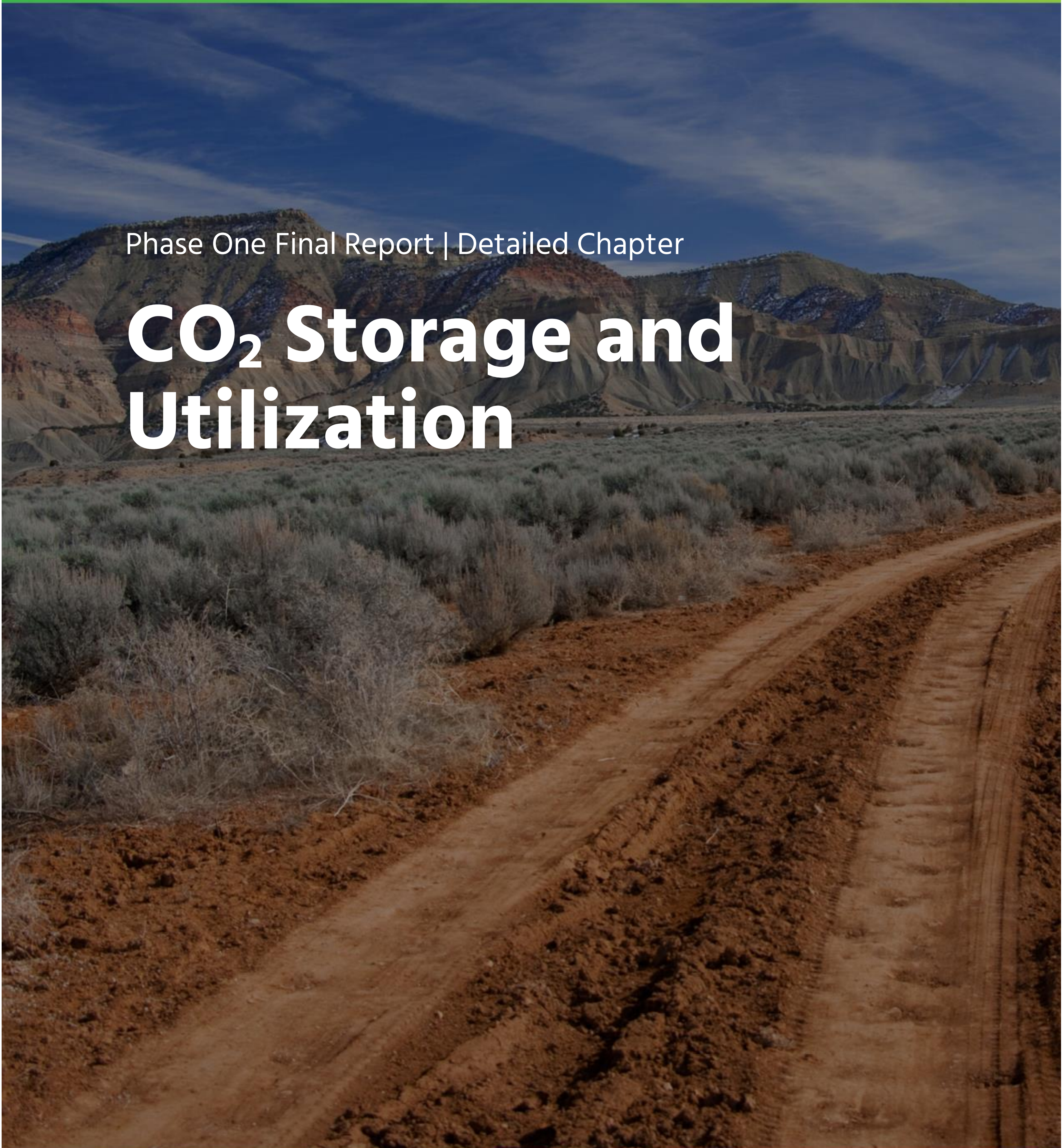
I-WEST



Phase One Final Report | Detailed Chapter

CO_2 Storage and Utilization

VERSION 1.0

NATIONAL ENERGY TECHNOLOGY LABORATORY

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About this report

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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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].

