline – carbonetics – a new applied field of study and training for carbon management. The goal of carbonetics is to advance carbon removal from the environment and provide a sustainable foundation for fighting climate change with a transition to renewable energy that cycles carbon taken from the air through long-term energy storage and transportation fuels. Carbonetics would provide research into carbon avoidance and removal forming a new discipline dedicated to fighting the growth of greenhouse gases.

Existing displaced workers have different challenges from the incoming workers. Not only does applicable training need to be developed, but training/education needs to be located where it is available to those workers. Also, provision needs to be made for education to be off hours for those still working and funding must be provided for those who have or will lose employment during the energy transition. Without life support funding, workers will not be able to sustain themselves while they are trained.

Table 5. Arizona public school rating by WalletHub [34]

	Ranking
Overall	49
Highest dropout rate	49
Highest student teacher ratio	50
US Department of Education	
Student reading proficiency	Bottom 10
Student proficiency in math	Bottom 10
High school graduates to college	Bottom 10
Bachelor’s degree in six years	Bottom 10
US News and World Report Education Rankings by state	
Higher education	33
K12	47

High skill jobs, whether “craft” or “professional”, are based on education/training from an early age, i.e., on K-12 education. In the Intermountain West, educational ranking by states varies

[34] Arizona Ranking. US News and World Report

significantly. If we consider Arizona, the state with the lowest ranking in the region[35], it is worth noting that Arizona may experience a larger challenge with training beyond secondary schooling (**Table 5**).

States and communities need to keep in mind and continue to be mindful of new ideas and possibilities. Many of the solutions and jobs are not known today, they have not been invented yet. By paying attention to the new ideas, we are better able to prepare the workforce for the changes and opportunities. For example, consider some of the following emerging “out of the box” ideas:

- DAC can be located anywhere. Some DAC designs are agnostic to location allowing for DAC to be built close to a sequestration site or where employment is needed or where product delivery is required.
- Mineralization using volcanic material. Sequestration need not be underground; it can be mineralization that allows the sequestered carbon to be stored above ground or even applied within structures.
- Solar is more opportunistic about space. The photovoltaic industry is just becoming aware of the competition for land that solar will be confronting. Placing solar in space that does not compete with agriculture and recreation will lead to creative applications, and thus jobs that may not be obvious. Consider solar being placed in unique ways such as covering aqueducts and canals, while also reducing evaporation.
- Carbon based fabrication where captured carbon will be the base for new fabrication and fuel development. These industries have not begun and are only just being delineated. The Intermountain West states ought to be in as good a position as anywhere else to recruit these new factories. It is probable that the US will insist on some of these factories being placed within North America, which will be supported by the added cost that will be applied to ocean transport due to the excessive CO_2 released by ships.
- “Sequestration as a Service” (SaaS) initiative (Wyoming) that would build commercial sequestration sites with wells for injecting CO_2 deep beneath the earth’s surface. These sites would be operated by entities with knowledge in the practice of injecting CO_2, which would then offer this as a service to any CO_2 emitter. Wyoming has extensive CO_2 infrastructure. Successful establishment of a SaaS industry would benefit all CO_2 emitters in the state and facilitate establishment of other forward-looking “all of the above” energy prospects such as hydrogen and DAC industries. Near-term initiatives include mitigating liability of Class VI wells used for CCS, utilizing CO_2 for cement, and mitigating CO_2

[35] “Less educated; less trained”. Arizona Republic. Rachel Leingang. September 2019

emissions from the combustion of fossil fuels. The workforce requirements to support this service sector encompass every skill set – from trades to legal and financial, and from executives to scientists, engineers, and laborers[36].

- Heavy batteries – Batteries have been viewed as an energy source that needs to be mobile. With the advent of large-scale battery backup for solar, batteries are being re-thought and the weight/portability is not a major consideration for stationary back-up. Iron and other materials are being investigated for fabrication.

The role of universities

As major institutions whose mission it is to educate, universities will have a crucial role to play in the energy workforce transition alongside community colleges and technical schools. These institutions are prepared to upskill and train workers for many of the future energy jobs, especially those that have a direct transfer from existing sectors. However, as discussed previously, the energy transition will also require entirely new fields of study and research with entirely new skills, as well as workers able to bridge between disciplines in ways that have not been achieved to date. Interdisciplinary and transdisciplinary educators and researchers will have to be created to in turn educate and train the new workforce. This will take time to establish, and some efforts are already underway.

Training workers

Differences exist between retraining, reskilling, and upskilling[38]. Retraining refers to teaching new skills on a completely new subject. Reskilling is training the skills needed for a slightly different job at the same company, and upskilling is teaching employees new skills to improve their performance in their current role without necessarily changing their position or career path[37]. The recommended approach is to focus on training, rather than re-training or reskilling. To view the needs of the workforce as anything other than education and training would be an unnecessary distraction. For instance, energy skills have not been particularly prone to re-training. Internal studies by Arizona Public Service, Palo Verde Nuclear generating Station, TECO Union plant, Calpine, and PetroSA GTL have shown that crediting experience and retraining is less effective than offering group training by starting the entire team at the same level assuming a need to bring the team up to the same level together.

Employers and training organizations do look for experience as a part of qualifying for training or education. However, here the energy industry is well accustomed with apprenticeship style training

[36] I-WEST Workforce Landscape. University of Wyoming School of Energy Resources. S. Gerace, K. Coddington, C. Nye. Dec. 2021

[37] What is retraining and why is it important? Sara Meij. Go Skills

models where workers learn “on the job.” After a base training, employees can then advance individually into more complex and complicated skill sets[38]. This will be necessary as one considers the data analytic skills that would be needed for almost all workers if they have to prepare for the infusion of digital technologies in this industry (e.g., sensors, etc.). This will have to be from the technician level to the analyst/engineer/manager levels. The specific analytics skills would be at different levels too.

Workforce training will be critical to maintain the expansion of new and revised technologies during the current energy transition. Some portion of the displaced workforce will be able to move to jobs related to what they have been trained to do. Others will need to acquire an entire new skill set. One might consider the transition from working a water powered mill to operating a steam engine to appreciate, graphically, the changes facing the workforce. Lateral skills mapping can help identify reskilling/upskilling program needs in this area.

Training trainers

The first question is who will provide “training for the trainer.” Currently there are many universities offering courses on climate and the environment while very few have courses on the technologies that are emerging. During the rise of the computer age, many U.S. universities had courses in the basic technologies required to staff this emerging field. Today there are few courses that even touch on carbon management methods and techniques that are emerging.

The major engineering disciplines and some scientific disciplines such as chemistry will cover some of the needed expertise, although this still leaves a large gap in who is being trained for point source capture, carbon to fuel, mineralization, direct air capture, sorbent structure, etc. Not only do we need individuals trained to work in these fields, but we also need to be educating the trainers, the teachers, the researchers, and the professors that will educate the coming workforce.

What does this mean for the regional universities in terms of the energy transition to carbon neutrality? How are they preparing? Are the universities raising funds and finding new teachers, labs, and classrooms? Are new degrees being defined and lesson plans organized? How are new labs being structured, what instruments are being purchased, and who is writing the new test procedures?

[38] Project Management Training for Engineers. R. Page, SCM. 2015

Universities, colleges, and community colleges will need to acknowledge and accept roles in education for professional workers and technical training for craft and operators. Training will need to be broad-based and may blur the traditional lines of universities and community colleges. This will need to be an effort that is universally acknowledged and will drive all educational institutions to play multiple roles.

Training programs

Training will play a significant role in the transition. Some training examples are included in **Appendix 3**; some model training programs have been created in the region. The Palo Verde Northern Arizona University training programs, the WYO-GTL program draft in 2014, and the Gila River Station rotational qualification program provide some examples. However, few documented studies exist that would apply to a shift in skills at the level mandated by the energy transition.

Roadmap for a regional energy workforce development

We attempt in this section to briefly indicate the urgency and then describe the work opportunities that we see coming. There will be work, but in many cases, it is going to be different from current roles. States are going to need to make projections and act on those projections[39].

Urgency

We will need to learn how to scale up new technologies using massive parallel implementations; measuring the carbon footprint; monitoring and certifying carbon sequestration; and designing economic frameworks that will allow us to pay for carbon removal, even if carbon utilization opportunities remain limited[40].

Two insights into the climate-energy nexus are necessary to note. First, energy is a critical and limiting resource for all modern societies. Without continued growth of energy supply, living standards will drop, causing instability and eliminating any chance of stopping the world's population explosion. Second, the world needs to reduce carbon emissions, even though fossil carbon is not running out. Returning to a safe level of CO_2 requires removal and storage of over 100

[39] The Fuse has Blown. Jeff Goodell. Rolling Stone. Dec 2021
[40] Lackner, L. Arizona I-WEST Workshop

ppm of CO_2 from the air, or about 1500 Gigaton of CO_2; more than the world emitted during the 20th century[41].

Developing a "workforce roadmap" for the Intermountain West involves planning (**Appendix 2**), education, research, training, recruitment, vision, and policy changes[42],[43]. Whichever way this plays out, the states have enormous opportunities to offer their population many new well-paying jobs.

What is needed

States might want to consider developing their own knowledge base as to what is happening and where we might consider focusing workforce efforts. One might want to consider beginning with expertise advising the state including economics, physics, law, statistics, and social services. We often think of workers as those who build or service things. For what is coming we need to consider the impacts on the overall populace and how we best serve them. Work in the areas of physics, social services, and policy will all offer work opportunities (**Appendix 1**). In the following we describe a scenario to create a basic roadmap for the future and detail the possibilities for many clean energy sectors. Quickly gathering information, analyzing approaches and needs, and committing to a plan to best serve each state and the region seems to be necessary and ought to begin.

Workforce roadmap

For a workforce roadmap scenario, we consider a range of timescales of 5, 10, and 15 years into the future.

Five years

The next five years will see a progression of new technologies struggling to find their place as a part of the solution. For the workforce this should be a time to position for the future. Education, training, and funding should be aligned to smooth the transition. Other than coal, jobs in energy will remain or decline slowly. There will be added work, particularly in infrastructure upgrades, renewables, and research. This phase will allow communities to educate, develop policies, recruit employers that have long-term growth, and reposition for the transition.

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[41] Lackner, L. Intro to DAC. ASU/CNCE 2020
[42] We should harness oil companies to reduce greenhouse gas emissions. Hugh Helferty. The Hill. Dec. 22, 2021
[43] Jenkins, S., Mitchell-Larson, E., Ives, M. C., Haszeldine, S., & Allen, M. (2021). Upstream decarbonization through a carbon takeback obligation: An affordable backstop climate policy. Joule, 5(11), 2777-2796

Ten years

In the next ten years, focus will shift toward solving and mitigating, and energy transition continues. For those trained for the new zero carbon energy future this will be a rich field. New technologies will still be fighting for investment and modest commercial application, but the winners will have begun manufacturing at some scale. Solar and wind farms will blossom, transmission will expand, EVs will displace combustion vehicles, and public transit will dominate transportation funding.

Fifteen years: Demand

Demand for renewables and capture equipment will outpace production. Work will be abundant for those with experience and training in the technologies that have survived and the new ones that have begun commercial production. Manufacturing, installation, and operation of the various applications of the new energy future will have a high demand for workers. Stability of the local environment will be important for manufacturers and operators, which may be an opportunity for the Intermountain West.

We also consider some form of virtuous cycle that allows some carbon combustion for electric generation, and thus some fossil energy jobs and carbon extraction jobs would remain. This scenario creates new jobs in capture and sequestration. The capture and storage process become a career path that is likely to remain until the twenty-third century. Also, there will be new jobs in the use of CO_2 for products including agriculture and food. There would be additional jobs in products based on carbon extracted from DAC including liquid fuel production for airplanes, ships, other transport, and specialty fuels such as race cars[44]; gas fuel production for power plants, blast furnace, and heating; production of base material for plastics and other carbon-based structural materials.

When viewing future work, to adequately prepare our workforce for the future, we must be realistic to provide training for work that will exist. In general, the discussion related to workforce on DAC can be applied to point source capture[45]. In the following we detail a possible workforce in each clean energy sector within the context of this scenario.

[44] Synthetic gas as cheap as fossil. Sarah Wells. Inverse. February 2020
[45] Habib paper

Work by category

Solar

Solar related employment is expected to grow rapidly over the next 15 years. Solar jobs pay above the U.S. average, with a median base pay of $58,523 per year, 12.4 % above the overall U.S. median base. Recent tariffs on imported solar components should help drive more fabrication in the U.S.[46].

Workforce growth in solar looks good for the Intermountain West. High percentage of "sun days," open space, and available workforce should play well for the workers. Better paying jobs adds to the attraction. Tariffs may allow the states to bid for manufacturing facilities providing good jobs that are community based. Although operating jobs at solar farms use less workers per megawatt than fossil operations, there is a broad range of skills associated with operation and maintenance which is likely to keep the pay scales competitive[47].

The I-WEST roadmap for employment in this field is straightforward, and includes educating the potential workforce in mechanical and electrical disciplines, software, expanding support for engineering degrees, and seeking opportunities to bring solar component manufacturing into the region.

Hydro

Hydro work is likely to decline along with the decline in megawatts generated. Intermountain West hydro facilities are closing, and new ones are not being added[48]. Natural resource protection and water conservation is forcing a reconsideration of hydro[49].

Wind

Wind represents a potential growth industry for the Intermountain West. While wind is limited to areas of high and relatively steady wind, such locations exist in the region. Manufacturing of

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[46] Glassdoor, Economic Research. Dr. A. Chamberlin. The Future of Solar Energy Jobs. Sept. 2018
[47] PB Project bid research 2016Wind power expansion. Gero Rueter. Dec 23, 2021. DW
[48] Dam it, don't dam it, undam it: America's hydropower future. Peter Gleick. Dec 17, 2017. Huff Post (Blog); Deal revives plan for largest US dam demolition. Gillian Flaccus. Nov 17, 2020. Assoc. Press; California hydroelectric plant expected to shut down for first time in 50 years. Joseph Choi, June 17, 2021. The Hill; Lake Powell could stop producing energy in 2023 as water levels plunge. Emma Newburger. Sep 23, 2021. CNBC
[49] How New England Bungled Its Plan to Transition to Renewable Energy. US News. A. Uteuova. Dec. 29, 2021

components is preferred in North America due to shipping costs. The path to greater growth in this field is dependent on a mix of challenges. The cost needs to come down, environmental issues with wildlife need to be resolved, open space needs to be opened to wind farms, transmission lines need to be extended to areas that are compatible with wind production, and the technology needs to improve.

Workforce needs are broad from manufacturing of a variety of components, to installation, to maintenance of devices. Turbine design and manufacturing has long been an American strength that could be leveraged into world leadership in engineering and fabrication of wind turbines. Blade component fabrication also fits historic U.S. skill sets. While the field application will be applied locally, we could focus attention also on design and manufacture[50].

Battery backup

Large scale battery backup is an emerging field. Grid battery back-up is newer and is now entering a new phase of application for renewable power for utility grids. Battery backup will be a rapidly growing field with serious technical and safety challenges in front of it. Current design and chemical components are all subject to change, opening up opportunities.

Workforce needs in this area are research and manufacturing. Intermountain West states could look to ways to gain from increased research in this field and consider encouraging manufacturing in the region. Manufacturing does have downsides as environmental issues are among the challenges holding back batteries. The environmental challenges of battery disposal will also create research and employment opportunities.

Alternate back-up

Other forms of back-up power may be developed. States might find this field attractive for research. Research may not create large numbers of jobs, but if it leads to a solution there is opportunity for job growth based on the research.

Nuclear

Nuclear will be an area of research with the potential for growth. Nuclear design and construction employees cross many disciplines, as does operation.

[50] Wind Power Expansion. Gero Rueter. Dec. 23, 2021. Deutsche Welle (DW)

Membrane capture of CO_2

Simple continuous transfer of CO_2 across the membrane as harvest into the "tube" as capture. While the chemistry and physics can be shown to work, the application as a functional physical model has not yet been achieved[51].

Point source capture and storage (PCCS)

Point source capture may allow existing coal plants and other CO_2 generators to continue operation, thus extending employment at the fossil facility[52]. A key topic for all carbon capture technology is identifying an economy framework that will allow, adopt, and promote development. Point source capture is a multiplier for employment. The design, installation, and operation of PCCS adds work opportunities. The continuation of existing fossil plants also allows workers to continue work at the existing location with existing skill sets.

CO_2 stimulated vertical agriculture

Vertical agriculture is predicted to become a part of our food supply chain. The questions are, will processes be developed that advantage agricultural growth based on added CO_2 and can the capture cycle be certified? Vertical agriculture will introduce new jobs with higher mechanical skills than older agricultural methods.

Mechanical direct air capture (DAC) of CO_2

DAC makes it possible to treat CO_2 as a waste stream to be cleaned up (see DAC Chapter). A waste removal effort to return the world to 300 or even 350 ppm would support an industry with a multi-trillion-dollar revenue stream. DAC would deliver CO_2 for storage and co-locate with storage infrastructure. It could also be used to produce liquid fuels and other carbon products from carbon dioxide taken from the air, and green hydrogen from water and sunshine. Solar energy would be converted into liquid fuels that feed into the transport sector, but also provide energy in rainy and cold parts of the country when and where renewables are not available. DAC opens up many new fields for labor. From design of the DAC systems to the design and operation of the off shoots such as captured carbon to fuel or other products, DAC would produce work in design, mass production, assembly, and operation.

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[51] ASU DOE MAAF Project
[52] Post Combustion Capture. Habib Azarabadi and Klaus Lackner. Environmental Science and Technology. 2020

Sequestration and long-term storage of CO_2

Many forms of carbon sequestration exist, including forests, grasslands, EOR, deep geological burial, mineralization, and more. Each of these have different timeframes and advantages. We must assure that storage is effective and long term; for example, if the biomass stored is going to rot away in a decade or two there must be at the start a functional and measurable means to understand how that is going to be retrieved or covered by other storage[53].

Job-growth is expected in sequestration. Different forms of sequestration are geographically specific, and training may be available to workers in each particular state. Certification, verification, and monitoring of sequestration sites will also create jobs and will require technical training.

New fuels and transportation

The race to create and produce “new fuels” is wide open. Some ideas will succeed, and others will fail[54].

Hydrogen will likely be an important part of the new fuel mix. Both grey and blue hydrogen require fossil fuel extraction. Green hydrogen relies on renewable energy making it a potential zero-emissions power source but currently only provides 1% of the world’s hydrogen[55]. Green hydrogen would be a dynamic job creator as the steps to produce are numerous and complex. Jobs could also be created in certification and verification. If this is one of the future fuels, many new jobs with new skills will result. The competition for green hydrogen will be natural gas with certified CCS and/or synthetic fuels from DAC and other sources.

Biofuels require fossil fuel to make (blend) and produce CO_2 when consumed[56]. It might be argued that by using DAC, fuels can be carbon free, however at this stage of development it is hard to understand the benefit of adding more steps to a process that is already complex[57]. Theoretically biofuels could be developed into agricultural and forest-based recycling. This would require the continued commitment of acreage to non-food based growing and certification.

[53] Three Ideas for Managing Carbon. Lackner. ASU. Nov 2000
[54] Americana, 400 Years of American Capitalism. Bhu Srinivasan. 2017
[55] The world is addicted to natural gas. Angela Dewan, CNN. Dec. 23, 2021
[56] Biofuel. Science Direct. Series of collected articles. 2014 to 2021
[57] Biofuel Basics. Office of Energy Efficiency and Renewable Energy. US DOE. undated

Sustainable Aviation Fuel (SAF) is difficult to distinguish from other biofuels and we have reached the same conclusions as for biofuels as to it viability by the mid 2030s[58]. There has been some consideration recently to broaden SAF to include DAC to fuel.

CO_2 capture to carbon fuel pre-supposes the success of DAC. The conversion process is explained in a number of research papers including "The Role of Direct Air Capture of CO_2 in the Developing Energy Transition"[59] and "Closing the Carbon Cycle"[60]. The workforce implications are quite broad. If this process were to succeed and become mainstream it would offer jobs in capture, concentration, and conversion to fuel. This fuel might in some instances be similar to natural gas extending the life (and jobs) of natural gas pipelines. The continuation of a carbon-based liquid and gas fuel would extend the use of many aspects of the transportation and energy generation sectors.

Electric vehicles are coming in large numbers, although it is unlikely that EVs will reach yearly production at the levels of internal combustion engine vehicles in the near future. EVs are currently more limited in application.

Mass transit is an energy-efficient means of transportation that places an additional burden on renewable generation and the grid. Mass transit offers jobs from fabrication and installation through operation.

Energy efficiency

Appliances will need to be more efficient although from a workforce perspective manufacturing is likely to continue at the current facilities unless new supply chain and shipping constraints arise. Thus, this would mean less opportunity for the Intermountain West to bring in new manufacturing. Some mitigation options like modifying agricultural processes, increasing home energy efficiency, and increasing building efficiency, will produce a wide variety of jobs.

Conclusion

This workforce analysis assumed that we are vigorous in our approach to a "net zero 2050" and the technologies this roadmap relies on will develop rapidly[61]. This creates job growth, but also creates

[58] What is SAF? British Petroleum. July 2021
[59] The Role of DAC in Developing Energy Transition. K Lackner. July 2019
[60] Closing the Carbon Cycle. CNCE/ASU. June 2019
[61] Climate Clubs Overcoming Free-Riding. William Nordhaus. American Economic Review. April 2015

concerns for states in which technological changes are not rapid enough. With clear focus on the goal of doing the best for our workforce, there are abundant possibilities for success. Vision and policy will need to be clear and forward looking. Leveraging the assets of the state and locale will require clear-eyed analysis of what one has and how those things might be best leveraged.

“The secret of change is to focus all of your energy, not on fighting the old, but on building the new.”

Socrates

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9. Ibid 8
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Appendix 1

Future Energy Workforce Needs

How might we look at the work that is coming or could be coming if the Intermountain West is positioned to gather its share of the new energy economy? Below is a list of energy work that might develop in the Intermountain West region in the next 15 years.

1. Technology development
    a. Engineering firms with a presence in the Intermountain West (IMW) such as Jacobs and Burns & McDonnell will have many opportunities to design and engineer the emerging technologies.
    b. The IMW Universities are positioned to be on the forefront of some of the emerging critical fields in the transition. The University of Wyoming is known to be a leader in climate research.
2. Manufacturing and Fabrication of Solar PV
    a. The design and fabrication of EV's is already occurring in the IMW and DAC devices and equipment will need to be manufactured.
    b. China currently produces solar PV but the lifespan is limited, opening a potential opportunity for fabrication outside of China. Also, First Solar is headquartered in the IMW and may return a portion of PV fabrication to the US.
3. Manufacturing and Fabrication of CO_2 Capture Devices

Currently there are two approaches to capture devices, and a third is being developed:

   i. Source capture
      Source capture will require the fabrication of many parts and pieces including the final equipment that will align to the "Stack". Therefore, fabrication will create jobs requiring a variety of skills and one might assume that much of this fabrication will go to companies that already make the pumps, fans and other equipment that are similar to what is manufactured today for other purposes. The final factory assembly and some of the components will be new fabrication facilities.
   ii. Direct Air Capture
      1. Active – fabrication and supply chain may be similar to the description above.
      2. Passive – fabrication for passive may be a hybrid, with some of the components coming from existing manufacturers, and other components may be entirely new, such as the vessel and the sorbent holder out of poly material creating a new fabrication design and execution. Could this new fabrication occur in the IMW? Currently there are supply discussions on-going that favor fabrication for passive equipment to be located "close" to the capture farm. Thus, if the IMW attracts the farms, the IMW has an opportunity to attract the accompanying fabrication of passive systems.
   iii. Developing a membrane that uses water evaporation to passively concentrate CO_2 in a continuous fashion
      This is under development.

4. Extraction

a. The IMW is an exporter of energy largely through the extraction of fossil fuels. While extraction will experience a decline, the probability that the decline will be gradual provides the opportunity for re-training and transition of the workforce.
b. One part of extraction will create new jobs. The pressure to contain methane leakage from wells will require new projects at well heads and probably piping or storage. Once captured, this now excess methane will need to be turned into a product – creating more jobs.

5. Renewables
    a. Solar install and operation are going to need to proceed at a much faster pace to meet the committed objectives of the energy transition. Solar installation and operation are less labor intensive than most forms of fossil energy generation, but the need for massive amounts of growth should provide a large number of jobs, including design and engineering jobs. The IMW has several advantages including open space for solar, more sunshine than other regions, an existing skilled workforce that will be looking for energy jobs, and research institutions currently working on solar.

        In addition to the quality concerns that impact solar, the use of land will need to be addressed. Locations still exist where expanding solar will not compete with other uses, and this is going to be a growing challenge. Solar may not be the highest and best use when compared to agriculture, housing, and other land use. We will need to design new approaches that accommodate dual uses.

        Currently only a very small portion of grid power uses solar, so land use is not now an issue, but will need to be considered in the future. With the expansion of solar into a significant portion of the US energy, solar will compete with agriculture, housing, park lands, transportation and forests for land. Solar will have many trade-offs to surmount, not the least of which will be the removal of woods and forests that provide a natural CO_2 collection sink and water collection tank.

        Renewables have some downsides including land use and geographic preferences (solar needs to be where the sun shines and wind power needs relatively constant wind), and intermittent supply. Solar will not be economical in all areas of the US or the Intermountain West due to the amount of sun power per day and the cost of land. Yet, solar canopies are barely beginning to show up in this country's acreage of parking lots. The Washington, D.C., Metro transit system, for instance, has just contracted to build its first solar canopies at four of its rail station parking lots, with a projected capacity of 12.8 megawatts. New York's John F. Kennedy International Airport is now building its first, a 12.3-megawatt canopy costing $56 million. Evansville (Indiana) Regional Airport, however, already has two, covering 368 parking spaces, at a cost of $6.5 million. According to a spokesperson, the solar canopy earned a $310,000 profit in its first year of operation, based on premium pricing of those spaces and the sale of power at wholesale rates to the local utility.

    b. Wind turbines are geographically more limited in the IMW than in some areas of the US (such as coastal states). However, there are a few excellent areas for wind generation and funding is already being directed to farms in these IMW regions. Wind turbines have the advantage of transitioning workers into a technology that many are already trained in – turbines. Due to the isolation of most of the farms there will be transmission jobs associated with wind generation advancement.

6. Battery Manufacturing
    a. Battery manufacturing employs a good number of high paying employees. The recently announced Kore battery plant will employ 3,000 permanent employees and

support 10,000 indirect jobs to produce lithium batteries. There will additionally be 3,400 jobs to construct the 1-million square foot facility.

   b. A transfer of some battery manufacturing back to the US would open up opportunities for the IMW. The Kore facility will be in Arizona, signaling the potential for the IMW region.

7. Generation

   The IMW is an exporter of electricity, and this is likely to grow. Arizona, the largest regional exporter, is a good example to follow. Arizona exported 300 trillion Btu of electricity in 2020. As the US 4th largest producer of solar electricity, a portion of the export was dedicated to solar generation based on customer contracts requiring (and paying a premium) for that generation source. Like other IMW states, AZ has many megawatts of stranded generation (generation plants that are not run at capacity). With the two new transmission lines being built (halted since the initial request from California in 2007) there will be more power flowing out of the state, and the underutilized natural gas plants and new solar farms in the Hassayampa Basin will operate closer to capacity.

   Arizona has 14,000 MW of natural gas generation in total underutilized. Other IMW states also have stranded natural gas generation. The IMW is surrounded by states without adequate generation. The potential for the IMW to be a supplier to other states and benefit from the job growth resulting from running these plants is a large potential job creator. If a rough rule of thumb is used that every 100 MW of generation creates 100 well-paying jobs 14,000 MW means a good number of jobs.

8. Direct Air Capture (DAC)

   a. DAC is expected to be a part of the transition to carbon neutrality and bringing the CO_2 ppm back to under 350. While the amount of DAC is thoroughly debated elsewhere it is fair to project DAC as being a job creator in the IMW. DAC has job creation potential from design through product development. The IMW already is a leader in DAC design and testing. Based on the ability in the IMW to tie DAC to solar, one ought to assume that DAC farms will be built in the IMW. DAC farms will require skilled workers to build and operate. The plans, including the concentration of the CO_2, will employ a full-time workforce with a range of technical and skilled craft jobs.

   b. As DAC farms are built in the IMW there will be the accompanying need for renewables to be built as a part of the concentration process. Once concentrated the CO_2 has numerous product routes including fuel. Fuel development from DAC would create more jobs including the pipelines to move the fuel to areas of the country that are less geographically blessed to capture CO_2.

   c. The engineering and fabrication of DAC equipment will also create new jobs. The manufacturing locations of DAC equipment have not been determined, and the IMW could be a potential location.

9. Pollution control and point source capture

   a. Point source or capture at the stack of CO_2 will create jobs to engineer, install, and to operate. Point source capture is plant specific which will mean the need for engineering at each site and the re-work to accommodate the addition of capture. Point source capture in most cases will result in a concentration facility at the location -more design and construction employment.

10. Source Capture of CO_2

   a. The capture of CO_2 at the "smoke-stack" is appealing as a concept but has not been successful as an application. Dr. Azarabadi's paper covers this thoroughly[62]. In

[62] Azarabadi, H., & Lackner, K. S. (2020). Post Combustion capture or direct air capture in decarbonizing US natural gas power? Environmental science & technology, 54(8), 5102-5111.

essence, for source capture to be economically feasible the plant emitting the CO_2 needs to operate in the range of 70% of the time. Fossil power plants are not operating at those load levels anymore. No plans currently exist for source capture in Arizona.

b. The advantage of source capture is the application of capture at the plant allowing for reduced operational cost, and potentially lower construction cost.
c. Source capture does present the challenge of what to do with the CO_2 as the site cannot be chosen at a sequestration site. This ought not be an insurmountable problem as the CO_2 might be converted to a product or mineralized for sequestration and transported to a sequestration location.

11. Electric vehicles (EVs) and EV Chargers
    a. The manufacturing of EVs is expected to rapidly increase. The IMW is fortunate that some of the EV startups are located in the IMW and some have already begun assembly plants in the IMW. This industry is just beginning to sort itself out, so it is premature to project how many jobs the IMW will be able to count on.
    b. EV public and private chargers will be installed. Installing and maintaining public charging is labor intensive.
    c. The current fabrication of chargers is not being done in the IMW.
12. Public transit
    a. Electric public and school transportation will receive $7.5B in the infrastructure bill. The largest portion goes to school buses, creating new work adding charging and other infrastructure for buses.
    b. Inner city electric transit is also growing, creating new construction jobs.
13. Transmission
    a. In a more electrified world, transmission grids will need a major makeover. This includes more expansive and robust transmission lines. The IMW has large open areas that transmission needs to cross, increasing the difficulty of maintaining lines and reaching them when disaster strikes.
    b. Similar to the rest of the country the IMW grids need upgrading and expanding. The recent events in Texas and California were caused by an antiquated grid that was not adequately tied to other systems. While more severe in those two states, the IMW states have similar weaknesses that need to be dealt with. Designing and building transmission is a large undertaking requiring a large workforce with specialized skills.
    c. In addition to the overall system weakness the IMW transmission system is particularly vulnerable to natural events. Fires, floods, and heat endanger many miles of IMW transmission. The lines that are vulnerable to fire, floods and heat sag will need to be upgraded or entirely rebuilt.
    d. Transmission needs go well beyond repair and upgrade. Renewables are going to often be installed and produced at locations not ideal for the existing grid. Coal plants were built away from urban areas, and perhaps some of those locations will be used for solar and wind, but there will be other locations chosen for land cost or wind or sun that may not have easy access to existing transmission.
14. Distribution
    a. During the initial rollout of EV chargers in Arizona it became clear that the distribution system was not adequate for level two and level three charger installations in many desired locations. The distribution system proved entirely inadequate in large portions of the rural system. Chargers will be only one of many challenges for distribution. Current distribution infrastructure is not prepared for distributed solar generation, nor is the grid ready for the removal of natural gas heating and industrial use. Other challenges include the need for substations that are adequate for the load

and more severe storms, increased multi-family housing, and an increase in electric supported mass transit.
   b. Electric distribution is too often viewed as a simple matter of connection. Distribution systems in much of the IMW has recently become a greater focus of interest and concern as distribution systems that were thought to have been complete and adequate for their application have become strained. Distribution networks generally were not built to have level 2 chargers in every garage, that were designed to operate in connection with gas heating. Consider the impact of removing gas heating and cooking from a high-rise residential building. The utility distribution to the building and the distribution within the building was not designed for the new electric load it is being asked to carry.

15. Mitigation and adaptation
    a. Systems from electric lines to plant infrastructure will need to be “hardened”.
    b. Part of adaptation and mitigation will be working with customers. Energy companies are going to be expected to play a role in mitigating the impacts and recovering from events in the future; this is a minor aspect of energy company employment today.
16. Batteries
    a. Fabrication of batteries has not been a major employer in the IMW. This may change as some battery start-ups are located in IMW states.
    b. Battery testing and installation will occur in all of the IMW states. Large back up battery installations for utilities and business will grow over the next 15 years. At least one international battery experimentation and battery testing facility is located in the IMW.
17. New fuels
    a. Hydrogen: New hydrogen programs are being introduced. Hydrogen has many potential applications as a fuel or as a vehicle for energy storage. While the IMW does not have any particular advantage over other parts of the country, it seems likely that some of this work will develop in the west/IMW (the 1st commercial hydrogen filling station is in California).
    b. Recycled carbon: The future of recycling carbon captured as CO_2 is interesting. If this becomes a means of creating and distributing fuels the IMW has some advantages including space, sun, and initial engineering efforts.
18. Bio
    a. Biology as capture may take many forms, and at its simplest is raising a forest to capture and hold CO_2.
    b. Biology as a source for fuel is complex, and the CO_2 discharge from burning the fuel needs to be addressed.
    c. Algae is a bio fuel that can (in the lab) be converted to fuel without releasing CO_2. The future application of algae as a CO_2 capture vehicle and then to a product is being worked on by several IMW universities and start-ups. Future success of one or more of these programs would open up another potential industry in the IMW.
19. Back-up power

    Solar and wind require that there be a backup power source to supply power when the renewables are not producing. Battery power can cover short term timeframes; nuclear energy is a potential back-up power.
20. Certification
    a. The “proof” of permanent storage for captured CO_2 will be an industry all on its own. Storage will need to be verified and periodically audited.
    b. Certification itself will for the early years be a process that changes with circumstances and new means of storage.
    c. Sequestration will have design, policy, financial and implementation considerations.
21. A-I (Artificial Intelligence) and controls

a. Control systems will play an ever-growing role in many of the systems that will need to be built and maintained.
b. A-I is going to need to be a part of many of the new technologies. As an example, consider the ramifications of A-I for direct air capture – the cycle timing of capture and harvest, adjustments for day and night, the weight of the lift in different weather, sorbent longevity, measurement of CO_2 on the sorbent, etc.

22. Sorbent and Chemistry
    a. For the CO_2 capture portion of the energy transition sorbents will play an outsized role in the potential for success. The chemical make-up will determine the propensity for capture and the ability to release the CO_2 for harvest. The chemistry will determine the volume of CO_2 capture in a given time scale.
    b. The chemical make-up will determine the ability of the sorbent to exist in different environments and probably sorbents will be designed for particular environments. The flexibility and brittleness will be important in application to the capture machinery.
    c. The ramifications related to sorbent chemistry are many and expand based on the interactions with the equipment, the environment, and the application to source capture, direct air capture, and mineralization.
23. Carbon-neutral fuels for jets
    a. Technically, CO_2 could be used to create virtually any type of fuel. Through a chemical reaction, CO_2 captured from industry can be combined with hydrogen to create synthetic gasoline, jet fuel, and diesel. The key would be to produce ample amounts of hydrogen sustainably. One segment keen on seeing synthetics take off is the aviation industry, whose airborne emissions are otherwise hard to abate. By 2030 this technology could abate roughly 15 Mtpa of CO_2[63].
24. Carbon fiber fabrication
    a. Carbon fiber (which can be both light and strong) is used to make products from airplane wings to wind-turbine blades, and its market is booming. The price of the component carbon is high ($20,000 a ton), and a CO_2-derived substitute could fit in this market. The volume of CO_2 used could become significant if cost-effective carbon fiber could be used widely to reinforce building materials. A number of pilot projects focus on cracking chemistry challenges involved, but a commercially viable process appears to be perhaps a decade or more away.
25. Industrial electrification
    a. Industrial companies could lower emissions by increasing electrification of their operations. Industrial sectors such as cement, chemicals, and steel together consume more energy than other sectors (such as electric power and transportation), and only 20 percent of that energy is electricity. Electrical equipment is less costly and more reliable for many industrial applications, but there are limitations. Electric furnaces, for example, can make heat up to 350°C, but not the high heat of up to 1,000°C that many industrial processes need. Innovation will be needed to address these gaps[64].
26. Advanced controls
    a. Grid utilization tends to average below 50 percent because the grid is built for times of peak demand and its performance worsens in extreme heat or cold. As more

[63] McKinsey Quarterly June 30, 2020
[64] Innovating to net zero: An executive's guide to climate technology; Tom Hellstern, Kimberly Henderson, Sean Kane, and Matt Rogers; October 28, 2021 (Items 26 through 30)

    renewables and storage systems are deployed at the grid edge, in homes and commercial sites, power grids will be more complicated to operate.
    b. Resilience, flexibility, safety, and efficiency can be improved with technologies such as solid-state transformers, advanced flexible AC controllers that allow more controlled grid flow, and high-voltage DC technologies for data centers.
    c. The broad stretches of low use land in the I-WEST region has created long transmission runs. These will need to be adjusted to renewable applications to the grid and the modifications on where power will be needed.
27. Software and communications
    a. Traditional electrical grids use idling power plants to maintain grid balance. Spinning reserves are expensive to run but can respond quickly when demand fluctuates. Modern electric grids should rely on ultrafast communications to maintain grid balance by managing every device on the network.
    b. Software-defined inertial substitution (to maintain grid balance when there are fewer spinning reserves), advanced "volt-var" management (to maintain proper voltage over long transmission lines or in highly congested urban markets), and network-wide instrumentation for condition monitoring and fault isolation would help utilities spot issues and prevent interruptions. Distributed energy-management software can coordinate all these elements. Digitized grids will require better cybersecurity protection.
28. Vehicle-to-grid integration
    a. As more drivers switch to EVs, the batteries in their driveways and garages could be hooked up to the grid to provide energy-storage capacity. One million typical EVs would offer about 75 gigawatts of storage, hundreds of times more than today's single biggest utility-scale storage facility provides. Accomplishing this integration requires technologies such as inverters that connect rooftop solar, wall batteries, EV batteries, and the grid, as well as fast chargers that buffer the grid from demand spikes while keeping EV batteries full.
29. Building-to-grid integration
    a. As buildings' energy controls improve, the buildings can be dispatched to the grid—that is, used to supply power—in ways that improve system performance. Buildings with energy storage or cogeneration could feed power onto the grid when called for.
    b. Buildings are going to be a frontier for many changes. Many of these improvements will relate to jobs for those in the energy sector.
30. Next-generation nuclear
    a. Nuclear energy has an uneven history: from the 1950s' promise of "too cheap to meter" energy to construction-cost overruns in the 1970s to post-Fukushima fears. Now, the push to decarbonize power has lent new appeal to nuclear generation, which is emissions-free.
    b. Emerging technologies include the sodium-cooled, molten salt, and helium-cooled reactors known as "GenIV"; small, sealed, modular, factory-built reactors; and fusion energy, an area where new start-ups are pushing costs down and timelines forward to prototype devices in the mid-2020s, ahead of government-backed research programs.