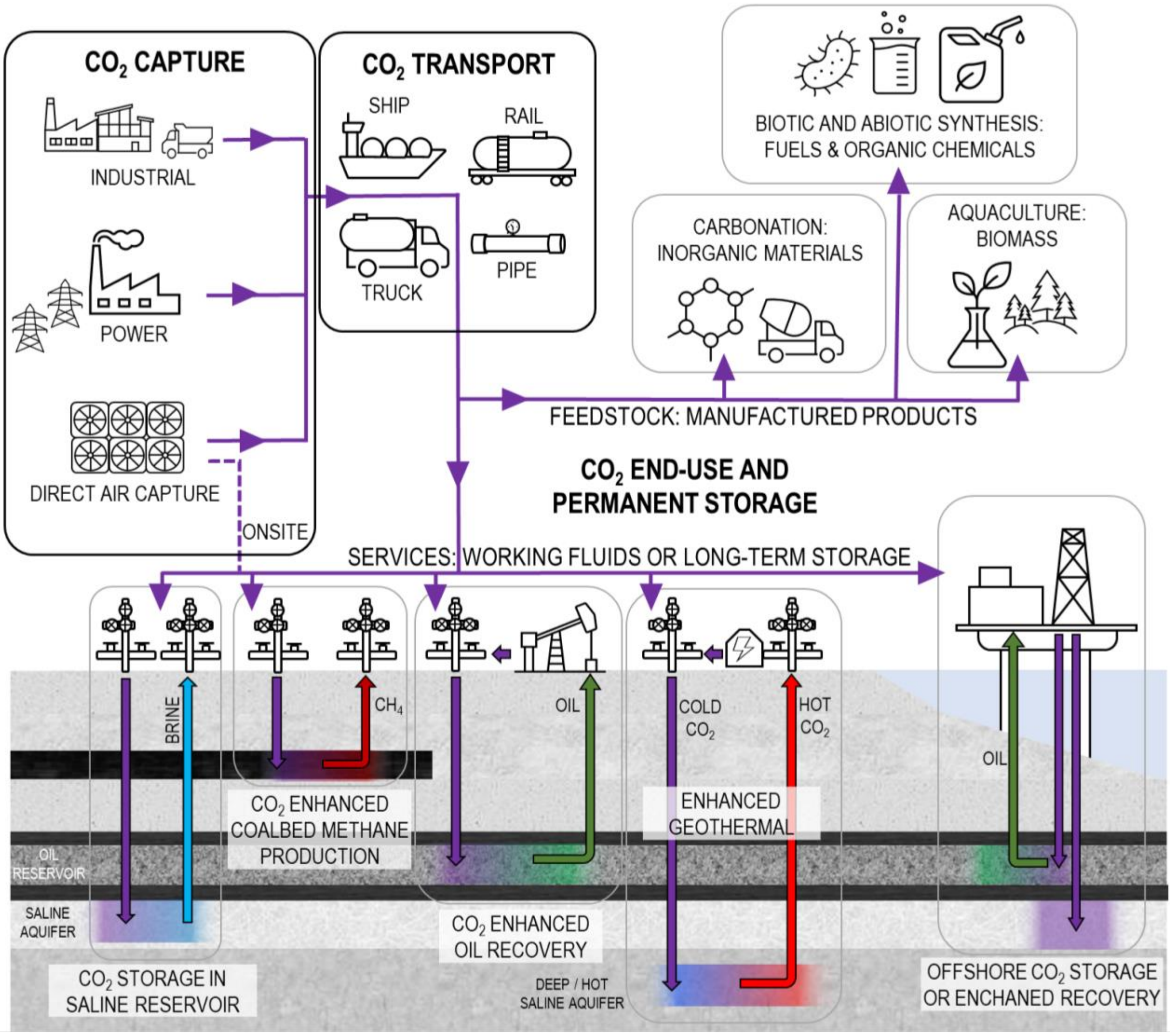


Figure 1. Schematic diagram of the portfolio of technologies spanning the CCUS value chain with an emphasis on transportation and subsurface utilization options

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.

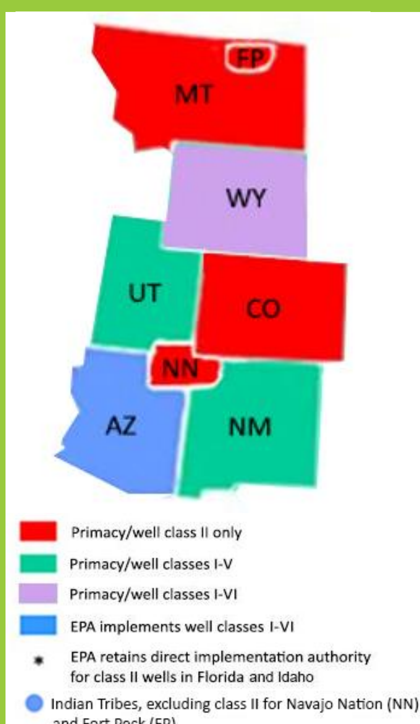


Figure 2. Map featuring UIC primacy status for states, territories, and tribes in the Intermountain West

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.

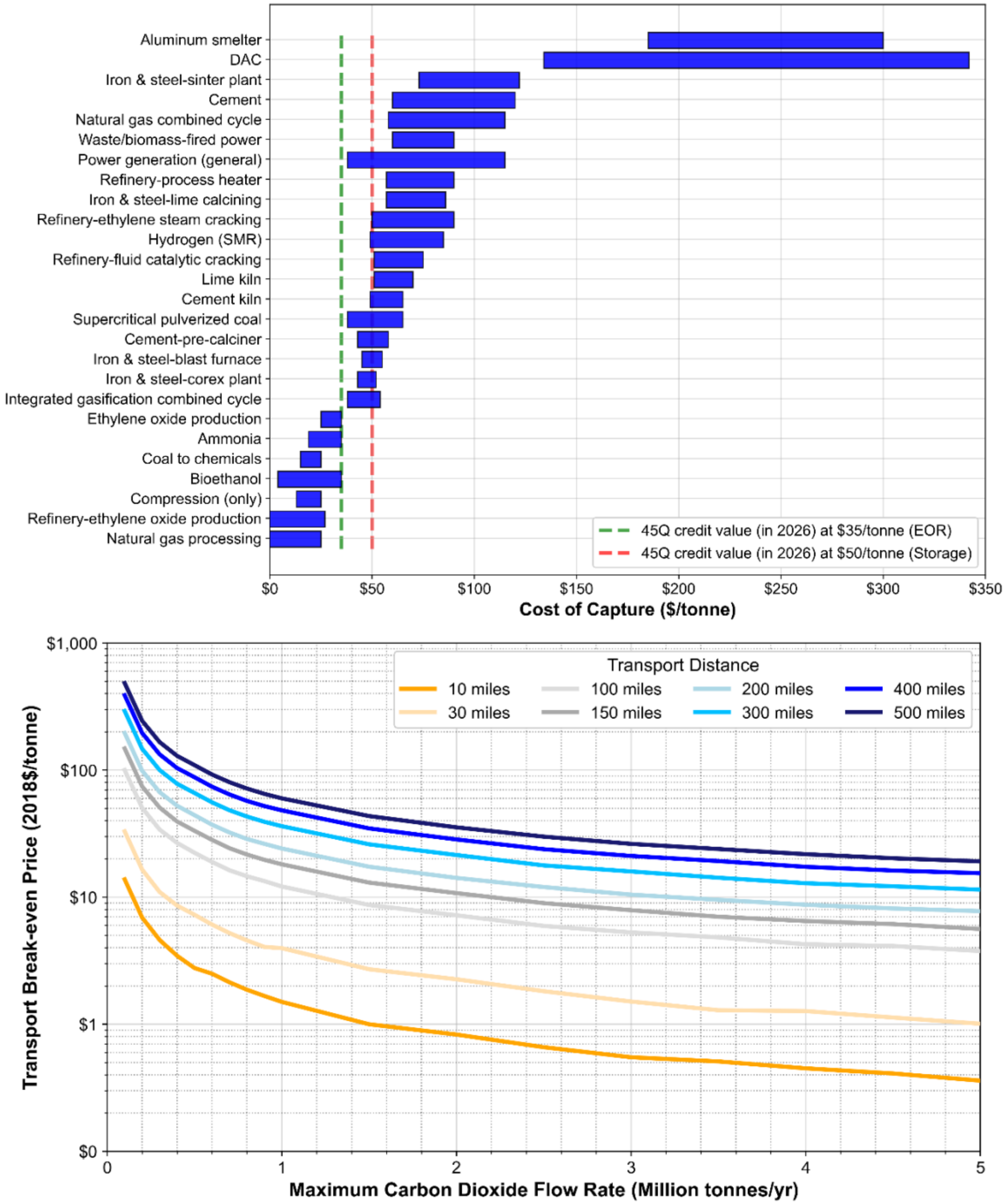


Figure 3. Levelized cost of CO_2 capture by sector (top) and CO_2 transport by flowrate and transportation distance (bottom)

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.