A short list of jobs associated with the work listed above:

- Engineers in all disciplines (and probably some new disciplines)
- Chemists
- Designers
- Ph.D. candidates, university faculty and research teams
- Social and field services to deal with storms, fires, and heat waves

- Battery engineers, chemists, designers, testers, technicians, and fabricators
- Construction (all crafts)
- Manufacturing line workers
- Plant operation, maintenance, outage support, start-up, and commissioning
- All craft - pipefitters, machinists, electricians, welders, etc.
- Forestry
- Biology
- Machinists
- Lawyers
- Scientists
- I&C technicians
- Truck drivers, equipment operators, and loaders
- Auto workers and mechanics
- Well workers, engineers, pipe fitters, equipment operators
- Land-use planning
- Longshoreman
- Management, sales, logistics, chemists, QA, safety, …
- Dispatchers, power plant workers, outage workers, plant operators
- Communications technicians
- Rail workers
- Heavy equipment operators, line crews, hot stick crews.

"We are caught in an inescapable network of mutuality, tied in a single garment of destiny. Whatever affects one directly, affects all indirectly."

Martin Luther King Jr.

Appendix 2

Conceptual outlines

How can we plan to best-serve our workforce? Plans ought to be place-based and adjusted to fit local circumstances, focused on local objectives and outcomes.

1. Prioritize those types of work that are anticipated or possible for the state. Then add more work ideas based on the state's experience and expectations. Ask local industries, NGOs, and communities what they see coming. Prioritize work opportunities based on the list developed by the state using Appendix One as a guide. Consider in prioritization what is likely or relatively available and what work the state would like to bring in. Also be careful to include work areas that are necessary, such as hardening of energy infrastructure and building grid capacity. Next, reorient the prioritized list based on timing, what is here now, what is coming during the next five years. Work the plan around the likelihood of the work and the timing of the work. Do not hold back from including potential work that may seem hard to get but would be beneficial for the state workforce. Build-in a change process within the plan, what is thought to be the best path at the start will be modified as time introduces new realities.

2. Build a briefing paper on the work that is coming (or may come) and include rough ideas on timing – "Work is Coming". For each type of work, clearly spell out the type of skill sets that will be in demand for the work, and rough ideas on numbers to be employed. Indicate, if known, what locales the work might take place in. Communicate "Work is Coming" (WIC) briefing to school districts, post-secondary schools, unions, town councils, utilities, major employers, recruiters, etc. Take extra steps with unions and post-secondary schools to discuss what the needs for various skill sets might be and how they are being addressed in preparing the workforce. Set up a team to build and distribute lesson plans and curriculum for secondary schools to help them prepare for the changes that are coming to the job market. The curriculum might focus on opportunities, but also provide "hope" that steps are being taken to mitigate the changes and disruption from the changing climate.

The Arizona Thrives Study[65] offers some ideas on how states might benefit from the future and how "hope" might be positioned within communications. The study found that absolute carbon emissions in Arizona as of 2019 have already declined by 26.6% since 2005. Carbon intensity of the same period declined by 28.3%. These numbers demonstrate that at least for Arizona, changes are in motion.

3. If we need or want a particular type of work, do we have the ability to train the workers? If not, what is needed? Do we need to train trainers or educators? Build a structured plan to develop the type of workers and the skill sets that the WIC indicates will be needed. Training takes time, particularly if the trainers or educators are not already in place. As new fields of

[65] Arizona Thrives: Projections for Arizona Carbon Emissions. Jan. 15, 2021. Arizona State University

work develop the skill sets of those who would do the training do not necessarily exist. Even starting with an experienced electrical or mechanical expert, a power plant operator takes at least two years of training, and a water chemistry tech an additional year. An engineer generally needs four to five years of university training and at least an additional year in the field. Physicists and scientists generally need a decade after secondary schooling before they can take on research. The state must address needs based on realistic lead times. Are the educators in place to do this, and if not how long might the educating of the educators take? The states ought to develop a comprehensive gap analysis based on skill sets they can list that are likely to be called on over the next decade and begin the process of building that workforce that has those skill sets. Some of this may be solved by recruiting, and of course some training will be carried out by private industry.

4. In parallel with step two, consider those areas of work/production that won't of their own volition come to the state but may be influenced to locate in the state. Which of these might the state want, and if desired does the state have a realistic chance of bringing some portion of that work to the state? Prioritize which industries or companies to recruit to the state. Build a plan to provide the state the opportunity to have the work brought in, including how to recruit and how to demonstrate the viability of the workforce that will be required. For example, EVs and chargers are going to be built in the US. Might the state pursue startups or even established manufactures? Manufacturing of existing and new EV/charging technologies is not necessarily established. Not only EVs but batteries, capture devices, electric trains, electric buses, electric outboard motors, carbon conversion, wind turbines and blades, and many more things that will need to be made do not have established manufacturing sites. The state will be competing with other states and with overseas opportunities. States understand and should exploit the advantages they may have over other states. States will have new advantages over foreign manufacturing for new fabrication.

5. States might group education and training into tiers based on when the work might be needed and what skill sets are likely. For example, transmission work is likely to begin very soon, while fabrication of new batteries will await the construction of the battery factory. For transmission work a focus on utilities and electrical unions to provide training for linemen, engineers, and heavy equipment operators would be wise. To attract a battery fabricator a focus on chemists, research scientists, line workers, supply-chain/procurement, and safety that will require courses at universities and other post-secondary schools.

Timeframe	High School & Tech Training		Post Secondary & University
Next 2 yrs.	Transmission, Distribution, building efficiency, installing EV chargers, conversion from natural gas to electric, source capture construction, civil construction to harden the energy infrastructure, pipeline conversion, methane site mitigation, hot stick crew, mine mitigation, trubine mechanic		Engineering and siting new transmission, grid management, distribution underground design & engineering, capture research scientists, scientists studying mitigation, capture device engineering, hydrogen vehicle engineering, Chemistry for sorbent design, geologist,
Next 5 yrs.	Battery manufacturing line work, EV manufacturing, electric train rail lines, electric train & bus manufacturing, Direct Air Capture farm installation & operation, gas & oil field conversion, agricultural changes, "restoration of "brown field" sites		Electrolysis design, CO2 concentration, carbon to plastics, captured carbon to fuel, bio capture engineers, agricultural mitigation and crop conversion scientists, chemists and chemical engineers for batteries and the application of captured CO2 to product, project manager

Figure A2.1. Example of components of a workforce plan. Each state will have their own set of prioritized work and timing.

The plan would need to be crafted to build on early education and training toward future need. For example, reading and math skills would need to be emphasized as these skills are a building block toward future training. Early training might be a requirement to secure later projects. As an example, DAC devices are now being manufactured and will soon be deployed in capture farms. Early training of operators and maintenance workers would provide the state with a small group that might train and lead the larger workforce that will soon be needed. The state that has this early cohort trained will stand at the front of the line for the coming larger farms.

6. States as a part of their planning need to build a workforce, including the engineers and planners, that allows the state to anticipate and mitigate energy shortages and energy over pricing. As these disruptions are inevitable the state should prepare to have in place the workers to best navigate the challenges that are ahead. The electrical and other engineers, dispatchers, load planners, renewable integration engineers, outage managers and schedulers, and others to ease the burden of shortages and to maximize the capacity factor of electrical producers.

7. Consider the risks within the plan and the risk of not including various aspects in the plan. Develop a mitigation strategy for each risk. Communities and states probably ought to recruit physicists, climate scientists, and others to advise on what is occurring and what solutions might be considered. Other risks that need to go into planning are using models. Might some forms of electric draw be avoided or minimized? What is the risk/reward balance of EV daytime charging, should a state encourage cyber coin mining, are data centers an advantage or too big a draw, should budget dollars be spent on roads or electric trains? Risk and mitigation is a powerful evaluation tool. It may be necessary to modify building codes to require greater insulation and passive energy saving measures for all new and remodeled buildings. On the other hand, it may be more effective and palatable to encourage rooftop solar. Thousands of these types of decisions will impact the workforce and what skill sets will be needed. Decisions of this type must consider workforce availability and how to build the workforce skill sets to fulfill the decisions.

8. Visit with constituencies and develop consensus. Outreach is critical in building support and starting a process of training a workforce for the future. Great change has historically created winners and losers, there is no reason to believe that the coming change will be different from the past.

9. Plans need to be able to change and they need a commitment to a timeframe. Follow the following steps: 1) create a schedule that is both ambitious and possible; 2) build a budget considering what the infrastructure legislation might be able to help fund; 3) draft a comprehensive inclusive plan for workforce growth and success; 4) prioritize what work is likely and what is desired and develop workforce training that considers priorities; 5) create within the plan a change consensus and approval process to deal with the adjustments that will come; and 6) communicate the plan and the vision.

10. It may be helpful for communities to consider use-case studies to align work with the skilled workforce that will be necessary to meet demand. A couple of sample use-cases below are described at the simplest level:
    a. Large distances of the distribution line will need to be buried to protect lines from high winds. Before planning such a step a community would need to consider start date, digging equipment and operators, delivery of material tied to procurement and supply chain specialists, community outreach officers, surveyors and right of way engineers, “blue stake” technicians, electrical and civil engineers, shoring material and the crews to put up shoring, U/G safety officers, procedure writers, management and accounting staff, line trucks, shading material and crew, joint use engineers, substation engineers and electricians, landscape crews, … One would need to map out the staffing needs, the qualifications, the timing and the education and training. The use case would consider these factors to create a schedule, a plan, and a budget.
    b. States will seek to have some of the CO_2 capture farms within their state as this form of industrial activity will help replace lost mining and coal plant jobs. Seeking to entice a developer to locate in a particular area requires an effort on the part of the

state and local community. The factors to consider might be staffing. The community leaders might draft a position paper on why the community has the manpower and training that would staff the capture farm. Staff potentially would need engineers and construction workers to build the farm, a permanent operations, maintenance, and support crew. The Ops crew would need to include equipment operators, plant operators, engineers, chemists, pipe fitters and welders, machinists, warehouseman, procurement, quality control officers, safety staff, and a range of maintenance specialists. Big farms will need large and skilled staffing. While some training and experience may be applied to workers in this new field all the staff will need some new training, and many will require extensive education. The use case would pull together the target capture developers, what features need to be covered, how to deliver the workers and the training, and what it takes to bring all the elements together.

Appendix 3

Listed here are a few examples of worker training programs.

Arizona Public Service and Northern Arizona University provide a Bachelor degree in electrical engineering technology for workers at the Palo Verde Generating Station. More information at: https://nau.edu/legacy/educational-partnerships/aps/

AZNext initiative is a workforce training accelerator partnership developing paid internships, apprenticeships, train-to-hire programs, boot camps, and simulated work experiences intended to create talent solutions to meet industry needs. The initative focuses on IT and cybersecurity and advanced manufacturing. More information at: https://wpcarey.asu.edu/aznext

Native Renewables, Inc. provides short-term workforce training on solar PV installation on Navajo and Hopi Nations. More information at: https://www.nativerenewables.org/

Institute for Tribal Environmental Professionals (ITEP) provides 1-2 days training for tribal environmental professionals nationally on a range of topics including air quality, climate change, energy and more. The energy training focuses on hand-on training for PV installation. More information at: http://www7.nau.edu/itep/main/Training/training_energy

Gila River Indian Community Utility Authority provides a 12-month Technical Training Program for Native members to prepare for GRICUA Line Worker, Solar Technician or Meter Technician Apprentice Programs. More information at: https://gricua.net/careers/training-programs/technical-training-program/

Appendix 4

This chapter drew information from current events and trends, from peer-review material, news articles, and internal documents and reports. To supplement and inform the analysis, the Intermountain West states were requested to provide information on specific aspects of the workforce in their states. The information from the two states that responded is included here.

Workforce Template for Response

Evaluate the workforce landscape

- *This subtask will assess the current energy-related workforce demographics and scope for workforce retraining*
    - *Catalogue existing regional workforce*
    - *Evaluate at-risk workforce in context of energy transition*
    - *Write summary of workforce landscape*
- *Product: written summary of the workforce landscape for the region, to be incorporated into final report*

WORKFORCE SUMMARY BY UTAH

Prepared by: Brooke Tucker
Energy & Geoscience Institute
University of Utah

Workforce today:

- Size of current workforce
    - Census: Utah Total employment, 2019: 1,373,876[66]
    - Census: Utah Civilian labor force, total, percent of population age 16+, 2015-2019: 68.3%[67]
    - Bureau of Labor Statistics: All occupations employment, Utah, May 2020: 1,489,020[68]
- Make up
    - Education levels as related to employment
        - Census Bureau: Bachelor's degree or higher, percent of persons 25 years+, 2015-2019: 34%[69]
        - State of Utah Public Health Indicator Based Information System Table[70]

[66] U.S. Census Bureau Quick Facts – Utah
[67] U.S. Census Bureau Quick Facts – Utah
[68] Bureau of Labor Statistics – Utah
[69] U.S. Census Bureau Quick Facts – Utah
[70] State of Utah Public Health Indicator Based Information System

Table A4.1. Utah workforce education

	Utah	U.S.
Less than High School	6.9%	11.4%
High School	23.1%	26.9%
Some college	25.5%	20%
Associates	9.7%	8.6%
Bachelor's	23.4%	20.3%

- Leading employment categories and projected growth
    - Utah's 2021 Employment Summary for October 2021[71] indicated:
        - Utah's unemployment rate was 2.2%, while the U.S.'s unemployment rate was 4.6%
        - Utah's job growth rate was 3.7% while the U.S.'s was -2.2%
        - Utah's largest private sector gains in the past two years:
            - Trade, Transportation and Utilities: 20,900 jobs
            - Professional and Business Services: 15,500 jobs
            - Construction: 10,800 jobs
            - Manufacturing: 7,900 jobs
        - Largest private sector losses during the past two years:
            - Leisure and Hospitality Services: -1,200 jobs
            - Natural Resources and Mining: -1,200 jobs
- Labor force employment vs. US average
    - Census: Civilian labor force, total, percent of population age 16+, 2015-2019: Utah 68.3%, U.S. 63%[72]

- Trends expected by 2030
    - In October 2021, Governor Cox released version 2.0 of the One Utah Roadmap[73]. The Roadmap calls for updating the statewide energy plan to ensure Utah's energy future is secure, innovative, and reliable. The Roadmap also highlights ways Utah can lead out on public-private partnerships focusing on clean energy (such as microgrids, battery storage, solar, hydrogen, etc.) in a fiscally prudent way.
    - PacifiCorp's 2021 Integrated Resource Plan[74] indicated its preferred portfolio may entail accelerated coal retirements, no new fossil-fueled resources, continued growth in energy efficiency programs, new transmission investments, and incremental renewable energy and storage resources.
    - A number of western states have passed Renewable Portfolio Standards[75]. As certain mandates go into effect over the coming years, it will likely affect generation portfolios and how the transmission system is utilized in the region.

[71] Utah Department of Workforce Services Utah Employment Summary: October 2021
[72] U.S. Census Bureau QuickFacts: Utah; United States
[73] One Utah Roadmap 2.0
[74] PacifiCorp 2021 Integrated Resource Plan
[75] Lawrence Berkeley Lab Renewable Portfolio Standards Resources

Energy transition is creating loss of jobs: (closure of mines, power plants, drilling, etc.)

- Numbers
  - Number of workers in the energy industry (mines, plants, utilities)
    - According to the Kem C. Gardner Policy Institute's Economic Impacts of Utah's Energy Industry Report, in 2017, Utah's Energy industry directly and indirectly supported 3.8% of the state's employment, 4.2% of its earnings, and 5.7% of its gross domestic product[76].
    - According to the 2020 U.S. Energy and Employment Report (USEER)[77], Utah has 31,468 Energy Workers:
      - 11,853 Electric Power Generation
      - 11,885 Fuels
      - 7,730 Transmission, Distribution, Storage
  - Estimate of lost jobs to date
    - The USEER report estimates traditional fossil fuel power generation jobs in Utah at 3,304 in 2020, which was down 3%.
    - Utah's 2021 Employment Summary for October 2021 indicated the mining and natural resources sector lost 1,200 jobs in the last two years[78]. COVID-19 may have impacted jobs numbers during the time period recorded.
  - Project for job loss due to closing and reduction of operation for the next 5 years
    - PacifiCorp's 2021 Integrated Resource Plan does not assume the closure of its Utah coal-fired power plants within the next 5 years[79].
    - The Intermountain Power Agency intends to convert the Intermountain Power Project (IPP) coal-fired plant to 30% hydrogen and 70% natural gas by 2025 and expand to 100% hydrogen by 2045. Construction for the conversion is expected to support about 450 construction jobs. The rebuilt plant is expected to employ 120 workers, less than the number that work at IPP now (~400[80])[81].

- Types/sectors of workers

  Sectors where jobs are declining (Utility, mines, extraction, etc.)
    - Prior to the COVID-19 pandemic, the energy sector had been one of the fastest growing job markets. From 2015 to 2019, the annual growth rate for energy employment in the United States was 3%—double compared to 1.5% in the general economy. The USEER report found that energy job totals reached 7.5 million by the end of 2020, a decrease of 840,000 jobs or 10% decline year-over-year. While there was a clear decline, there were also positive signs that the sector was on the rebound—at the pandemic's peak in mid-2020 energy jobs had decreased by 1.4 million. By the end of 2020, 520,000 energy jobs had already returned. Additionally, employers that responded to the survey also signaled confidence in the upward employment trend continuing through 2021[82].

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[76] Kem C. Gardner Policy Institute, Economic Impacts of Utah's Energy Industry, 2017 (published February 2020)
[77] 2020 U.S. Energy and Employment Report - Utah
[78] Utah Department of Workforce Services Utah Employment Summary: October 2021
[79] PacifiCorp 2021 Integrated Resource Plan
[80] ABC Utah: Utah's largest coal plant converting to hydrogen power
[81] Salt Lake Tribune: Intermountain Power Project's switch from coal to hydrogen could power rural Utah job growth
[82] U.S. Department of Energy, US Energy & Employment Jobs Report Fact Sheet

- Geographic area
    - For information and maps on resource potential areas and development activities across the state of Utah, please see Utah's Energy Landscape 5th Edition[83].

Future perspectives

- Energy transition is expected to cause changes in Utah
    - Impact of gas and oil based on current trends and regulation
        - Crude oil and natural gas liquids reserves mostly correlate with oil prices but with a several year lag after major price spikes. After peaking in 2013 at 896 million barrels, reserves retreated with falling prices, but bounced back to 528 million barrels in 2018[84].
        - Although Utah holds less than 1% of the nation's proved natural gas reserves, the state has 3 of the 100 largest U.S. natural gas fields. Utah's marketed natural gas production, most of which is in Uintah County in the northeastern corner of the state, accounted for about 1% of U.S. natural gas output in 2020. The state's natural gas production rose steadily for three decades starting in the mid-1980s, and it peaked in 2012. Annual production has decreased every year since in response to low market prices and reduced crude oil drilling[85].
        - Among the 50 states, Utah has the fourth-highest number of producing oil and natural gas leases on federal lands[86].
    - Impact of mining
        - The majority of Utah coal, 64% in 2018, was used in-state. In the past, Utah was a significant net exporter of coal, but out-of-state domestic demand has decreased from a high of 16 million tons in 2001 down to only 1.9 million tons in 2018. Utah's foreign exports peaked in the mid-1990s at about 5 million tons, then dropped to near zero in the mid-2000s. However, the foreign export market has seen a resurgence in the past few years, increasing to 3.1 million tons in 2018[87].
    - Growth or decline in pipeline installation
        - Utah is crossed by several interstate pipelines that transport natural gas from the Opal Hub in Wyoming, from the Piceance Basin in western Colorado, and from Utah's in-state production to markets in Nevada, Idaho, and Colorado[88].
        - Utah's five oil refineries, all located in the Salt Lake City area, process nearly 200,000 barrels of crude oil per calendar day. Much of the oil processed by the refineries is brought in by pipeline from Utah, Colorado, Wyoming, and Canada. Utah's refineries have about three-tenths of the refining capacity in the Rocky Mountain region. Pipelines carry refined products from Salt Lake City's refineries to markets in Utah, Idaho, Nevada, Wyoming, eastern Washington, and Oregon. Petroleum products also enter Utah by pipeline from refineries in Wyoming and Montana[89].
    - Solar energy generation growth

[83] Utah's Energy Landscape 5th Edition, Utah Geological Survey
[84] Utah's Energy Landscape 5th Edition, Utah Geological Survey
[85] U.S. Energy Information Administration – Utah State Profile and Energy Estimates
[86] U.S. Energy Information Administration – Utah State Profile and Energy Estimates
[87] Utah's Energy Landscape 5th Edition, Utah Geological Survey
[88] U.S. Energy Information Administration – Utah State Profile and Energy Estimates
[89] U.S. Energy Information Administration – Utah State Profile and Energy Estimates

        - In 2018, Utah ranked 26th in the nation in percent of total net electric generation from renewable resources (11.2%). Of particular note, Utah is one of only seven states where electricity is generated from geothermal resources. Utah's renewable electric generation is dominated by 914 MW of newly installed utility-scale solar farms (50%), followed by hydroelectric (21%), wind (18%), and geothermal (10%) power. The biomass portion is mainly electricity generated from burning landfill gases. Renewable energy sources now account for 11% of Utah's total electricity generation.
        - The total capacity of net-metered PV solar installations (i.e., roof-top solar) in Utah has increased exponentially in the past few years, from a total of 3.4 MW in 2010 to 273 MW in 2018; 78% of which was in the residential sector[90].
        - Potential new transmission investments are underway in Utah, including PacifiCorp's Gateway South project, which filed for a Certificate of Public Convenience and Necessity at the Utah Public Service Commission in September 2021[91], and the TransWest Express project, which recently concluded its open solicitation process[92].
    - Wind generation growth
        - Wind energy produced about 15% of Utah's renewable electricity in 2020. Utah has five wind farms operating with about 390 megawatts of generating capacity. The state's two largest wind farms send power to southern California. There is commercial wind power potential in the Wasatch and Uinta mountain ranges in Utah's north-central region and on the mesas in western Utah[93].
    - EV infrastructure
        - During the 2020 session, the Utah Legislature passed H.B. 396[94], which directed the Utah Public Service Commission to authorize Rocky Mountain Power to recover a $50 million investment in an electric vehicle charging infrastructure program. Rocky Mountain Power filed its proposed program with the Utah Public Service Commission in August 2021[95].
        - During the 2020 session, the Utah Legislature also passed H.B. 259[96], directing the Utah Department of Transportation to lead the creation of a state-wide electric vehicle charging network plan, which was released later that year[97].
    - Public transportation
        - As Utah's population grows, public transportation is an important tool to help improve air quality along the Wasatch Front.
    - New green industries (capture, mitigation, batteries, EV's, etc.)
        - The state of Utah is well positioned to serve as a hub for emerging clean industries. The University of Utah Energy and Geoscience Institute has provided extensive characterization of geological formations and carbon sequestration opportunities across the state of Utah.
- Transition to a carbon neutral energy economy would offer these potential workforce opportunities:
    - Building insulation and other upgrades

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[90] Utah's Energy Landscape 5th Edition, Utah Geological Survey
[91] Utah Public Service Commission Docket No. 21-035-55
[92] TWE Project Open Solicitation
[93] U.S. Energy Information Administration – Utah State Profile and Energy Estimates
[94] H.B. 396 Electric Vehicle Charging Infrastructure Amendments
[95] Utah Public Service Commission Docket No. 20-035-34
[96] H.B. 259 Electric Vehicle Charging Network
[97] State of Utah Electric Vehicle Master Plan, Second Edition 2020

    - Public transit
    - Renewables
    - Carbon capture
    - Methane to liquid fuels
    - Forestry
    - Infrastructure upgrades (EV charging, electric transmission & distribution, bike paths, etc.)
- The workforce will need to adjust
    - To deal with the loss of energy jobs
        - Are there transition programs in place?
        - Are workers geographically located in areas that will have future work?
        - Can skills be transferred?
    - To prepare for the new renewable, capture and energy jobs:
        - Is training adequate?
            - In the USEER Report[98], employers in Utah gave the following as the top three reasons for reported difficulty in hiring:
                - Lack of experience, training, or technical skills
                - Competition/small applicant pool
                - Difficulty finding industry-specific knowledge, skills, and interest
        - Who will design and build these new projects?
            - Investor-owned utilities
            - Electric cooperatives
            - Independent power producers
            - Independent transmission developers
            - Research universities

Other data sources used:

- 2020 U.S. Energy and Employment Report - Utah
- Economic Impacts of Utah's Energy Industry, 2017, Kem C. Gardner Policy Institute
- Utah's Energy Landscape 5th Edition, Utah Geological Survey
- U.S. Energy Information Administration – Utah
- One Utah Roadmap
- Foundations for a Better Energy Future
- Utah Department of Workforce Services – Economic Data
- PacifiCorp 2021 Integrated Resource Plan
- Bureau of Labor Statistics – Utah
- Utah Department of Workforce Services Utah Annual Report, 2019 Labor Market Information (Published January 2021)
- 2021 Utah Economic Report to the Governor

[98] 2020 U.S. Energy and Employment Report - Utah

WORKFORCE SUMMARY BY WYOMING

Prepared by: University of Wyoming School of Energy Resources
Selena Gerace
Kipp Coddington
Charles Nye

Workforce Today

Size of current workforce in Wyoming

Civilian Labor Force: 293,000
Employed: 281,000
Unemployed: 12,000
Unemployment rate: 4.1%

The unemployment rate in Wyoming has been steeply declining since reaching a peak of 8.1% in May of 2020. As of October 2021, it was down to 4.1% which is lower than the pre-pandemic level of 4.8% in February 2020 (Figure A4.1).

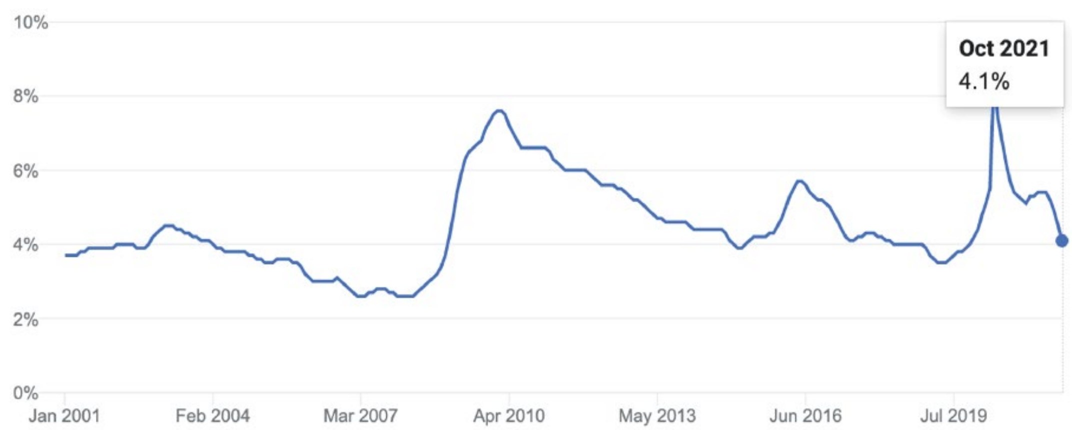


Figure A4.1. Wyoming Unemployment Rate, January 2001-October 2021
Data Source: Bureau of Labor Statistics

Education levels as related to employment

Nationally, employment rates increase with education level. The Bureau of Labor Statistics (BLS) reports that labor force participation rates are 58.1% for men and 33.3% for women without a high school diploma. With a Bachelor's degree, these rates increase to 79.3% for men and 68.5% for women.[99]

High percentages of Wyoming's workforce have at least a high school diploma (Figure A4.2). For members of the workforce ages 25 and up, over 90% have a high school diploma or higher. Much lower proportions of the workforce have a higher degree. For workforce participants ages 35-44, just over 30% have a Bachelor's degree or higher. For ages 25-34 and 45 and over, under 30% have a Bachelor's degree or higher.

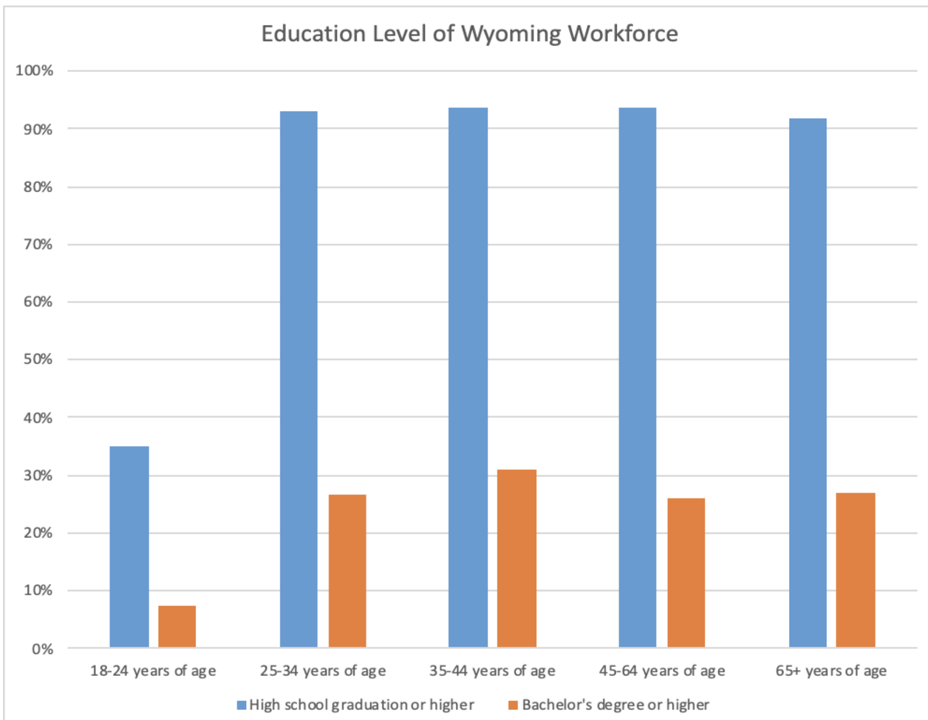


Figure A4.2. Estimated Percentages of Education Levels of Wyoming's Workforce
Data Source: American Community Survey, conducted by the U.S. Census Bureau

In Wyoming, the percentage of jobs that require at least some postsecondary education is lower than for most other states in the nation--only 39.3% of all jobs in the state. Louisiana is the only state that had a slightly lower percentage of jobs requiring post-secondary education, at 39.2%.[100]

The largest proportion of jobs in Wyoming requires just a high school diploma (44.6% of total jobs in the state). 20.7% of jobs require a Bachelor's degree and 16.1% of jobs do not require

[99] https://www.bls.gov/spotlight/2017/educational-attainment-of-the-labor-force/home.htm
[100] https://doe.state.wy.us/lmi/trends/0621/0621.pdf

any formal education. Only 2.3% of jobs in Wyoming require a Master's degree, but this is higher than the proportion of jobs in the US requiring a Master's degree (1.7%).

Nationally, higher levels of education are correlated with higher wages. In 2018, jobs that required some postsecondary education paid a median rate of $17.81 per hour, while jobs that only required a high school education paid $16.48 per hour. Likewise in Wyoming, wages increased with increased education level. The average annual wage for jobs that do not require any formal education in Wyoming is $31,916, while the average annual wage for jobs that require a doctorate or professional education is $114,593.

Interestingly, Wyoming has a higher-than-average annual wage than the US average in 17 of the 508 occupations in the state. Fourteen of those 17 jobs require a high school diploma or less and were positions often found in mining such as derrick operators ($58,890) and continuous mining machine operators ($80, 890).[101].

Leading employment categories and projected growth

Industries that employ the most people in Wyoming in the first quarter of 2021 include local government, leisure and hospitality, retail trade, health care and social assistance, and educational services (Table A4.2).

Industry	Number of People Employed
Local Government	44,784
Leisure & Hospitality	31,807
Retail Trade	28,638
Health Care & Social Assist.	25,374
Educational Services	22,983

Table A4.2. Industries with Highest Average Monthly Employment in Wyoming
Data Source: Wyoming Workforce Services, Trends Vol. 58 No. 10.[102]

In Wyoming, there are nine industries that are currently experiencing growth, as of the second quarter of 2021 (Table A4.3). Top growing industries were food manufacturing, data processing, and administration.

[101] https://doe.state.wy.us/lmi/trends/0621/0621.pdf
[102] https://doe.state.wy.us/lmi/trends/1021/1021.pdf

Growing Industries	Annual % Increase in Employment
Food Manufacturing	37.80%
ISPs, Search Portals, & Data Processing	15.20%
Administrative & Support Services	12.50%
Couriers & Messengers	11.50%
Warehousing & Storage	8.70%
Primary Metal Manufacturing	8.60%
Construction of Buildings	8%
Pipeline Transportation	6.70%
Wood Product Manufacturing	6.30%

Table A4.3. Growing Industries in Wyoming
Data Source: Wyoming Workforce Services, Wyoming Growing and Declining Industries Report, Second Quarter 2021.103

Nine industries are experiencing declines in Wyoming (Table A4.4). Interestingly, the topmost declining industry is oil and gas extraction (-20.2% change from last year). Three of the other eight declining jobs are also mining-related industries: support activities for mining (-14%), petroleum and coal products manufacturing (-12.7%), mining (except oil and gas) (-7.3%).

Declining Industries	Annual % Decrease in Employment
Oil & Gas Extraction	-20.2
Heavy & Civil Engineering Construction	-15.8
Support Activities For Mining	-14
Petroleum & Coal Products Manufacturing	-12.7
Nursing & Residential Care Facilities	-8.3
Mining, Except Oil & Gas	-7.3
Merchant Wholesalers, Durable Goods	-7.3
Broadcasting, Except Internet	-5.7
Support Activities for Transportation	-5.4

Table A4.4. Declining Industries in Wyoming
Data Source: Wyoming Workforce Services, Wyoming Growing and Declining Industries Report, Second Quarter 2021.[104]

[103] https://doe.state.wy.us/lmi/G_DInd/Report_21Q2.pdf
[104] https://doe.state.wy.us/lmi/G_DInd/Report_21Q2.pdf

Labor force employment vs. US average

Wyoming's current unemployment rate (4.1%) is similar to the US unemployment rate, which was at 4.2% in November 2021 (Figure A4.3). The US unemployment rate reached a peak of 14.8% in April 2020 and has been declining since.

Figure A4.3. US Unemployment Rate, January 2001-November 2021
Data from the Bureau of Labor Statistics

Trends expected by 2030

The number of Wyoming jobs is expected to grow by 7% by 2028 (above 2018 levels), with an addition of more than 19,000 new jobs. However, not all sectors will see job growth. For example, mining jobs are expected to decline, which will be significant since mining has been an important industry in Wyoming historically. Oil and gas extraction is expected to decline by 1.4%, down from 3,039 in 2018 to 2,997 by 2028. Likewise, all other mining (including coal) is expected to decline from 8,101 to 6,671, a decrease of -17.7%. Jobs in the utility industries are expected to increase, however. In 2018 utilities employed 2,508 people in Wyoming; by 2028 they are expected to employ 2,615—a 4.3% increase[105].

Other industries that are expected to decline include retail trade (-1.4%), information (-9%), and management of companies and enterprises (-1.4%). Industries that are expected to expand include leisure and hospitality (13.3%), professional, scientific, & technical services (16.8%), health care & social assistance (16.5%), administration & support & waste management & remediation services (15.4%), construction (11.4%), wholesale trade (10.5%), and real estate & rental & leasing (10.1%)[106].

[105] https://doe.state.wy.us/lmi/trends/0820/0820.pdf#page=5
[106] https://doe.state.wy.us/lmi/trends/0820/0820.pdf#page=5

1. Energy transition causes loss of jobs

Consumer preference and prices have always played a role in energy markets. Historically this was seen in the benign consumer-preference to cook with natural gas, the dominance of electric lighting, and the volatile geopolitics of petrostates. What is new is the rising importance consumers place on low-pollutant (esp. low carbon) energy sources. An anticipation of this new pollution concern can be seen in the activism leading to the 1970 Clean Air Act amendments. Anthropogenic global climate change became a public concern in the late 20th century, and culminated with the US EPA's 2009 endangerment finding that greenhouse gases are "air pollutants" under the Clean Air Act.

Numbers of workers in energy industries and job losses

Coal Mining

The number of people employed in coal mining in Wyoming has risen over the last 20 years, from 4,285 in 2001 to 4,781 in 2020. However, it has declined significantly since reaching its peak of 7054 employees in 2009 (Figure A4.4).

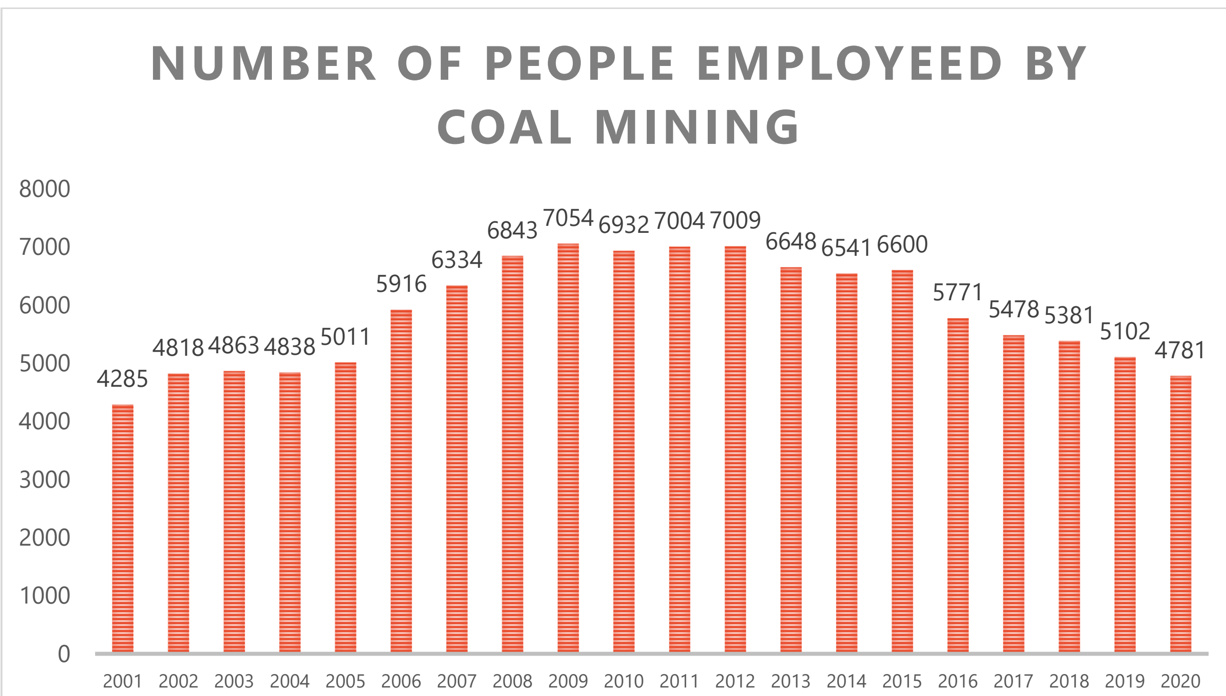


Figure A4.4 Wyoming residents employed in coal mining 2001-2020
Data Source: Bureau of Labor Statistics.[107]

[107] https://www.bls.gov/data/

Oil and Gas

The number of people employed by the oil and gas industry in Wyoming has declined in the last 20 years. In 2001, there were 3323 jobs in oil and gas, while in 2020 there were 2,757. Similar to coal, oil and gas has seen a particularly steep drop in jobs in recent years. It reached a peak in 2008 with 4,673 jobs and has been steadily decreasing since 2014 (Figure A4.5).