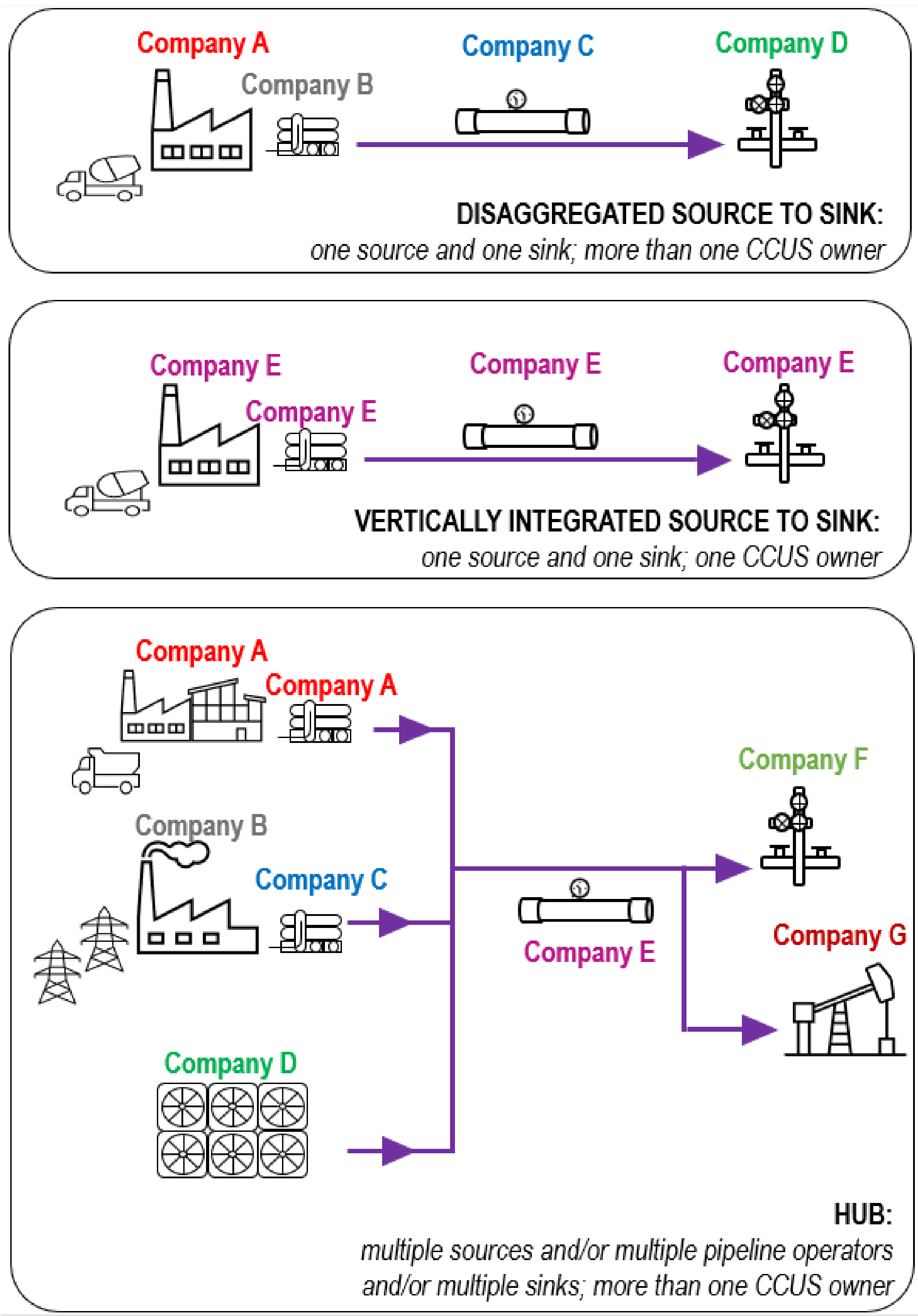


Figure 4. Schematic examples of CCUS business models

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.