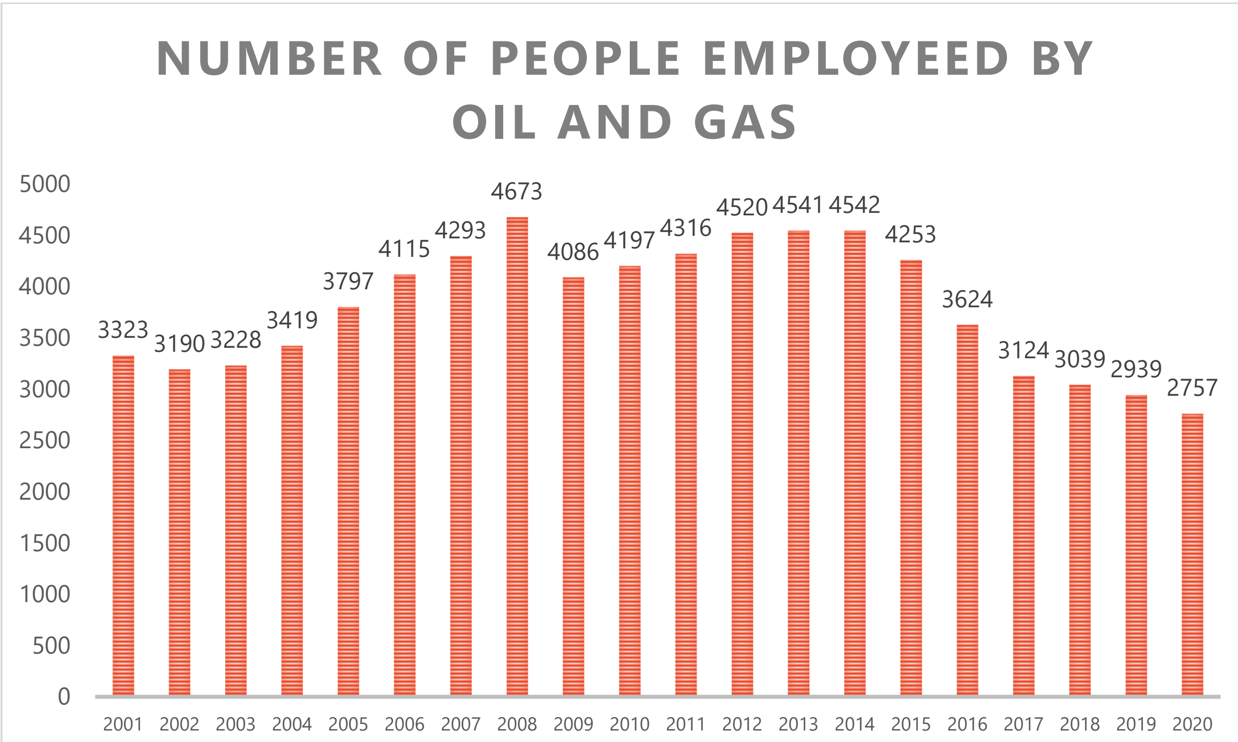


Figure A4.5: Wyoming residents employed in oil and gas 2001-2020
Data Source: Bureau of Labor Statistics.[108]

Utilities

The number of jobs in utilities has been relatively consistent in Wyoming since 2007. There has been a slight increase since 2003 when utilities employed 2,314 people to 2020 when they employed 2,582. However, there have not been any big increases or decreases in utility employment levels. They also are not predicted to decrease as other fossil-based energy industry jobs are in Wyoming (Figure A4.6).

[108] https://www.bls.gov/data/

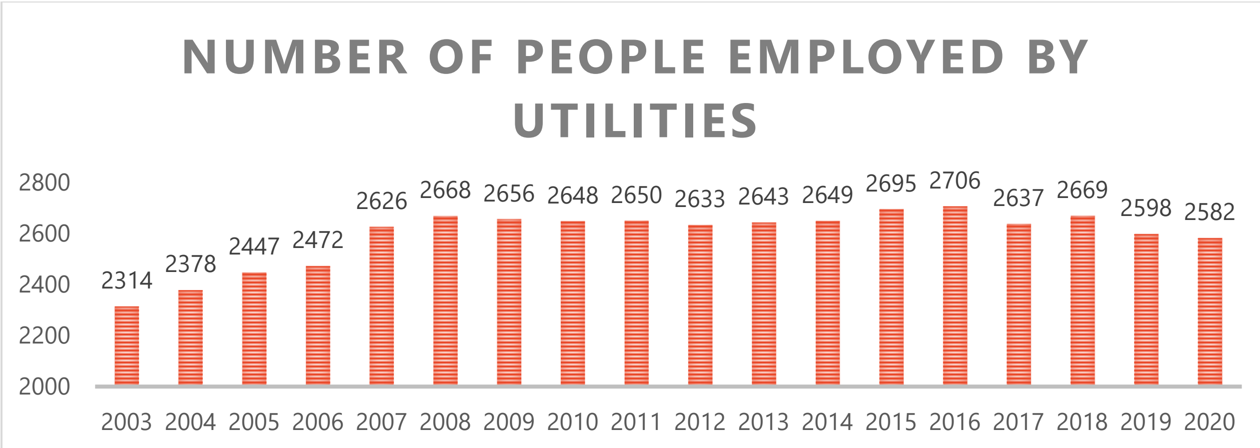


Figure A4.6. Wyoming residents employed by utilities 2001-2020
Data Source: Bureau of Labor Statistics.[109]

Projected job losses due to closing and reduction of operation for the next 5 years

Jobs in fossil-based industries are projected to continue to decline in Wyoming especially in light of the fact that Wyoming's largest electric utility, Rocky Mountain Power, intends to retire its coal plants in the state in the years ahead. Their stated goal in their 2021 Integrated Resource Plan (IRP) is a 74% reduction in greenhouse gas emission below 2005 levels by 2030. To meet this goal, they are scheduled to retire 14 of their coal-fired power plants across several states by 2030, and a total of 19 by 2040. Though they converted one unit at a coal-fired power plant to natural gas and are considering a similar conversion of two more units at a separate plant in Wyoming, they are not otherwise choosing to invest in future natural gas construction. This will certainly have an impact on mining jobs in Wyoming, as well as jobs at fossil-based power-plants. However, Rocky Mountain Power is planning to continue to invest heavily in renewable energy technologies in the state (i.e., wind, solar, grid-scale storage) that should lead to new jobs in these new energy industries. How many jobs will be created and if they will be located in Wyoming, however, remains to be seen.[110].

2. Future perspectives

The energy transition affects Wyoming through a reduced emphasis on fossil energy. Wyoming can expect reduced demand for coal, oil, and natural gas. Like all energy transitions before, the present transition stresses existing industries and may eventually relegate some industries to niche applications.

Coal, oil, and gas industries are central to Wyoming's economy. Both regulation and trends in consumer choice are reducing demand for coal (Figure A4.7). Demand for Wyoming's oil and gas continues to operate in somewhat normal conditions.

[109] https://www.bls.gov/data/
[110] https://www.pacificorp.com/energy/integrated-resource-plan.html

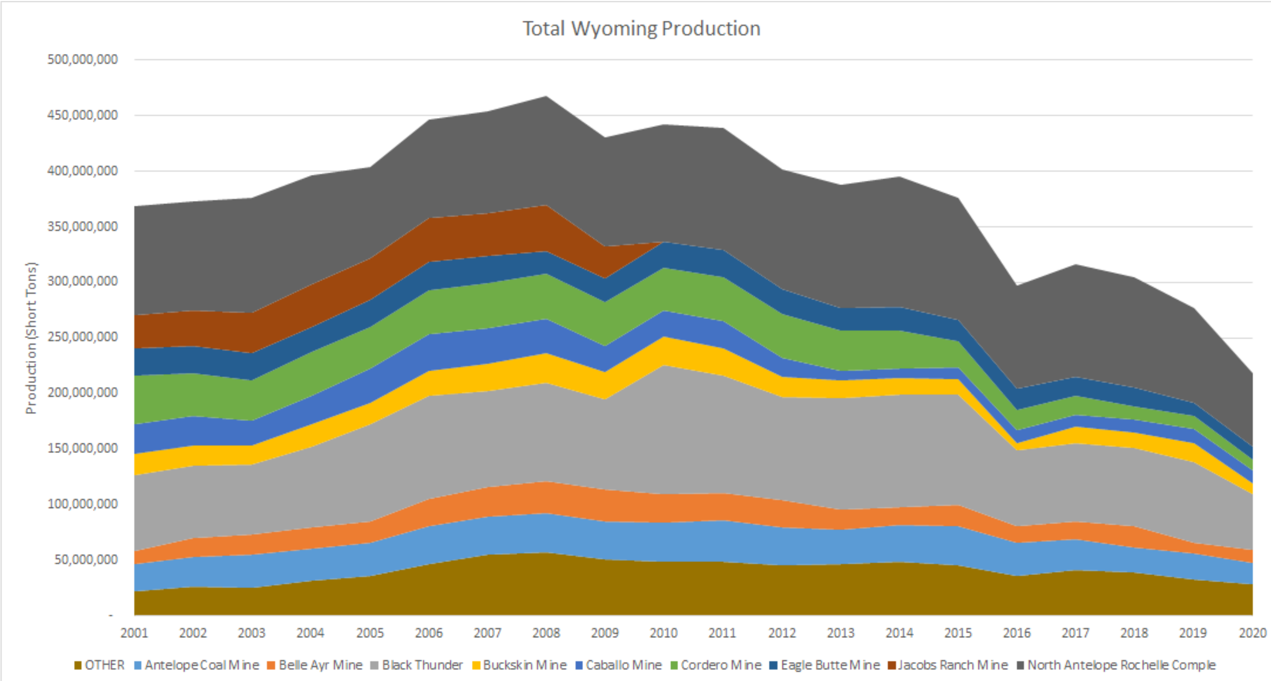


Figure A4.7. Stacked yearly output of Wyoming Coal mines, showing the long-term decline in production since 2008. Most of Wyoming's exports come from the Black Thunder mine (light gray) and North Antelope Rochelle mine (dark gray).
Data Source: EIA Coal Data Browser https://www.eia.gov/coal/data/browser/

Wyoming has seen limited growth in solar PV generation. The only commercial operation in the state is Sweetwater Solar, installed by 174 Power Global. However, Wyoming has seen significant investment in wind generation. This is not only due to the strictly greater average wind speeds in the state, but also the tendency of these winds to blow at dusk and early night, allowing electricity from them to serve peak demand in the Rocky Mountains and west coast. Formal electric vehicle infrastructure is limited to larger cities supportive of EV such as Jackson, Cheyenne, and Riverton, but private charging at home and incidental locations means electric vehicles can be found almost anywhere in Wyoming. The trend towards EVs in towns is increasing, but almost all rural areas such as ranches or utilities are dominated by gasoline vehicles. Public transportation follows EV trends, being overall rare, but present in Wyoming towns.

The climate conditions found in much of the central and southwest of the state are conducive to solar PV generation. Wind generation could expand more, and spread out across Wyoming to smooth out production spikes and gaps. Wyoming's cities could benefit from EVs and public transit, but remote areas with rugged geography and harsh weather will probably require gasoline vehicles well after EVs provide the majority of transport in the rest of the United States. Wyoming can adapt to the energy transition, but requires electric grid improvements to compensate for the large distances between population centers in the state.

For many years during the energy transition Wyoming will be a unique state using old technologies internally for daily life, but taking advantage of new technologies to deliver exports and novel work opportunities. For example, although no CO_2 has been stored in the state aside from that stored as part of enhanced oil recovery (CO_2-EOR), Wyoming has two well-characterized saline storage complexes. Given economic support and political support for carbon capture & storage (CCS) and carbon capture, utilization and storage (CCUS), Wyoming's geology enables carbon capture which could be the envy of North America.

Transition to a carbon neutral energy economy would offer these potential workforce opportunities

Wyoming has some transition programs in place, but most workers self-train or move to other positions that require similar skills. Examples include natural gas pipeline workers shifting to hydrogen and CO_2 pipelines, or oil and gas drillers switching to water, geothermal, and sequestration wells. These examples are in areas which will have future work nearby. Coal mines train general skills which can be transferred to any heavy equipment operation, but lack an adjacent industry to shift to, much less one located near existing coal mines. Some oil and gas workers will be able to move into new renewable capture and decarbonized energy jobs, but most coal and other workers do not have a clear path through the transition.

Existing Policies, Laws, Regulations, and Initiatives

Relevant state policies fall into the following categories: (1) government agencies; (2) infrastructure; (3) policies, laws and regulations; and (4) research.

Government Agencies. Several state agencies in Wyoming have missions that are dedicated, in whole or in part, to advancing policies and projects related to CCS/CCUS, CO_2-EOR, critical minerals (CM)/rare earth elements, and future fuels such as hydrogen. These agencies include, but are not limited to: (1) the Wyoming Energy Authority (WEA) (formerly the Wyoming Infrastructure Authority), whose mission is “to advance Wyoming’s energy strategy by driving data, technology and infrastructure investments” (https://www.wyoenergy.org/); and (2) the School of Energy Resources at the University of Wyoming (UW), whose mission is “dedicated to the energy-driven economic development for the state of Wyoming” (http://www.uwyo.edu/ser/). Other agencies playing a role include the Enhanced Oil Recovery Institute which leads in areas such as CO_2-EOR.

Infrastructure. Wyoming’s Integrated Test Center (ITC) in Gillette provides a facility for CCUS researchers to work on technologies while making use of flue gas from Basin Electric Power Cooperative’s (BEPC) Dry Fork Station (DFS). The ITC is one of only two such facilities like it in the United States, and the only one that operates at its scale. The ITC is a public-private partnership that brings together government, industry and cooperatives with the shared goal of developing commercially viable uses for CO_2 emissions from power plants. BEPC, along with co-owner Wyoming Municipal Power Company, is the site for the ITC at DFS and has provided significant in-kind contributions for the design, engineering and construction of the facility. Tri-State Generation and Transmission Association committed $5M to match Wyoming’s $15M commitment. The National Rural Electric Cooperative Association provided an additional $1M in support as well.

Also in Gillette, in June 2021 ground was broken on the $3.5M Wyoming Innovation Center, a facility that will focus on the development of high-value, non-fuel, coal-based processes and products. The project is the first major capital investment as part of the Carbon Valley™ initiative being advanced by Energy Capital Economic Development, Campbell County and the City of Gillette. The project is supported by funding from the Economic Development Administration ($1.46M), the Wyoming Business Council ($1.5M), the City of Gillette, Campbell County, and private businesses.

In his March 2, 2021, State of the State address, Governor Gordon called on the state to become “net negative” in CO_2 emissions. With the assistance of a leading energy consultancy, WEA is currently working to develop an energy strategy that implements that vision. The energy strategy:

> Focuses on empowering the nation with a net-zero energy mix. This includes harnessing the full value of our energy resources with an "all-of-the-above" energy mix: products from our legacy industries, along with the newer players of renewable energy and emerging opportunities in hydrogen, advanced modular nuclear, geothermal and rare earth elements.

A final version of the energy strategy is expected to be complete in the first half of 2022.

WEA is leading and/or otherwise supporting the following initiatives: (1) UW's Wyoming CarbonSAFE project; (2) ITC; (3) Wyoming Pipeline Corridor Initiative (WPCI); (4) "Sequestration as a Service"; and (5) Wyoming Hydrogen Initiative. More details on each of these are provided next.

- *Wyoming CarbonSAFE*. The Wyoming CarbonSAFE Project, which stands for the "Carbon Storage Assurance Facility Enterprise," is one of thirteen original CCUS project sites in the United States funded by DOE with the ultimate goal of ensuring carbon storage complexes will be ready for integrated CCUS deployment. Through a competitive down-select process, four of the original projects have advanced to Phase III (site characterization and CO_2 capture assessment), including Wyoming CarbonSAFE.
- *ITC*. The ITC is discussed above.
- *WPCI*. The WPCI aims to establish corridors on public lands dedicated for the future use of pipelines associated with CCS, CCUS, CO_2-EOR and the delivery of associated products. In coordination with the U.S. Department of Interior's Bureau of Land Management (BLM), researchers, industry representatives and state organizations, approximately 2,000 miles of pipeline corridors were identified throughout central and western regions of Wyoming with the goal of reducing the time and cost it takes for developers to permit these large infrastructure projects while also balancing the environmental concerns associated with these lands by reducing the disturbance footprint. The WPCI was initially proposed in 2012 as part of Governor Mead's energy strategy. The public comment period on BLM's draft environmental impact statement closed in July 2020, and the record of decision was granted by BLM in January 2021.
- *"Sequestration as a Service*." "Sequestration as a Service" (SaaS) is a WEA initiative that would involve building commercial sequestration sites with wells for injecting CO_2 deep beneath the earth's surface. These sites would be operated by entities with vast knowledge in the practice of injecting CO_2, which would then offer this as a service to any CO_2 emitter. Wyoming has a competitive advantage for this service. It already has extensive CO_2 infrastructure, it leads the nation in CO_2 centric policy, it has an experienced workforce in CO_2 operations, and it has a favorable business environment. Successful establishment of a SaaS industry would benefit all CO_2 emitters in the state and facilitate establishment of other forward-looking "all of the above" energy prospects such as hydrogen and direct air capture (DAC) industries. Near-term initiatives include mitigating liability of Class VI wells used for CCS, utilizing CO_2 for cement, and mitigating CO2 emissions from the combustion of fossil fuels. The workforce requirements to support this service sector encompass every skill set – from trades to legal and financial, and from executives to scientists, engineers, and laborers. SaaS supports Wyoming's heritage industries and also provides a bridge for Wyoming to

become economically sustainable and a critical leader in the net-zero energy economy, making it an important initiative in our state's energy strategy.

- *Wyoming Hydrogen Initiative*. Through public and private partnerships in research, development, demonstration, and deployment activities, Wyoming is investigating the potential for upgrading its rich hydrocarbon resources to decarbonized hydrogen and leveraging our world-class renewable resources for production of zero-carbon hydrogen. Hydrogen manufacturing could be centralized or dispatched in modular form, making it suitable for a wide range of siting locations and thus encouraging statewide economic inclusion. The state's natural gas pipeline infrastructure could be repurposed to transport hydrogen while the existing power grid could support additional electric generation. Wyoming has a unique opportunity given its overlapping abundance of natural resources (both hydrocarbon and renewable) and existing infrastructure to support hydrogen production and become an export powerhouse in the future.

More than a decade ago the Wyoming Legislature enacted a statutory framework for CCS and CCUS projects, including permitting. That framework:

- Specifies who owns the pore space (*Wyo. Stat. § 34-1-152 (2020)*);
- Establishes permitting procedures and requirements for CCS sites, including permits for time-limited research (*id. § 35-11-313*);
- Provides a mechanism for post-closure "measurement, monitoring and verification" ("MRV") via a trust fund approach (*id. § 35-11-318*);
- Provides a mechanism for unitization of storage interests (*id. §§ 35-11-314, 315, 316, 317*)
- Specifies that the injector, not the owner of pore space, is generally liable (*id. § 34-1-153*);
- Clarifies that vis-à-vis storage rights, production rights are dominant but cannot interfere with storage (*id. § 30-5-501*); and
- Provides a certification procedure for CO_2 incidentally stored during EOR (*id. § 30-5-502*).

On March 24, 2020, Wyoming Governor Gordon signed into law H.B. 200, a new CCUS-related law in Wyoming entitled "Reliable and Dispatchable Low-Carbon Energy Standards." The law requires regulated utilities to closely evaluate whether they can retrofit CO_2 capture technology to their coal plants. The law is emblematic of Wyoming's efforts to encourage coal-fired power plants in the State to retrofit CCS/CCUS technology, and thus cements Wyoming's role as being in the vanguard of CCS/CCUS standards for electricity generation in the United States.

In the summer of 2021, the Joint Minerals, Business & Economic Development Committee of the Wyoming Legislature considered draft legislation related to potential state roles in: (1) the long-term stewardship of CO_2 in geologic storage; and (2) voluntary carbon markets. Both bills remain pending and have not been formally introduced.

Wyoming remains at the vanguard of states with progressive low-carbon regulations. For example, in the fall of 2020, the U.S. Environmental Protection Agency approved the Wyoming Department of

Environmental Quality's (DEQ) application for primacy over the Class VI program of the Safe Drinking Water Act's Underground Injection Control Program. DEQ's final Class VI regulations were released in the fall of 2021. Wyoming remains one of one two states (North Dakota being the other) with Class VI primacy.

In the fall of 2021, the Wyoming Public Service Commission published the final regulations governing implementation of H.B. 200, discussed above.

The School of Energy Resources at UW is dedicated to energy-driven economic development for the state of Wyoming. Created in 2006, the School of Energy Resources (SER) enhances the university's energy-related education, research and outreach. SER directs and integrates cutting edge energy research and academic programs at UW and bridges academics and industry through targeted outreach programs. SER's mission spans academics, research and outreach, all of which bear on energy transition issues to a greater or lesser extent.

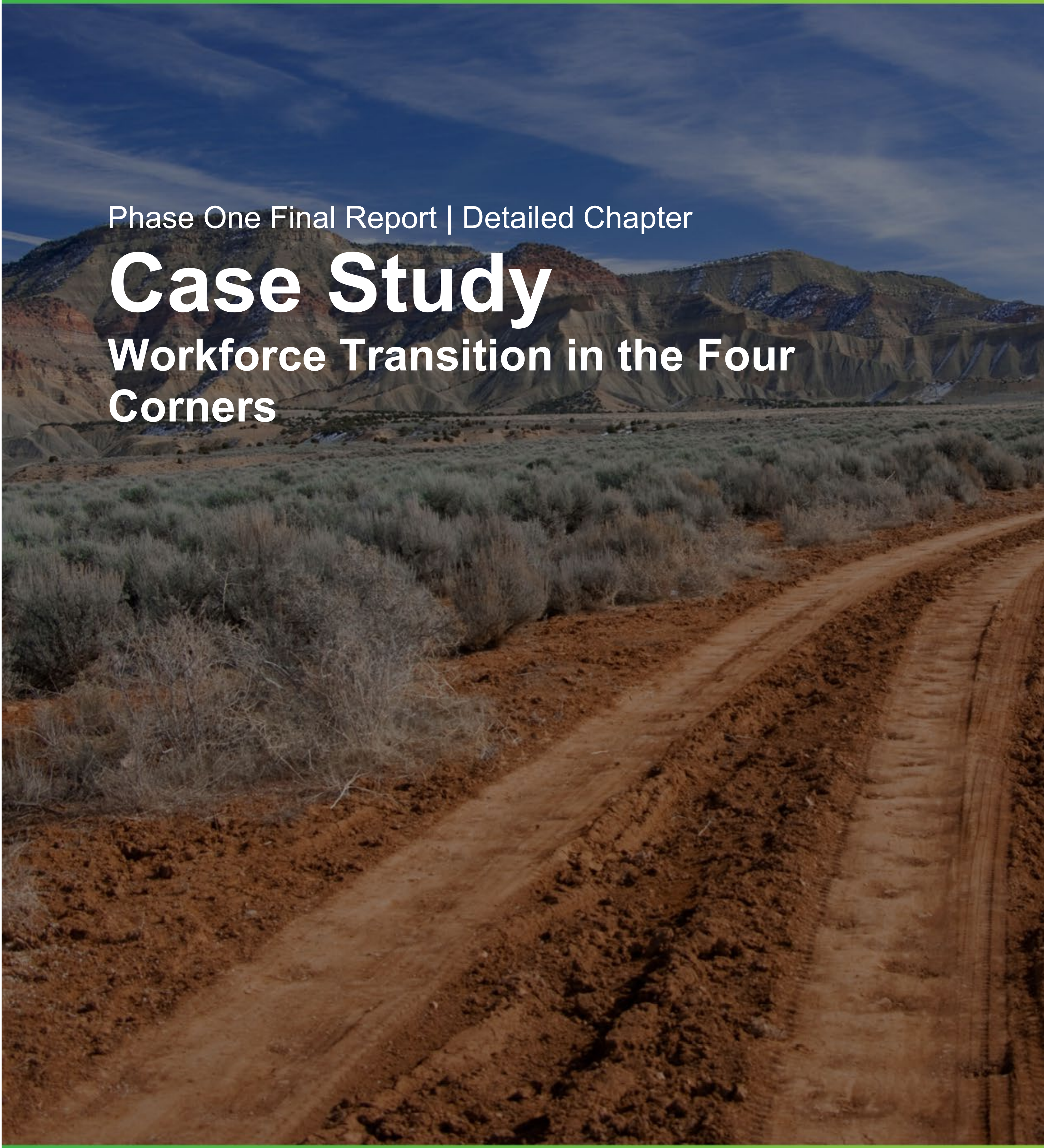
In terms of research, SER largely operates by providing seed-funding to topic-specific centers of excellence, several of which are working on issues to prepare Wyoming for ongoing changes to energy systems and markets. The Center for Economic Geology Research, for example, leads applied research on the geologic storage of CO_2, CM/REE identification and characterization, and related topics. The Center for Carbon Capture and Conversion leads applied research on topics such as non-Btu products from coal. The Center for Air Quality is advancing research related to detecting and reducing fugitive methane emissions from the production, processing, transportation and storage of natural gas and oil.

I-WEST

Phase One Final Report | Detailed Chapter

Case Study

Workforce Transition in the Four Corners



VERSION 2.0

SAN JUAN COLLEGE

JUNE 2023

About this chapter

The Intermountain West Energy Sustainability & Transitions (I-WEST) initiative is funded by the U.S. Department of Energy to develop a regional technology roadmap to transition six U.S. states to a carbon-neutral energy economy. I-WEST encompasses Arizona, Colorado, Montana, New Mexico, Utah, and Wyoming. Each state is represented in this initiative by a local college, university, or national laboratory. Additional partners from beyond the region were selected for their expertise in applicable fields. In the first phase of I-WEST, the team built the foundation for a regional roadmap that models various energy transition scenarios, including the intersections between technologies, climate, energy policy, economics, and energy, environmental, and social justice. This chapter presents work led by an I-WEST partner on one or more of these focus areas. A summary of the entire I-WEST phase one effort is published online at www.iwest.org.

Author

Alicia Corbell, San Juan College

Table of Contents

Introduction

Photo credit: Alicia Corbell

The Four Corners region encompasses Colorado, Utah, Arizona, and New Mexico. For generations, fossil fuel production and related supportive industries have been vital to the overall prosperity and growth of the region. Partners and stakeholders, ranging from tribal nations, private companies and state and federal agencies, have played roles in the supplying of reliable energy to the Western United States for decades. Due to the region's unique dependency on fossil fuels, efforts to shift energy production away from traditional sources and systems will have significant impacts on area tribes, the regional workforce, and regional economy. In terms of ceasing coal generation, the proposed changes will prematurely shutter San Juan Generating Station, San Juan Mine, the Four Corners Power Plant, and Navajo Mine. Thousands of workers will be forced to find new careers [1].

Established in the early 1970s, the San Juan Generating Station was a coal-fired facility that was built with four units in Waterflow, New Mexico, and upon completion in 1982, generated 1,848 megawatts of base load power for western states, primarily California and Arizona. Its operations have been overseen by the majority owner, Public Service Company of New Mexico (PNM). Due to changing energy interests, only two units remained in operation with complete closure scheduled for October 2022. The co-located San Juan Mine, providing a mine-mouth operation, was initially an open-surface mine, but transitioned to underground long-wall mining in 2001. The mine was originally owned and operated by BHP and was sold to its current operator, Westmoreland Coal, in 2016.

The Four Corners Power Plant is a 1,540 megawatt coal-fired facility located on the Navajo Nation near Fruitland, New Mexico. Upon its completion in 1970, the plant operated five units and generated 2,100 megawatts of base load power. In 2013, three of the five units were decommissioned, their sites reclaimed, and the generation capacity reduced to its current level. Then, in 2016 the two remaining units underwent a major environmental upgrade, bringing them in line with the current federal emissions regulations. The Four Corners Power Plant remains largely owned and operated by the Arizona Public Service Company. It is noteworthy that Navajo

Transitional Energy Company, a tribally owned autonomous entity, owns a minority share in Four Corners Power Plant and is the sole owner of the Navajo Mine.

Since the 1960’s, these facilities have provided steady employment, economic support, and significant energy production. At the peak of employment, the two coal-fired power plants and the associated coal mines employed over 2,000 workers, a large percentage of whom are members of the Navajo Nation [2].

Following the approval of the NM Energy Transition Act in 2019 [3], coal-fired power generation can no longer meet the emissions threshold specified in the law, and therefore operate, without equipping the facilities with some means of capturing the excess CO_2. Contained within the law are provisions for the employer to provide substantial monetary resources that would support and encourage the separating employees to seek re-training and education assistance. However, due to pending lawsuits, the financial resources have yet to be established.

Upon the release of PNM’s Integrated Resource Plan in 2017 [4], a local economic development organization, Four Corners Economic Development, commissioned a third-party economic impact report to forecast the negative impact to the region. Additionally, the organization worked closely with PNM and Westmoreland Coal to extract anonymous employee data which would provide an accurate and clear picture of the workers facing termination. The results of the study and the employee details are described below and only focus on San Juan Generating Station and San Juan Mine.

The study shows that transition efforts will have significant and lasting impacts on the Four Corners region and its diverse workforce that includes Native Americans and Hispanics. Below, we detail the impacts of the closure of the San Juan Generating Station on the region, local workforce, and economy. We also discuss the rise of new technology and the shift of the energy industry, as well as efforts by San Juan College to mitigate effects on the workforce.

Impacts of the closure

The implementation of the Energy Transition Act and previous efforts to move from a coal economy to a green economy will results in the elimination of hundreds of jobs from the San Juan Generating Station, San Juan Mine, Four Corners Power Plant, and Navajo Mine. The closure will also result in the significant loss of property tax revenue that benefits San Juan County, New Mexico, San Juan College, and the Central Consolidated School District. In order to best mitigate the impacts, it is absolutely critical to understand the impending losses and the demographics of the workforce to create a path towards a sustainable future.

The 2018 impact report from Four Corners Economic Development (4CED) gathered the following data from employees from the San Juan Generating Station and the San Juan Mine [5]:

Average Employee Salary	**$86,000 Per Year**
Average Employee Age	47 Years Old
Average Years of Service	14 Years
Percentage of Tribal Employees	40%
Percentage with Healthcare from Employment	96%

The following employee information is gathered from the Four Corners Power Plant:

Average Employee Salary	**$84,650 Per Year**
Average Employee Age	49 Years Old
Average Years of Service	11 Years
Percentage of Tribal Employees	80%

The closure of the San Juan Generating Station and the San Juan Mine will impact the following entities:

San Juan County, New Mexico

Lost Wages	**$56.6 Million Per Year**
Lost Benefits	$20 Million Per Year
Direct Impacts	1,600 San Juan County Residents (minimum)
Indirect Impacts	5,000 Residents

Governments (Loss of Taxes)

San Juan County	**$3.8 Million Per Year**
NM State	$1.9 Million Per Year

Local School Districts

Central Consolidated*	**Loss of $1.5 Million in Student Funding**
Farmington Municipal	Loss of $1.7 Million in Student Funding
Aztec Schools	Loss of $165,000 Million in Student Funding
Bloomfield Schools **	Loss of $77,000 Million in Student Funding

*Central Consolidated serves at 91% Native American student population and a reported rate of 72% of students being financially disadvantaged
**Bloomfield Schools serves 100% financially disadvantaged students

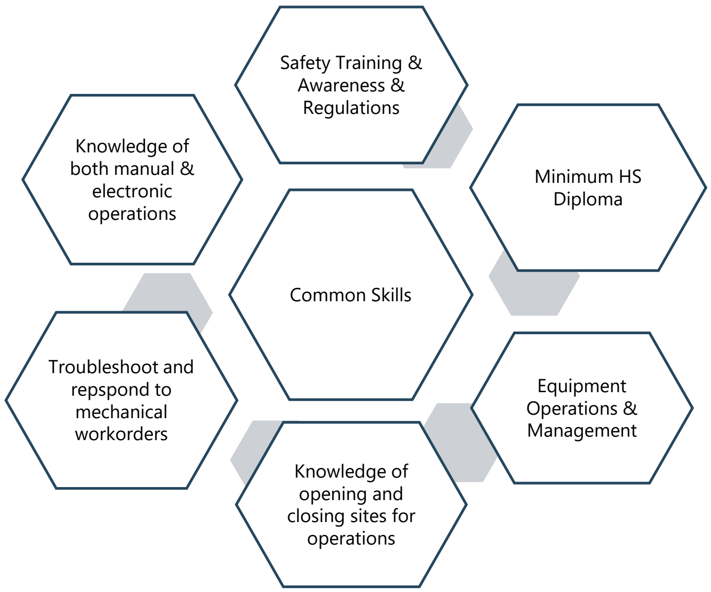
A six-county report from the Four Corners with a focus on the closure of the San Juan Generating Station by the Economic Modeling Specialists Intl. (https://kb.Emsidata.com) in 2017 concludes [5]:

Annual Loss in Earnings	**$117,212,94.00**
Total Jobs Lost	1,586
Loss of NM Taxes	$20.8 Million Annually
Loss of Local Taxes	$24 Million

The data above show that the San Juan Generating Station, San Juan Mine, and the Four Corners Power Plant employ their staff on average for a minimum of ten years with successful retention. This can be attributed to high salaries, comprehensive employee benefits, and the ability for employees to remain in the region. It is noteworthy that three entities employ majority Native Americans. During hearings pertaining to the results of the 2017 PNM Integrated Resource Plan, Native American and Hispanic workers, male and female, told their story of supporting extended family on their salary and being able to send their children to college and university. Many want to stay on the lands in which they were raised but know that if they are unable to find comparable work with comparable salaries, they will have to leave and seek work in other industries, including copper and other mines.

Translating skills

The impending closure of each entity will result in a large pool of displaced workers, many of whom have the following skills most commonly associated with the roles of an underground miner, surface miner, operator, distributors, dispatchers, or laborer:



The San Juan College School of Energy has trained generations of plant operators, engineers, mechanics, and instrumentation technicians for the local fossil fuel facilities and continues to provide the necessary safety training. Due to the nature of their education, the skills trained power plant workers possess are skills that can be leveraged into a new economy based upon carbon capture, hydrogen, and helium with the addition of short-term stackable credentials.

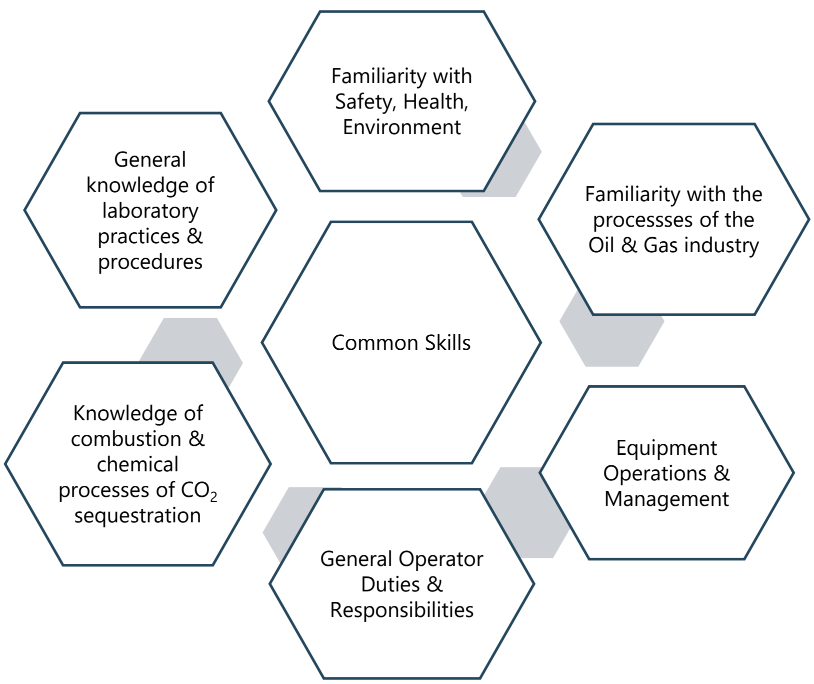
A case in point is the proposed large-scale carbon capture island by Enchant Energy Corporation. Enchant Energy is an energy company focused on carbon capture and storage (CCS) based in Farmington, New Mexico. The goal of Enchant Energy is to repurpose the San Juan Generating Station with carbon capture technology and extend the life of the plant, thereby providing time for other clean energy solutions to emerge or evolve. This technology will allow for the CO_2 emissions to be captured and either sequestered or sold for enhanced oil recovery or other purposes.

These pioneering efforts will improve sustainability and mitigate the loss of unemployment by ideally retraining and upskilling current San Juan Generating Station employees. While the front-end engineering and design (FEED) study is completed [6], San Juan College is actively partnering with Enchant Energy and Farmington Electric Utility System via a Memorandum of Understanding to ensure that career pathways are available for current workforce to migrate into expanded roles which will include carbon capture and either sequestration or transportation. It is anticipated that the existing training that teaches the fundamental skills of carbon capture will be augmented to encompass all the needed abilities.

In the event that sequestration is selected as the means of disposing the CO_2, workers employed in the local oil and gas industry can once again receive training that will close any skill gaps that are unique to Class 6 wells. The local college, San Juan College, is working closely with industry partners as they prepare to drill a test well near the San Juan Generating Station.

If the captured carbon is sold for use in the Permian Basin, it is anticipated that an existing pipeline will be utilized. Existing workforce once again is capable of maintaining the line.

Carbon capture technicians are likely to require the following skills:



It is clear that there are significant overlaps in the attributes, making a transition by means of stackable credentials a logical progression.