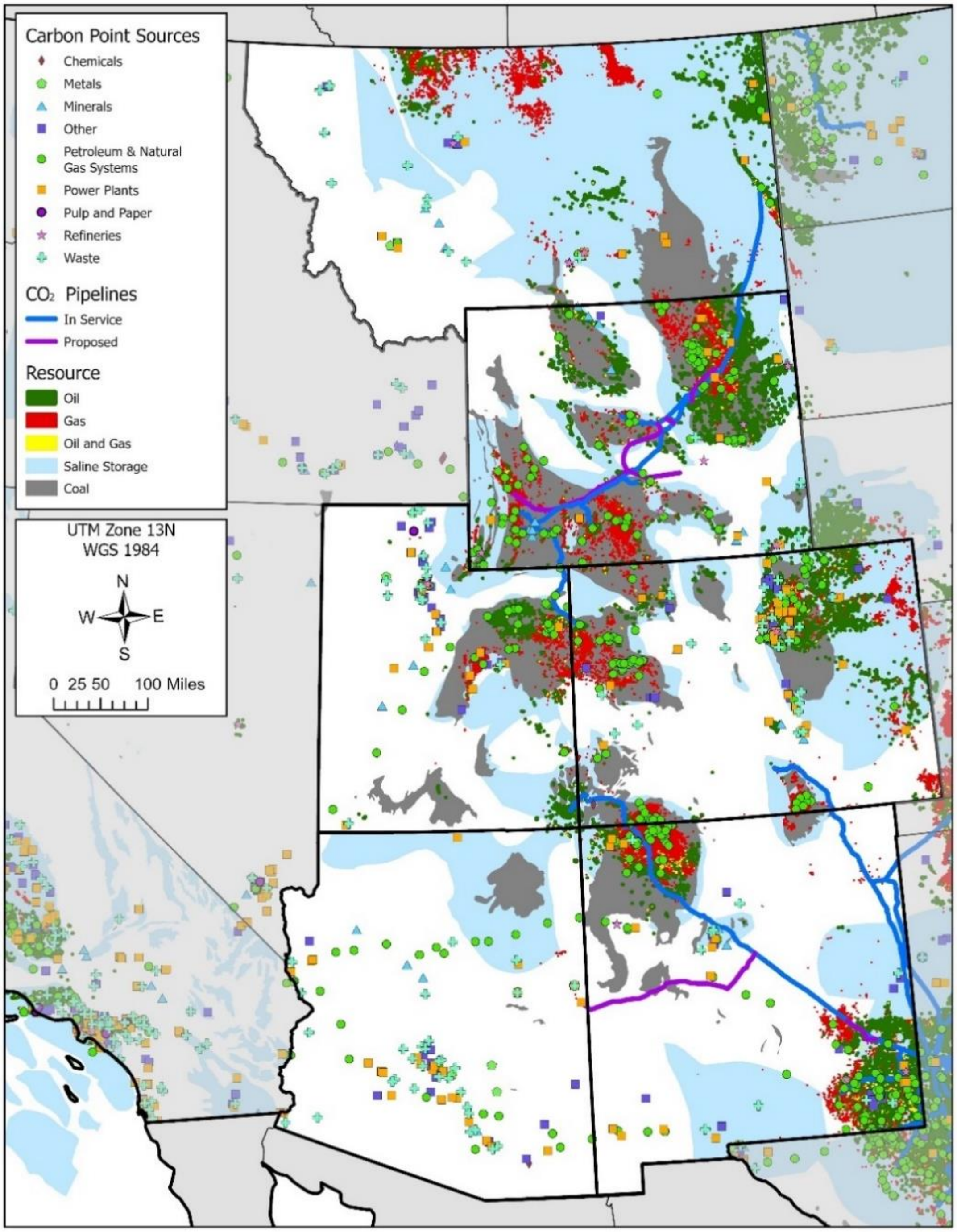


Figure 5. CO_2 sources, GCS areas, and CO_2 pipeline infrastructure

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].

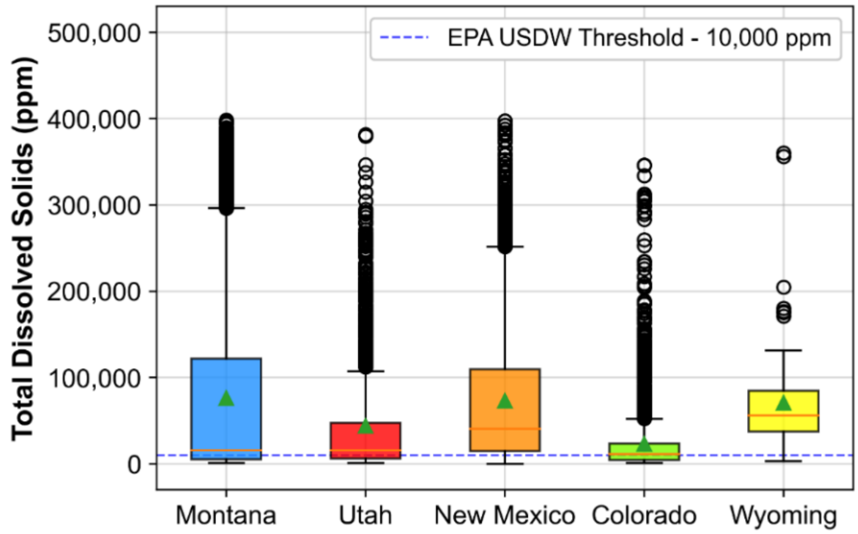


Figure 6. Box and whisker plot depicting TDS ranges in aquifers in the Intermountain West states

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].

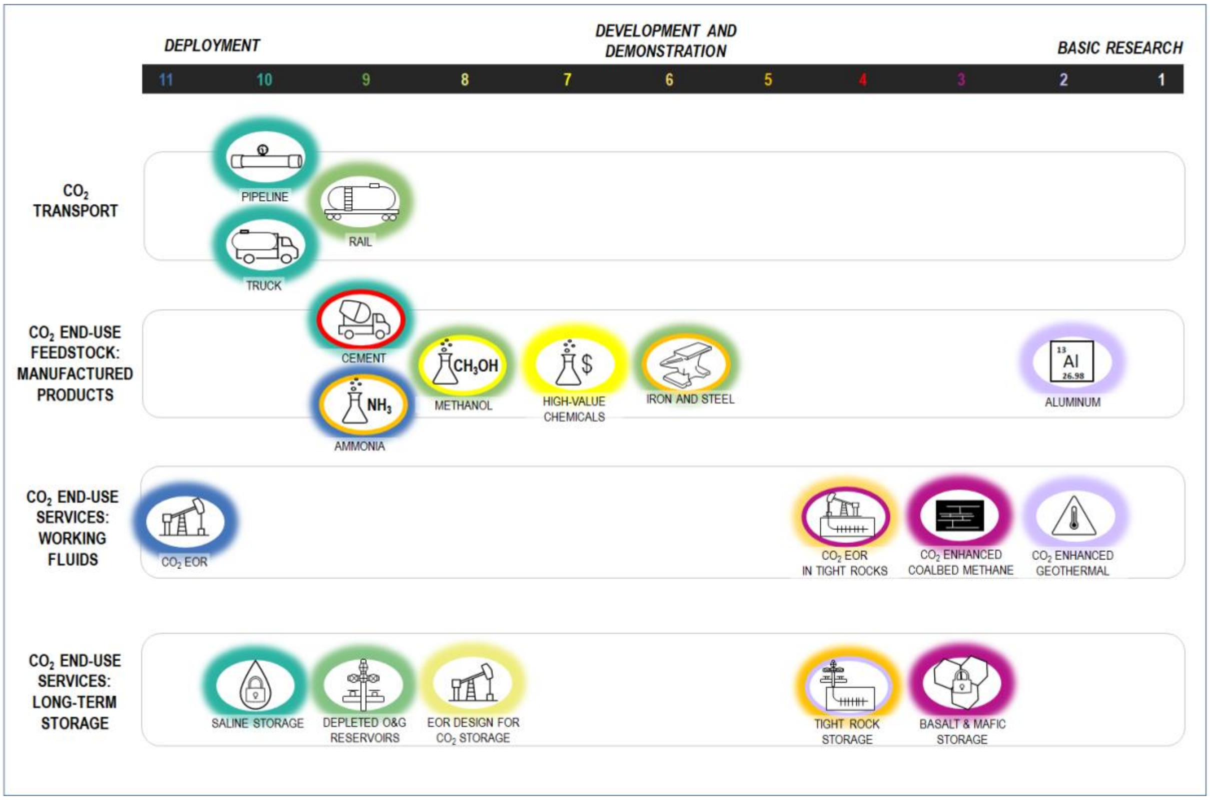


Figure 7. Current and emerging portfolio of technologies spanning the CCUS value chain

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)

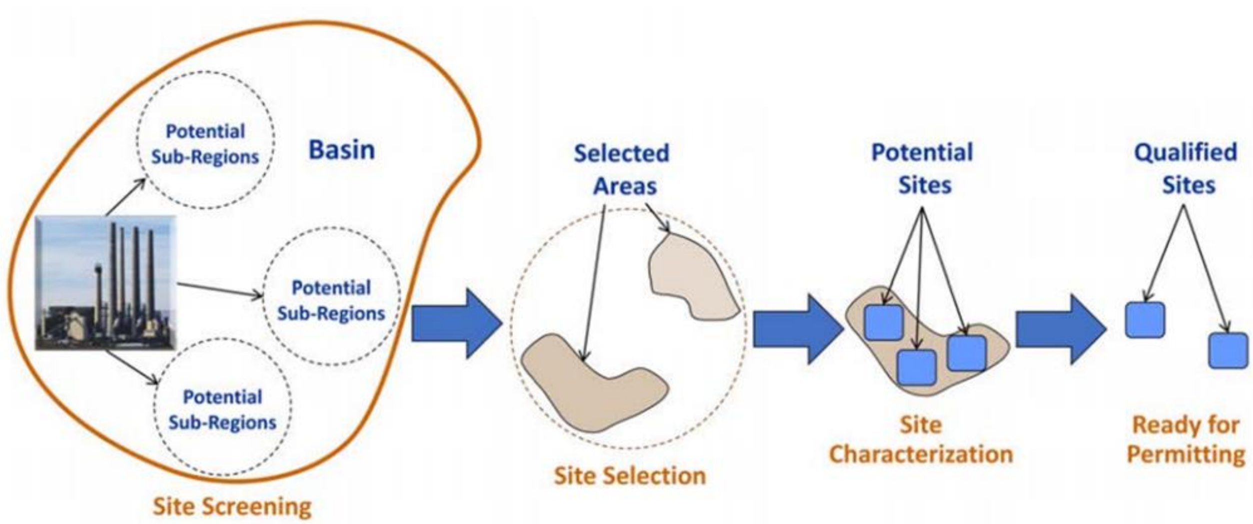
[76]. Selection of a viable GCS site must address capacity, injectivity, containment, and salinity characteristics. A qualified project site, therefore, is one that meets all required technical and non-technical criteria for CO_2 storage and is ready to seek permit to inject. Several stages of site development 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

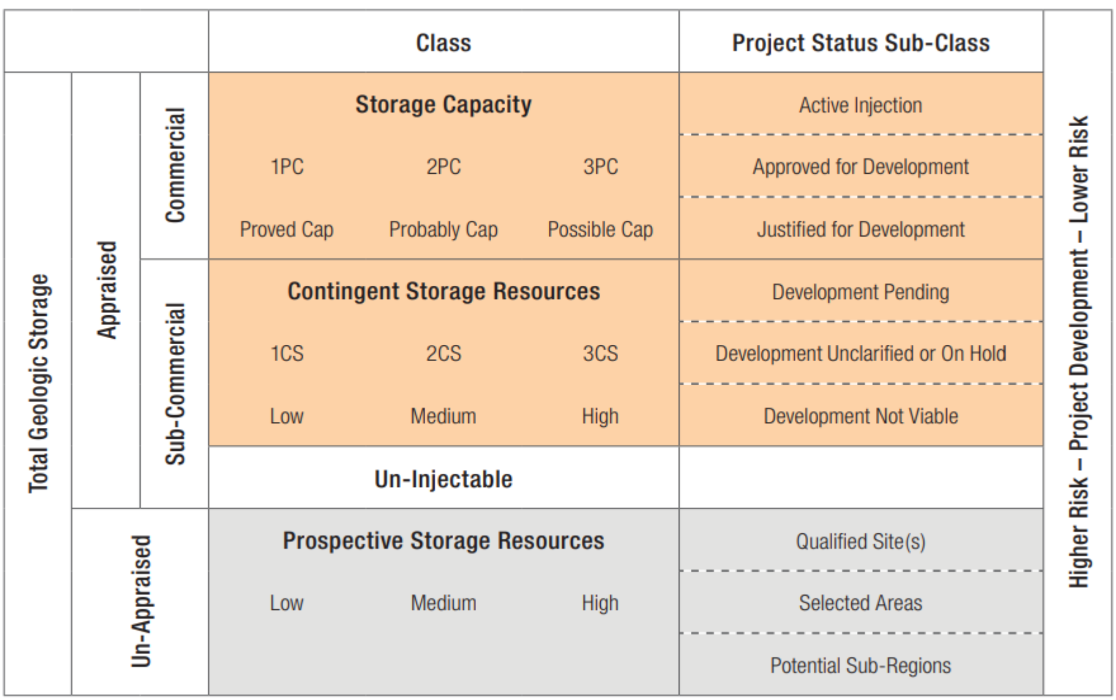


Source: National Energy Technology Laboratory (NETL) [108]

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.