An early coal mitigation effort

Recognizing the need to shift the energy industry, the federal government under the Obama administration had created the Partnerships for Opportunity and Workforce and Economic Revitalization (POWER) Initiative [7] to help communities that would be negatively impacted by the closure of coal industries. The initiative's goal was to invest nearly $10 billion into coal-dependent communities, workforce, and technology. In order for an entity to receive funding, the entity must use the funding to:

1. Diversify their local economy
2. Create jobs in new or existing industries
3. Attract new sources of job-creating investment
4. Provide a range of workforce services and skills training for high-quality, in-demand jobs

Securing POWER funding was highly competitive, and funds were awarded to projects designed to produce significant economic diversity and provide workforce development.

San Juan College and the POWER initiative

San Juan College is a majority-minority serving institution recognized as a regional leader in education throughout the Four Corners. Educating approximately 10,000 students annually, it consistently ranks in the top 10 institutions of higher education for the awarding of degrees and certificates to Native American students.

An early adopter of the American Association of Community Colleges Guided Pathways Project, the College has worked in collaboration with local school districts to introduce seven defined pathways into K-12 education and get students on track early. One of the pathways is Energy, Manufacturing and Transportation and this pathway is the most relevant to this transition. This pathway contains Career Technical Education that is based upon employer feedback either from advisory committees or small groups of stakeholders, thereby ensuring that the skills employers need are the skills the graduates possess.

As an example, in the School of Energy, curriculum has often been and continues to be developed in partnership with industry to ensure that necessary workforce skills are delivered in time. The degrees and certificates contain broadly based, adaptable skills that are applicable in many energy, manufacturing, and industrial careers.

Associates of Applied Science degrees or certificates are offered in the following fields:

- Instrumentation, Controls, and Electrical Technology
- Industrial Process Operator
- Industrial Maintenance Mechanic
- Advanced Petroleum Production Operations
- Natural Gas Compression
- Tribal Energy Management
- Occupational Safety
- Commercial Construction Safety

Perhaps because of the extensive relationship with industry and the impact of coal in the community, San Juan College was awarded $1.4 million for the Four Corners POWER Initiative (FC-POWER-I) in 2015. The initiative objectives were to provide the opportunity for cross-training and re-training through a short-term certificate leading to direct employment and a long-term approach to obtaining a degree. The initiative included the following efforts:

- Purpose One: Four Corners POWER Initiative Liaison
- Purpose Two: Transitional Employment and Educational Needs
    - Short-Term Training Certification
        - Commercial Driver's License
    - Long-Term Certification and Degrees
        - School of Energy Programs
- Purpose Three: Center of Excellence in Information Assurance

Here, we focus on the outcomes of Purpose Two, which provided full funding of a certificate program. At that time, the Instrumentation, Controls, and Electrical Technology program was the sole certificate option in the School of Energy. Therefore, the majority of displaced mine workers enrolled in and successfully completed this program during academic years 2016-2017 and 2017-2018.

- In academic year 2016/2017, 185 students enrolled in the Instrumentation Program. 17 students were female and 44% of students identified as Native American. The success rate for this cohort, with success being defined as earning a C grade or higher, was 87%.
- During the following academic year, 2017/2018, a total of 148 students enrolled in the Instrumentation program. Nine of the students were female and 47% of the students identified as Native American. This cohort achieved a success rate of 93%.

Data is not available that indicates their current job status or industry of employment. However, most indicated that they were positioning themselves for a time in which they would not be employed at San Juan Mine. Instrumentation technicians are currently in high demand and graduates from this program work across various industries including aerospace, pharmaceuticals, energy, semi-conductors and many others.

However, one particular student for whom the outcome is known was displaced due to the reduction of the staff at San Juan Mine. He enrolled in the Instrumentation, Controls, and Electrical Technology certificate program and graduated in 2017. This graduate is currently employed at a local natural gas exploration and operation company as a Horizontal Specialist.

Another area pursued by five workers was cyber security. Students enrolled in an intensive series of non-credit CompTIA courses. The complete training package consisted of six modules. After each module was completed, students took the associated CompTIA assessment and upon passing, received a corresponding industry certification. Prior to completing all six modules, each student became successfully employed in cyber security in other parts of the Southwest US with just the certifications they held at that time.

In both fields of study, workers demonstrated their ability to re-train successfully and position themselves to continue high-wage careers, and sometimes pursued them immediately.

Clean hydrogen

As stated in other parts of this report, clean hydrogen is likely to play a significant role in a new energy economy. Whether the clean hydrogen begins as green hydrogen or blue hydrogen, there will be roles for workers currently working in fossil fuel industries to play.

In the case of blue hydrogen, current natural gas related careers will still be needed. The School of Energy has been working closely with BayoTech, Inc., a New Mexico on-site hydrogen production company, via a Memorandum of Understanding to determine and then provide the necessary skills for their technicians. Once again, the broad-based skills gained in the first five programs listed as School of Energy programs are the same skills needed for the production of hydrogen utilizing steam methane reformers with the addition of a stackable Hydrogen Safety credential which is under development. In order to provide blue hydrogen or be deemed clean hydrogen, the units must be equipped with carbon capture equipment, the basics of which graduates from the School of Energy Industrial Process Operator Program possess. With an augmented carbon capture curriculum contained within a stackable CCS credential, current oil and gas workers will be able to support blue hydrogen.

With respect to the production of green hydrogen, large amounts of water are required. With continuing drought conditions in the West, there are efforts underway to treat produced water that results from the extraction of oil and natural gas. One application under investigation by the New Mexico Produced Water Consortium as an industrial application is the use of treated produced water for the production of green hydrogen. Industrial water technicians will be needed in this aspect of the process. Once again, existing workforce involved in the treatment of industrial water can be trained through an advanced credential to address the unique aspects of this process.

References

[1] Bryan, S.M. (2022) “US shifts away from coal hist home in San Juan County”. Daily Times, Associated Press.

[2] Fordham, A. (2022) “Despite promises of help, a community struggles after San Juan Generating Station closes”. KUNM

[3] https://www.nmlegis.gov/Sessions/19%20Regular/final/SB0489.pdf

[4] https://www.pnm.com/documents/396023/396193/pnm+2017+irp+final.pdf/eae4efd7-3de5-47b4-b686-1ab37641b4ed

[5] https://www.nmlegis.gov/handouts/ALESC%20082119%20Item%208%20.1%20-%20Central%20CSD%20Presentation.pdf

[6] https://osti.gov/biblio/1889997/

[7] https://www.eda.gov/archives/2016/power/

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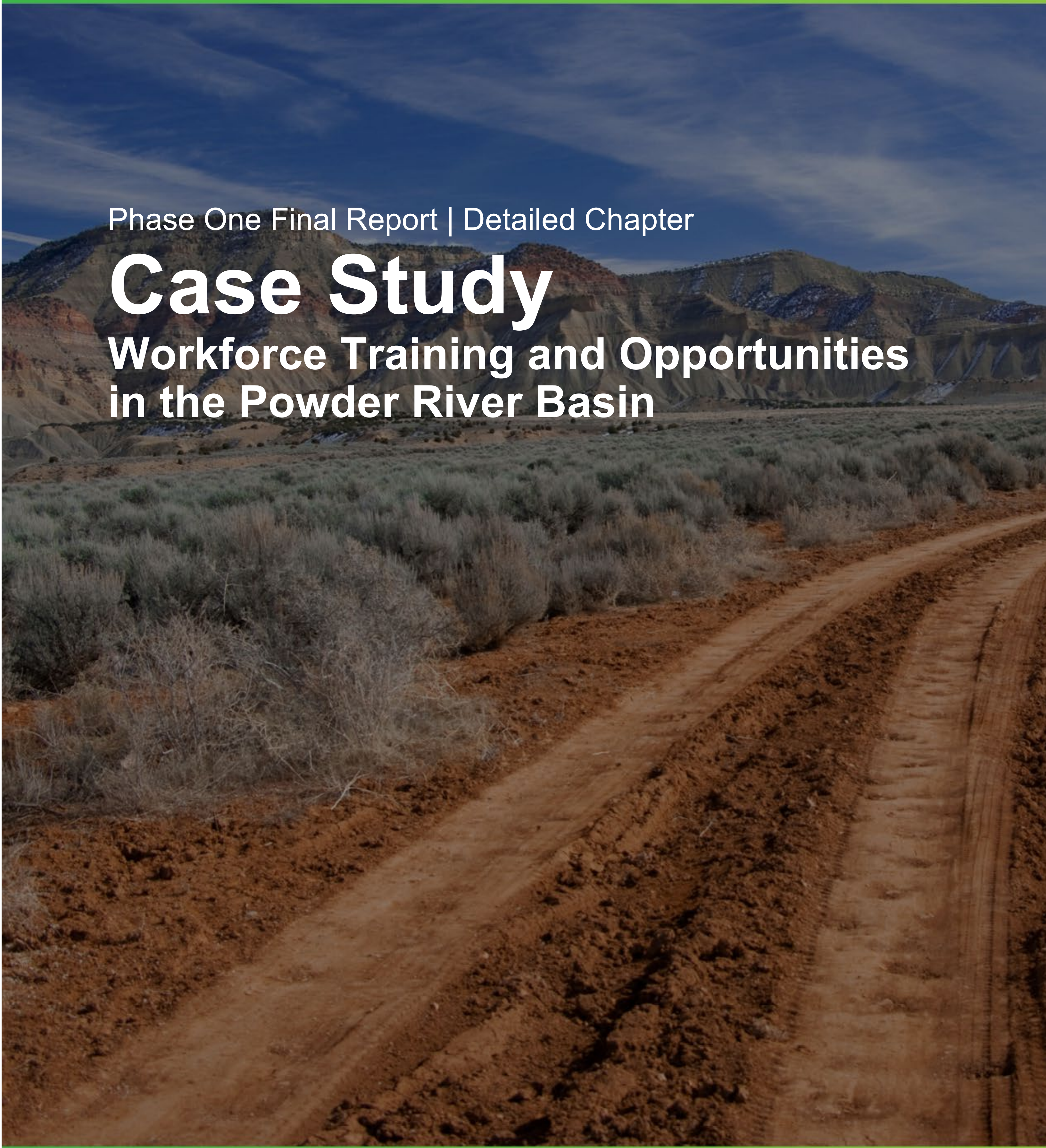

Phase One Final Report | Detailed Chapter

Case Study

Workforce Training and Opportunities in the Powder River Basin

VERSION 2.0 UNIVERSITY OF WYOMING JUNE 2023

About this chapter

The Intermountain West Energy Sustainability & Transitions (I-WEST) initiative is funded by the U.S. Department of Energy to develop a regional technology roadmap to transition six U.S. states to a carbon-neutral energy economy. I-WEST encompasses Arizona, Colorado, Montana, New Mexico, Utah, and Wyoming. Each state is represented in this initiative by a local college, university, or national laboratory. Additional partners from beyond the region were selected for their expertise in applicable fields. In the first phase of I-WEST, the team built the foundation for a regional roadmap that models various energy transition scenarios, including the intersections between technologies, climate, energy policy, economics, and energy, environmental, and social justice. This chapter presents work led by an I-WEST partner on one or more of these focus areas. A summary of the entire I-WEST phase one effort is published online at www.iwest.org.

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Table of Contents

Introduction

The Powder River Basin (PRB), located in northeastern Wyoming and southeastern Montana, has the potential to develop a thriving rare earth element and critical mineral (REE/CM) extraction and processing industry. Not only does the PRB have large coal reserves (from which REE/CM can be extracted) but it also has many of the infrastructure and workforce requirements needed to support such an industry. Current research is being conducted to determine the concentrations and availability of REE/CM in coal and coal byproducts in the PRB through the DOE-funded Carbon Ore, Rare Earth and Critical Minerals (CORE-CM) project at the University of Wyoming School of Energy Resources. This case study supplements that work by assessing the requirements and retraining opportunities to develop a trained workforce for REE/CM industries in the PRB. This is especially crucial and timely at the moment, as coal production is declining and the communities in the PRB work to diversify their economies and create new economic opportunities in the region.

Background on Wyoming and Campbell County Energy Workforce

As national demand for energy has shifted away from carbon-emitting forms of energy and towards low-carbon forms of energy, production of Wyoming's fossil resources has been declining. For example, Wyoming coal production has been steadily declining since reaching a peak of over 450 million short tons in 2008, down to just 218 million short tons in 2021[1]. Likewise, natural gas production has declined from over 2.5 billion MCFs in 2009 to less than 1.4 billion MCFs in 2021[2]. Oil production has been more volatile in recent years, reaching a low of 51 million barrels in 2009, but increasing up to 85 million barrels in 2021[3].

These declines in fossil energy production have had a significant impact on Wyoming communities, both in terms of revenue and jobs. The state of Wyoming, and many of its counties and municipalities are highly dependent on revenue from fossil fuels. Between 2015-2020, an average of 59% of annual state and local revenue was generated from fossil fuel production and extraction,

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[1] Wyoming Geological Survey. 'Wyoming Coal.' Accessed May 2022. https://www.wsgs.wyo.gov/energy/coal.aspx#:~:text=Since%201865%2C%20more%20than%2012.5,and%20Lincoln%20counties%20in%20Wyoming

[2] Wyoming Oil and Gas Conservation Commission. 'Graph Gas Production. Accessed May 2022. https://wogcc.wyo.gov/data

[3] Wyoming Oil and Gas Conservation Commission. 'Graph Oil Production'. Accessed May 2022. https://wogcc.wyo.gov/data

totaling $4,264 million annually, and over $7,000 per resident[4]. This revenue, which funds schools, governments, and other social services, is important for essential community functions and many communities currently do not have a plan for how to replace it as fossil energy production declines.

The loss of jobs in energy-producing communities has also been significant. In Campbell County, located in the PRB, the number of people employed in coal mining has declined from over 5,000 in 2013 to 3,500 in 2020 (Figure 1). Fewer people have been employed in oil and gas extraction in Campbell County historically, but the decline in employment has been dramatic. In 2013, there were 650 people working in oil and gas extraction and by 2020 there were fewer than 250 (Figure 2). This significant loss in jobs has created a strong impetus for new industries and economic diversification in places like Campbell County.

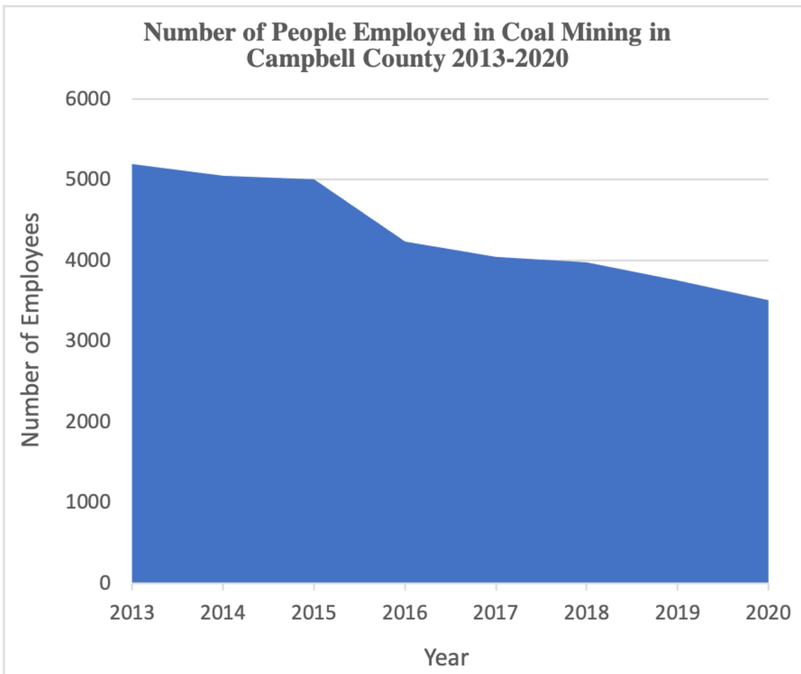

Figure 1: Number of people employed in Coal Mining in Campbell County, WY, 2013-2020[5].

[4] Raimi, Daniel, Emily Grubert, Jake Higdon, Gilbert Metcalf, Sophie Pesek and Devyani Singh. 2022. "The Fiscal Implications of the US Transition away from Fossil Fuels." Resources for the Future

[5] U.S. Bureau of Labor Statistics. "Databases, Tables & Calculators by Subject.: Accessed May 12, 2022. https://www.bls.gov/data/home.htm

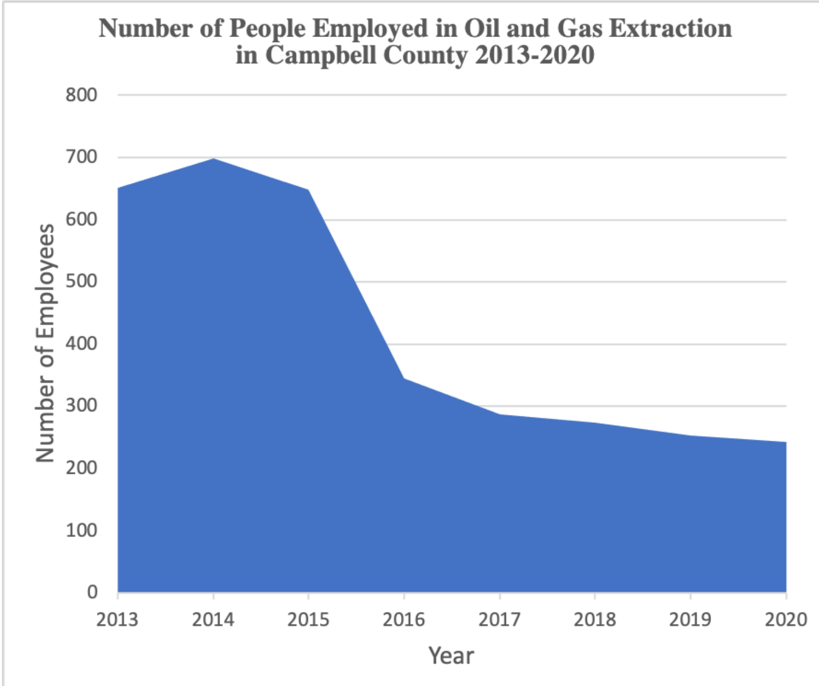

Figure 2: Number of people employed in oil and gas extraction in Campbell County, WY, 2013-2020[6].

Opportunities for REE/CM Industries

The complete REE/CM supply chain includes exploration for identifying REE deposits, extraction, and mining of REE; processing and concentration of the REE from the feedstocks; and down-stream manufacturing using REE in products. Developing REE industries means that jobs will be created in each of these stages of the supply chain. For the purposes of this report, we will focus on the opportunities for the first three stages: exploration, extraction, processing. Below is an overview of the resources available in and around the PRB that will help to contribute to the development of REE/CM industries.

Coal reserves in the PRB

Wyoming has vast coal reserves from which REE/CM could be extracted. As the top coal producing state nationally since 1986, Wyoming produces 40% of the nation's coal. The majority of that coal is produced in Campbell County in the PRB, which is the most prolific coal field in the world. There are currently 11 operating coal mines in Campbell County (Figure 3) and, in 2021, Campbell County

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[6] U.S. Bureau of Labor Statistics. "Databases, Tables & Calculators by Subject.: Accessed May 12, 2022. https://www.bls.gov/data/home.htm

produced almost 230 million short tons of the 238 million short tons of coal produced in total in Wyoming. Most of the coal mined in Wyoming is shipped via railroad throughout Wyoming and to 26 other states[7].