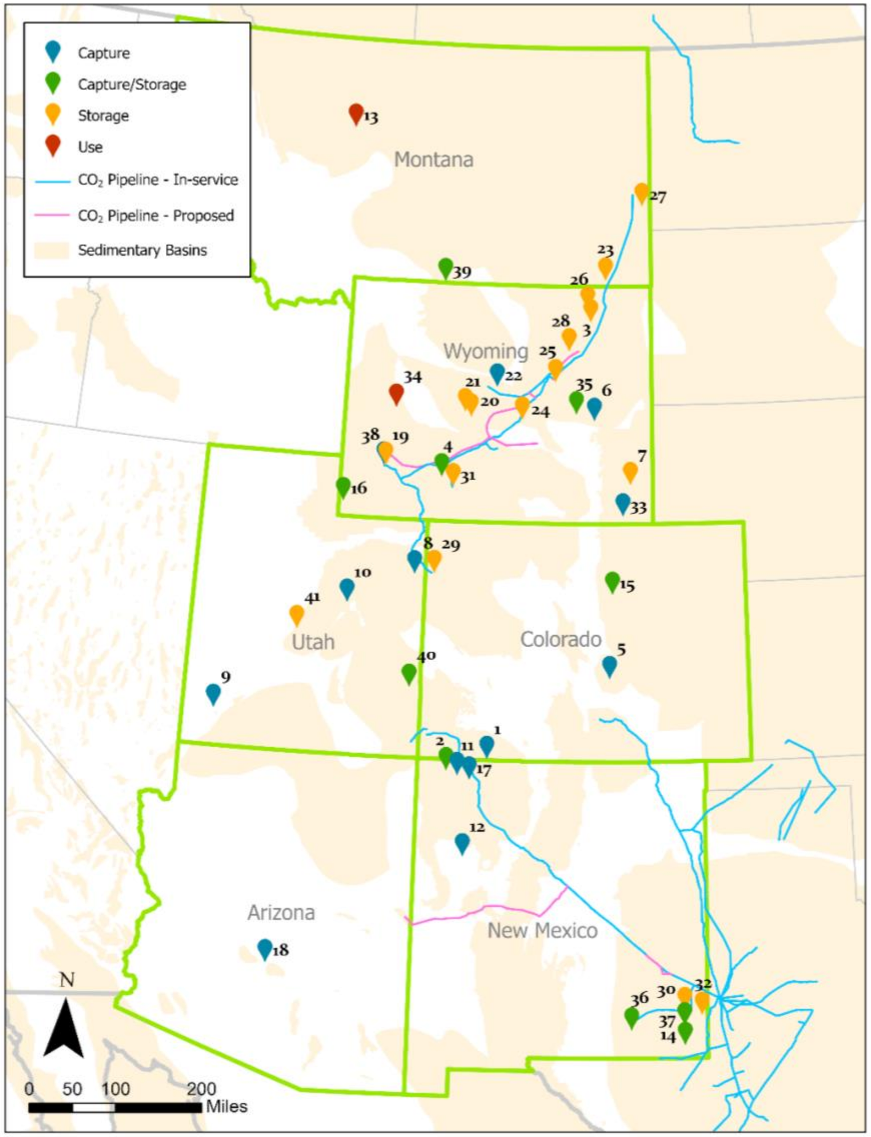


Figure 10. Map of CCUS-related projects on-going or proposed in the region

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

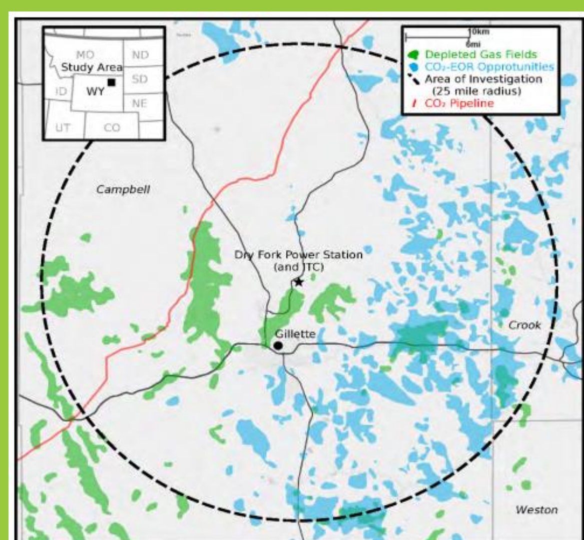


Figure 11. CO_2 storage and transportation opportunities identified within 25 miles of the Dry Forks Station

- 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]
-

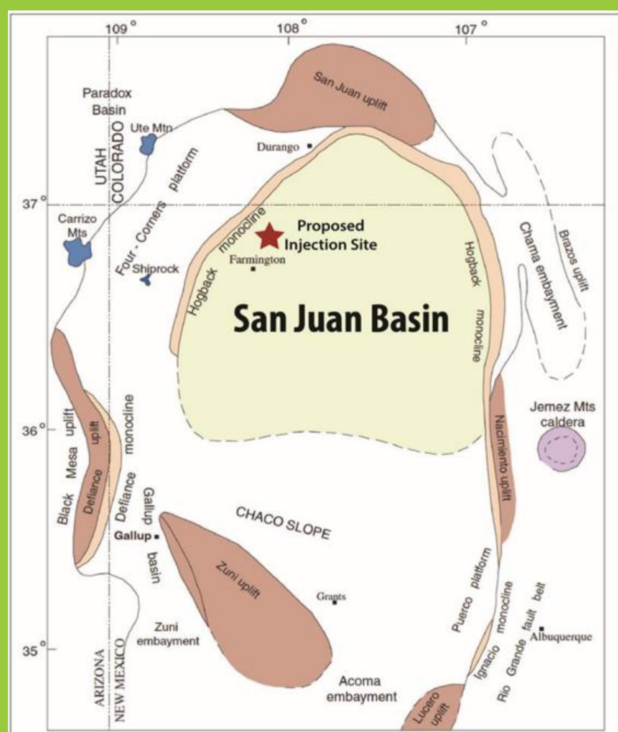


Figure 12. Location of proposed injection site within San Juan Basin [111]

- 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.

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).

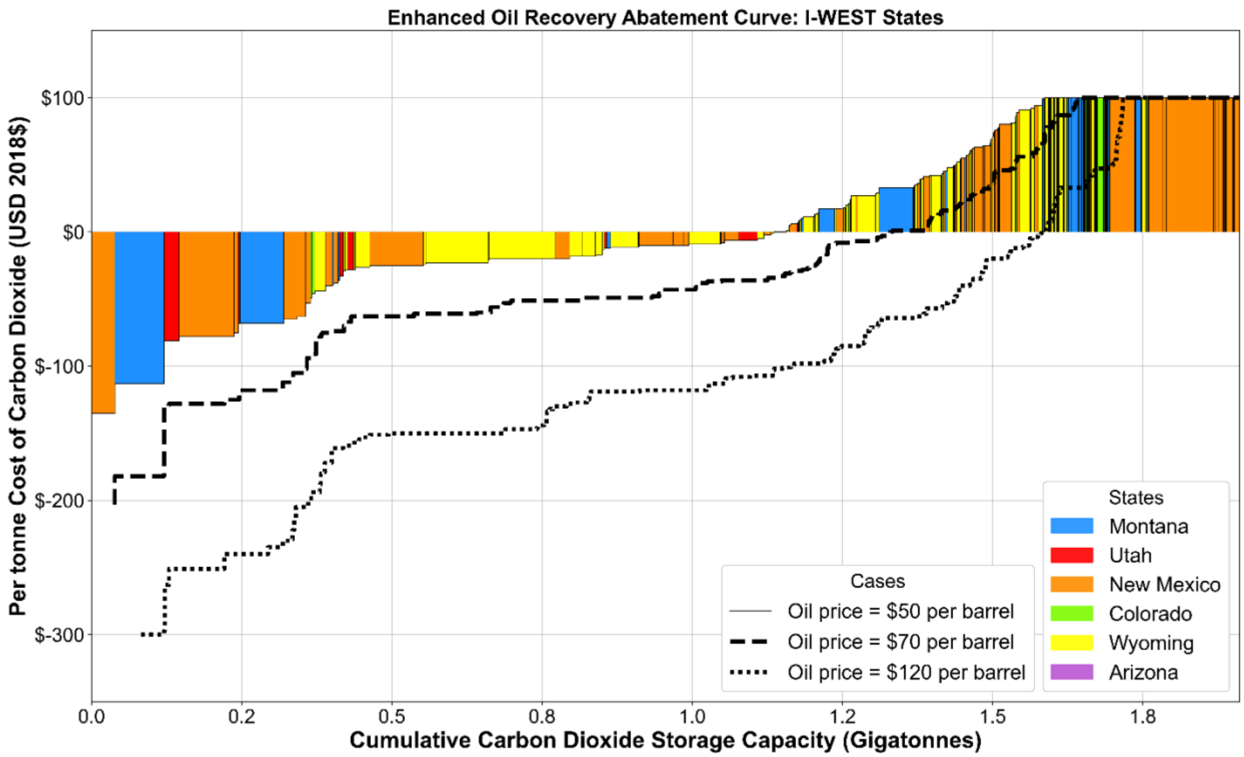


Figure 13. CCUS abatement curve applicable to CO_2-EOR in the region

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.

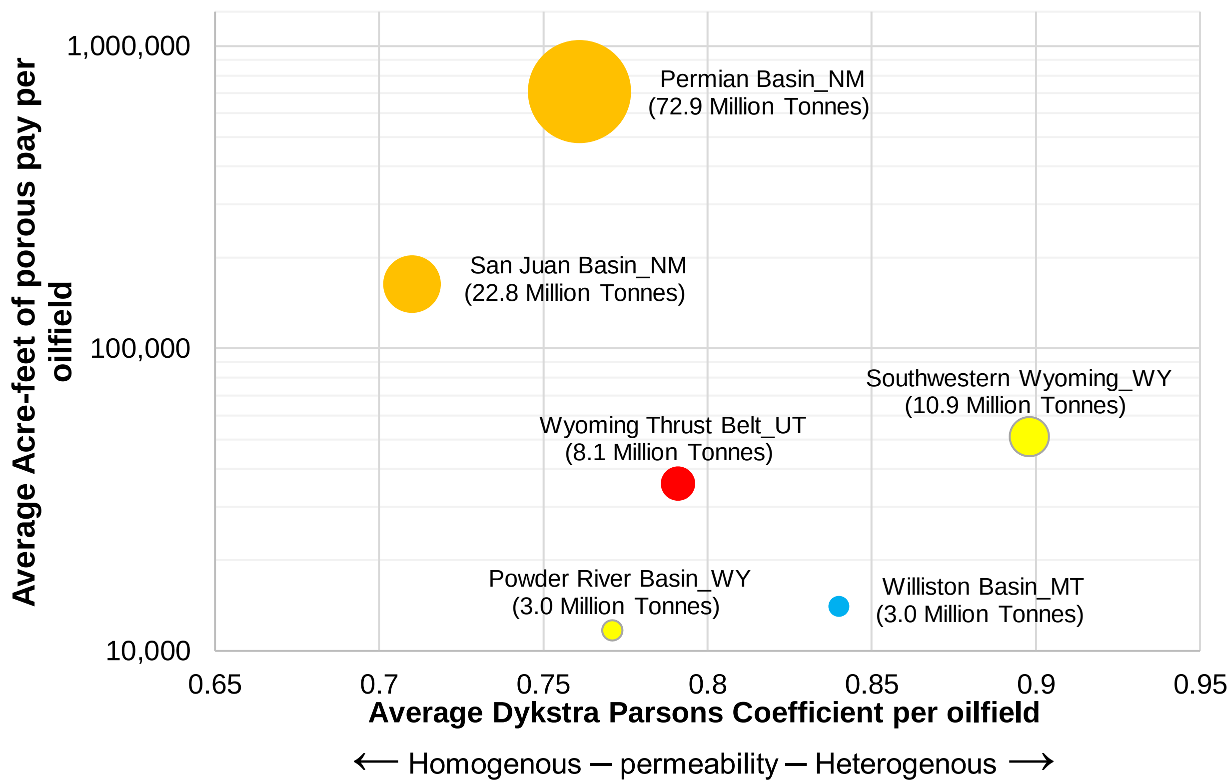


Figure 14. Average shovel-ready oil field reservoir quality for oil fields economical at \$70/STB and \$25/tonne CO_2 for transportation by province-state combination, sized by average purchased CO_2 per field

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.