The PRB is 19,500 square miles in area and has the largest resource of low-sulfur, low-ash, subbituminous coal in the nation. The United States Geological Survey (USGS) estimates there are 1.15 trillion short tons of coal resources remaining in the basin. Of this, 25 billion short tones are estimated to be economically recoverable[8].

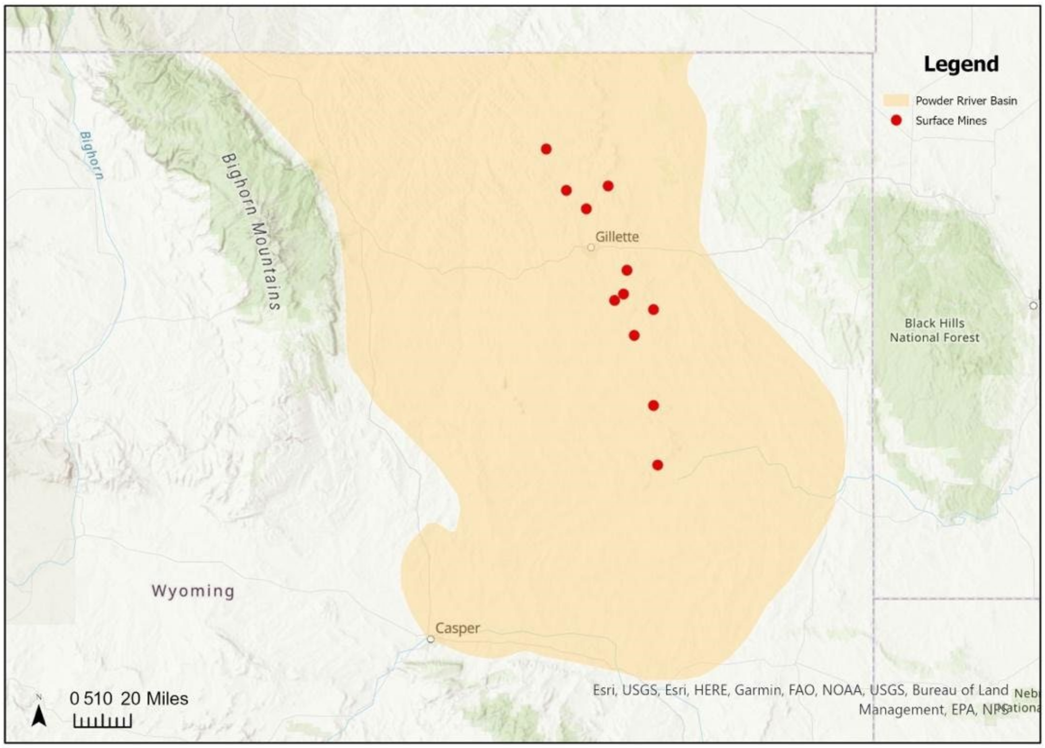

Figure 3: Coal mines (Surface Mines, red dots) in the Powder River Basin[9].

[7] Wyoming State Geological Survey. "Coal Production and Mining." Accessed May 2022. https://www.wsgs.wyo.gov/energy/coal-production-mining.aspx
[8] Luppens, James A., David C. Scott, Jon E. Haacke, Lee M. Osmonson, and Paul E. Pierce. "Coal Geology and Assessment of Coal Resources and Reserves in the Powder River Basin, Wyoming and Montana." 2015. United States Geological Survey. https://pubs.usgs.gov/pp/1809/pdf/pp1809.pdf
[9] Wyoming State Geologic Survey

Workforce and infrastructure availability

Transportation and other infrastructure

The mines in the PRB are already within close proximity to all the necessary infrastructure for extraction—roads and railroads for transportation, transmission lines, etc. They are also already equipped with all the necessary mining equipment and have developed supply chains to obtain new equipment as needed.

REE/CM processing plants will need to be permitted and constructed, as well, to build out a REE/CM processing industry. There are currently no similar facilities (e.g., chemical manufacturing) in the PRB. However, all necessary materials to construct and operate such as facility should be readily available in the Gillette area or could be transported to the PRB.

The Bear Lodge Project

The Bear Lodge Project, operated by Rare Element Resources, is an REE mining and processing project that is located just east of the PRB, near Sundance, Wyoming. It includes one of the largest conventional REE deposits in the US and is expected to be a dependable, long-term source of REEs domestically. Currently, Rare Element Resources is completing economic analyses and working with regulatory agencies on permitting. Once it is operational, it could contribute to a basin-wide REE industry in the PRB[10].

The Wyoming Innovation Center

The recently completed Wyoming Innovation Center is a facility designed to encourage innovative alternative uses of coal. Located in the PRB, near the Dry Fork Power Station, the Innovation Center provides the necessary infrastructure, including lap space, water, and testing sites located within close proximity to nearby mines. It is a public-private partnership that will give companies and organizations an opportunity to research and develop processes for making products from coal or extracting REE/CM from coal and coal byproducts.

Community College and Makers' Space

The City of Gillette in the PRB has well-established and state-of-the-art educational facilities. Gillette College, the local community college, offers degrees and certifications that already directly train the energy workforce. For example, they offer a Mine Safety and Health Administration training program (which notably features virtual reality training which shows miners hazards that cannot be

[10] Rare Element Resources. "Bear Lodge Project Overview". Accessed May 17, 2022. https://www.rareelementresources.com/bear-lodge-project/overview#.YoQIZ5PMLtU

seen from the cab of heavy equipment), a Mining Technology program, and a Mine Management Certificate[11, 12, 13].

Additionally, Gillette has a well-equipped Maker's Space that provides the community with access to cutting-edge equipment such as robotics, 3-D printers, welders, etc. Called *Area 59*, this space gives people in the community an opportunity to learn to use this equipment and to make/manufacture products[14]. The skill-development and ability to develop product prototypes could be valuable for a variety of applications in developing new industries.

Trained workforce and social license

As the home of the most prolific coal mine in the world, the PRB already has an extensive trained workforce for mineral extraction. Coal mining has been a major industry in the region for decades and many of the skills needed will be similar to the skills needed for REE/CM industries. Additionally, Campbell County is strongly supportive of new energy industries. Wyoming as a state has strong social license for energy development, in general[15]. And, Campbell County is particularly encouraging and inviting of new innovative industries. They are a partner on the CORE-CM project through the University of Wyoming School of Energy Resources which is exploring the potential for REE/CM industries. Additionally, the economic development organization in Campbell County, Energy Capital Economic Development, is also strongly supportive of and partnering with the CORE-CM project.

Training Opportunities

Skills needed

Exploration

Exploration of REE/CM (to determine where REE/CM are located) is one of the industries that will need a trained workforce. This will mostly be done by geologists, and Wyoming already has a well-

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[11] United States Department of Labor. "Wyoming: State of Wyoming Program Summary". Accessed May 9, 2022. https://www.msha.gov/wyoming

[12] Gillette College. "Mining Technology AAS". Accessed May 9, 2022 http://catalog.sheridan.edu/preview_program.php?catoid=13&poid=1681&returnto=400

[13] Gillette College. "Mine Management Certificate". Accessed May 9, 2022 http://catalog.sheridan.edu/preview_program.php?catoid=14&poid=1822&returnto=430

[14] Area 59. "Equipment". Accessed May 9, 2022. https://area-59.com/equipment

[15] University of Wyoming School of Energy Resources. "Social License for Wyoming's Energy Future". Accessed May 10, 2022. http://www.uwyo.edu/haub/_files/_docs/ruckelshaus/pubs/2020-wyomings-energy-social-license-report.pdf

developed geology workforce. However, as REE/CM industries develop, there will be need for more geologists, including field geologists, geochemists, geophysics, and mineralogists[16, 17].

Mining

Many of these necessary jobs will require the same skills that the workforce in the Powder River Basin already has, since the extractive process is expected to be similar. There may be a difference in the quantity of the skilled labor needed. For example, if a company were to start mining a new coal bench, additionally trained labor may be needed[18]. There may also be a need for more mining engineers as REE/CM mining expands, since it is a field that has seen many retirements in recent years and a shortage of students applying for mining engineering degree programs. To ensure an adequate workforce, it will be important to encourage education for a new generation to do this work[19]. Table 1 provides an example of the types of jobs required to operate a REE/CM mine from the Bear Lodge Project operated by Rare Elements Resources in northeastern Wyoming.

Title	
Operations Hourly Workforce	
	Shovel/Loader Operators
	Truck Drivers
	Drillers
	Dozer/Grader Operators
Maintenance Hourly Workforce	
	Heavy Equipment Mechanics
	Fuel/Lube—Light Vehicle
	Electrician
Salaried Personnel	
	Mine Superintendent
	Maintenance Foreman
	Shift Boss
	Maintenance Planner
	Sr. Mine Engineer
	Ore Control/Geology
	Surveyor
	Clerk
	Security

Table 1: Example of mining labor requirement for REE/CM mining based on Rare Element Resources' Bear Lodge Project[20].

[16] Miskovic, Eli: Assistant Professor, University of British Columbia. Interviewed. Conducted by Selena Gerace. May 2, 2022
[17] Sauer, Kirsten: Research Scientist, Los Alamos National Laboratory. Interviewed. Conducted by Selena Gerace. April 25, 2022
[18] Green, Dave. Project Manager, Dry Fork, Mine. Interviewed. Conducted by Selena Gerace. May 3, 2022
[19] Miskovic, Eli: Assistant Professor, University of British Columbia. Interviewed. Conducted by Selena Gerace. May 2, 2022
[20] Roche Engineering. "Bear Lodge Project: Pre-Feasibility Study Report." 2014. Rare Element Resources

Processing

The processing of REE/CM from the raw material (e.g. coal or coal byproducts) can be divided into two categories: 1) development of processing procedures and, 2) operation of processing facilities.

The development of the procedures for REE/CM processing is the research phase of developing the industry. It will rely mainly on chemical engineers, chemists, geochemists, and metallurgy engineers. These unique and technical skillsets will be necessary for figuring out how to extract REE/CM from coal and coal by-products and how to get the REE/CM to the level of concentrations needed[21, 22].

Title	
Operation	
	Metallurgist
	General Foreman
	Operation Team Leader
	Ore Handling Operator
	Crusher Operator
	Classification Operator
	Dewatering Operator
	Magnetic Separation Operator
Operation support	
	Safety Engineer / Trainer
	Secretary/Process Clerk
	Accounting Clerk
	Warehouse Personnel
Maintenance	
	Superintendent - Mech Eng. - Planner
	Mechanical Clerk
	Mechanical Foreman
	Mechanical
	Maintenance Helper
	Electrical Engineer - Planner
	Electrical Clerk
	Electrical Foreman
	Electrician
	Intrumentation Tech.
Assay Laboratory	
	Chief Analyst
	Assay Lab Technician
	Laborer

Table 2: Example of labor requirement for Physical Upgrade Plant based on Rare Element Resources' Bear Lodge Project[23].

[21] Miskovic, Eli: Assistant Professor, University of British Columbia NBK Mining Institute. Interviewed. Conducted by Selena Gerace. May 2, 2022
[22] LiOakey, Katie. Associate Professor, University of Wyoming Department of Chemical Engineering. Interviewed. Conducted by Selena Gerace. May 9, 2022
[23] Roche Engineering. "Bear Lodge Project: Pre-Feasibility Study Report." 2014. Rare Element Resources

For the daily operations of the processing facilities, trained operators, laboratory technicians, and maintenance personnel will be essential[24, 25, 26]. Table 2 and Table 3 show examples of labor requirements at two types of processing facilities: 1) a Physical Upgrade Plant (PUG), where the barren rock will be removed from the ore to increase the concentration of REE, and 2) a Hydrometallurgical Plant, where chemical processing of will remove impurities and recover the REE[27]. Both of these plants require skilled labor in Operation/Operational Support, Maintenance, and Laboratory. Within these categories, the specialties range from metallurgists, operators of specific machinery, safety engineers, mechanists, electricians, and lab technicians.

Title
Operation
Operation Team Leader
Production materials receiving
Pre-Concentrate handling Operator
Leaching Operator
Precipitation Operator
Oxidation/HCl recovery operator
Ammonium Nitrate Operator
Operation Support
Area Manager -Chemical Engineer
Process engineer (Chemical)/Env.
Geologist
Technician-Env
Secretary/process clerk
Accounting clerk
Warehouse personnel
Security Guards
Maintenance
Superintendent-Eng.-Planner
Mechanical Planner
Mechanical Clerk
Mechanical foreman
Mechanic
Maintenance Helper
Electrical Engineer-Planner
Electrical Planner
Electrical Clerk
Electrical Foreman
Electrician
Instrumentation Tech.
Assay Laboratory
Chief Analyst-Environment
Assay lab technician
Laborer

Table 3: Example of labor requirement for Hydrometallurgical Plant based on Rare Element Resources' Bear Lodge Project[28].

[24] Miskovic, Eli: Assistant Professor, University of British Columbia. Interviewed. Conducted by Selena Gerace. May 2, 2022
[25] LiOakey, Katie. Associate Professor, University of Wyoming Department of Chemical Engineering. Interviewed. Conducted by Selena Gerace. May 9, 2022
[26] Heinrichs, Mike. Program Manager, Battelle. Interviewed. Conducted by Selena Gerace. May 29, 2022.
[27] Rare Element Resources. "Proposed Operations". Accessed May 17, 2022 https://www.rareelementresources.com/bear-lodge-project/proposed-operations#.YoPyYZPMLtU
[28] Roche Engineering. "Bear Lodge Project: Pre-Feasibility Study Report." 2014. Rare Element Resources

Potential new skills needed

Depending on how technologies change, the skills and jobs required for REE/CM industries could change as well. For example, advances in automation could disrupt the industry greatly. If most of the processes could be automated, many jobs could be eliminated. However, it is estimated that this is still 10-15 years away. If automation is widely adopted, it will not eliminate the need for many of the more highly skilled jobs, such as metallurgy engineers[29].

Biologically enabled solutions could be another disruptive technology. Microbes could be used to separate and process the REE/CM. If this does develop, the jobs and skills needed would be more biology-based[30].

In current mining techniques, there is already some use of autonomous vehicles, diesel/electric hybrids, electric vehicles, and drones. But the use of all of these could be expanded in the future, requiring additional need for expertise in the specialized skills for operating and maintaining the technology and equipment[31]. Robotics is another technology that could be widely adopted in mining, sampling, and loading/unloading processes[32].

Training opportunities

Universities

Some of the necessary education and training to develop the workforce for REE/CM industries will need to happen at the university level. For example, there will be a need for chemical engineers, metallurgy engineers, mining engineers, and geologists who have bachelor's degrees, Master's degrees, and Doctorates[33, 34]. This is especially true of the jobs necessary for doing research and development of REE/CM extraction processes, as well as jobs for processing of REE/CM that are further downstream, including final purification. These jobs will involve methodologies for more advanced chemical processes, so advanced degrees will be needed[35].

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29 Miskovic, Eli: Assistant Professor, University of British Columbia. Interviewed. Conducted by Selena Gerace. May 2, 2022
30 Heinrichs, Mike. Program Manager, Battelle. Interviewed. Conducted by Selena Gerace. May 29, 2022
31 Grubb, Travis. Dean of Career & Technical Education, Gillette College. Interviewed. Conducted by Selena Gerace. April 5, 2022
32 Grubb, Travis. Dean of Career & Technical Education, Gillette College. Interviewed. Conducted by Selena Gerace. April 5, 2022
33 Miskovic, Eli: Assistant Professor, University of British Columbia. Interviewed. Conducted by Selena Gerace. May 2, 2022
34 LiOakey, Katie. Associate Professor, University of Wyoming Department of Chemical Engineering. Interviewed. Conducted by Selena Gerace. May 9, 2022
35 Heinrichs, Mike. Program Manager, Battelle. Interviewed. Conducted by Selena Gerace. May 29, 2022

Community Colleges

Jobs in more upstream parts of REE/CM processing, which involve less material and less complex chemical processes, will require considerable workforce with Associate degrees and technical training. For example, there will be a need for far more trained laboratory technicians and operators, positions that will be essential for ensuring that plants run safely, efficiently, and continuously. This type of training is one that community colleges are well equipped to provide[36]. And, of course, much of the training needed to develop the workforce for the mining industry is already done at the community college level and it will be important that workforce training continues.

Gillette College Current Programs

Gillette College already provides Associate degrees and technical training in many of the fields that are important in mining and will be important in developing a workforce for REE/CM processing. For example, programs include:

- Diesel Technology
- Electrical Apprenticeship
- Industrial Electricity
- Industrial Technology
- Welding
- Engineering
- Mine Safety and Health Administration
- Mining Technology
- Mine Management Certificate

Future Program/Training Potential

Gillette College is poised to develop future programs to train the workforce for new skills and jobs that will be needed for future energy jobs, as well. For example, they are developing an Operator Program that would include training in operating dozers, excavators, blades, forklifts, and skid steers. (They have applied for a grant to fund this program and are waiting on approval.)[37]

Additionally, Gillette College is partnering with the University of Wyoming Maker's Space and the University of Wyoming School of Energy Resources to develop training modules that will be

[36] LiOakey, Katie. Associate Professor, University of Wyoming Department of Chemical Engineering. Interviewed. Conducted by Selena Gerace. May 9, 2022
[37] Grubb, Travis. Dean of Career & Technical Education, Gillette College. Interviewed. Conducted by Selena Gerace. April 5, 2022

available through University of Wyoming's Maker's Space. These trainings will be available as part of the Maker's Space 'Badge' program in which 'badges' are issued to indicate completion of a specific training. Some of the trainings are completely virtual, while others involve a combination of virtual and hands-on training[38].

UW Maker's Space already offers a wide variety of badges in topics ranging from safety to modeling and design to 3D printing. Participants sign up for badge trainings online and, once the trainings are completed, badges are issues and operate like a certificate from an issuing authority. Badges also provide a way for employers to find trained personnel with specific skillsets. If participants give approval, they will be added to a database that employers can search and send job postings to [39].

Gillette College and the UW School of Energy Resources 3D Visualization Center are planning to work together to developing a series of badges specific to REE/CM industry skills and information as part of the CORE-CM Initiative[40]. Gillette Colleges will provide the raw material/information for the trainings and the 3D Visualization Center will adapt this information into educational modules.

These badges will provide a convenient and adaptable way to offer trainings in specialty skills and knowledge that will help to prepare the workforce for jobs in REE/CM industries. Potential topics for REE/CM badges include:

- Foundational information about rare earth elements and critical minerals (e.g., how they are extracted, what products they are used for, etc.);
- Information about career opportunities in mining, energy, and other regionally relevant industries;
- General information about energy and other infrastructure that will be relevant for REE/CM industries.

Badges could also be issues for current programs that Gillette College offers that will be necessary for REE/CM industries. For example, equipment operator programs (dozer/excavator/forklift/skid-steer) or commercial driver's license (CDL) programs.

[38] Wyrkshop Maker's Space. "Badges". Accessed May 13, 2022. https://www.wyrkshop.org/badges
[39] Wyrkshop Maker's Space. "Badges". Accessed May 13, 2022. https://www.wyrkshop.org/badges
[40] University of Wyoming School of Energy Resources. "Powder River Basin CORE-CM". Accessed May 13, 2022. https://www.uwyo.edu/cegr/research-projects/core-cm-prb.html

Conclusion

Community colleges, such as Gillette College, are poised to play an important role in providing trainings that will develop the necessary workforce for REE/CM extraction and processing. While training at the university level will also be important, people with Associates degrees and technical training will likely make up the majority of the industry. This type of workforce training will be essential as states and communities that are currently dependent on revenue from fossil energy industries seek economic development opportunities in new low-carbon energy industries. It will be important for communities to ensure they have a well-trained and prepared workforce to meet the needs of these industries.

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