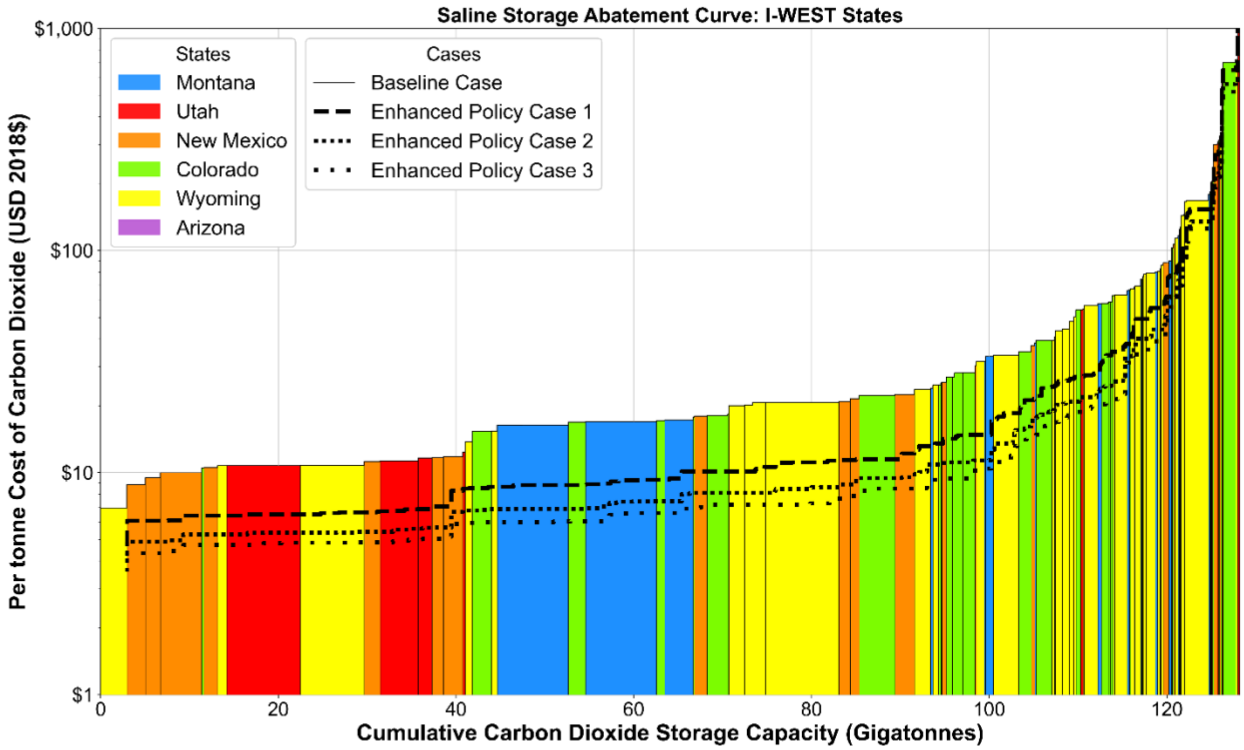


Figure 15. CCUS abatement curve applicable to saline storage resources in the region

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.

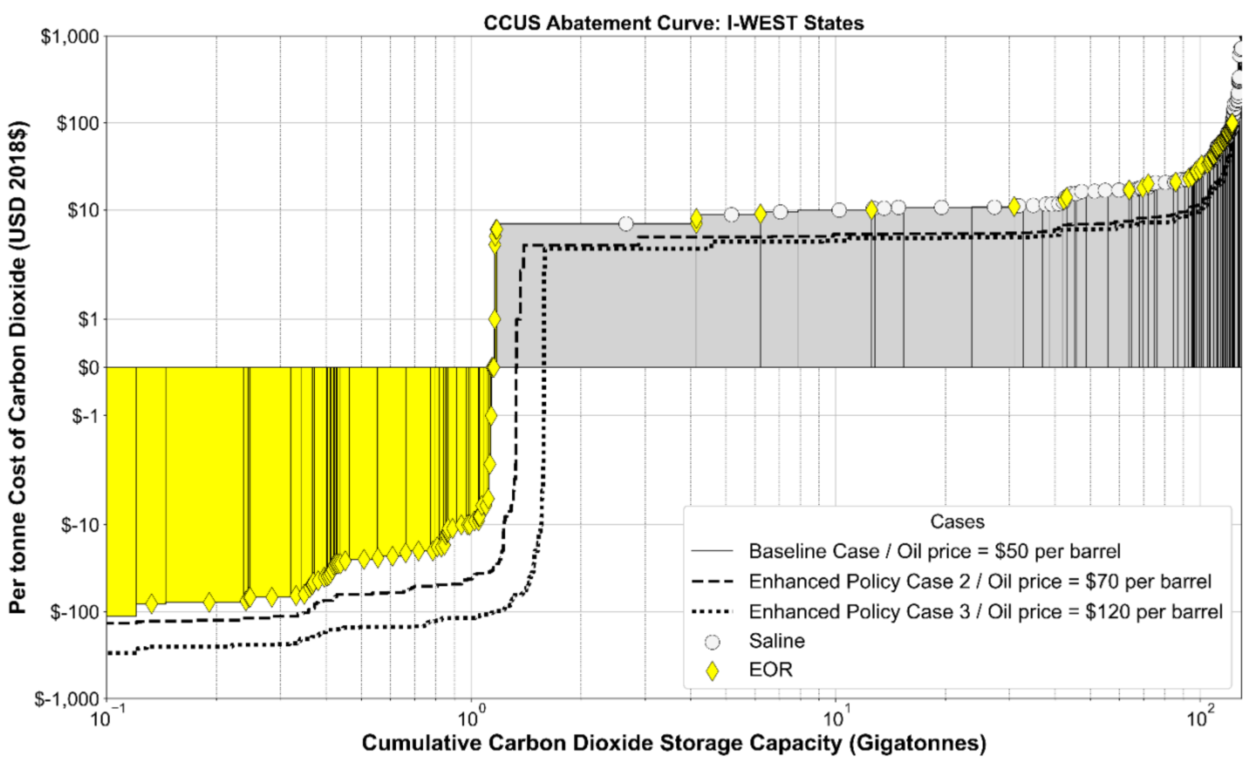

Figure 16. CCUS abatement curve applicable that includes both saline storage and CO_2-EOR in the region

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.

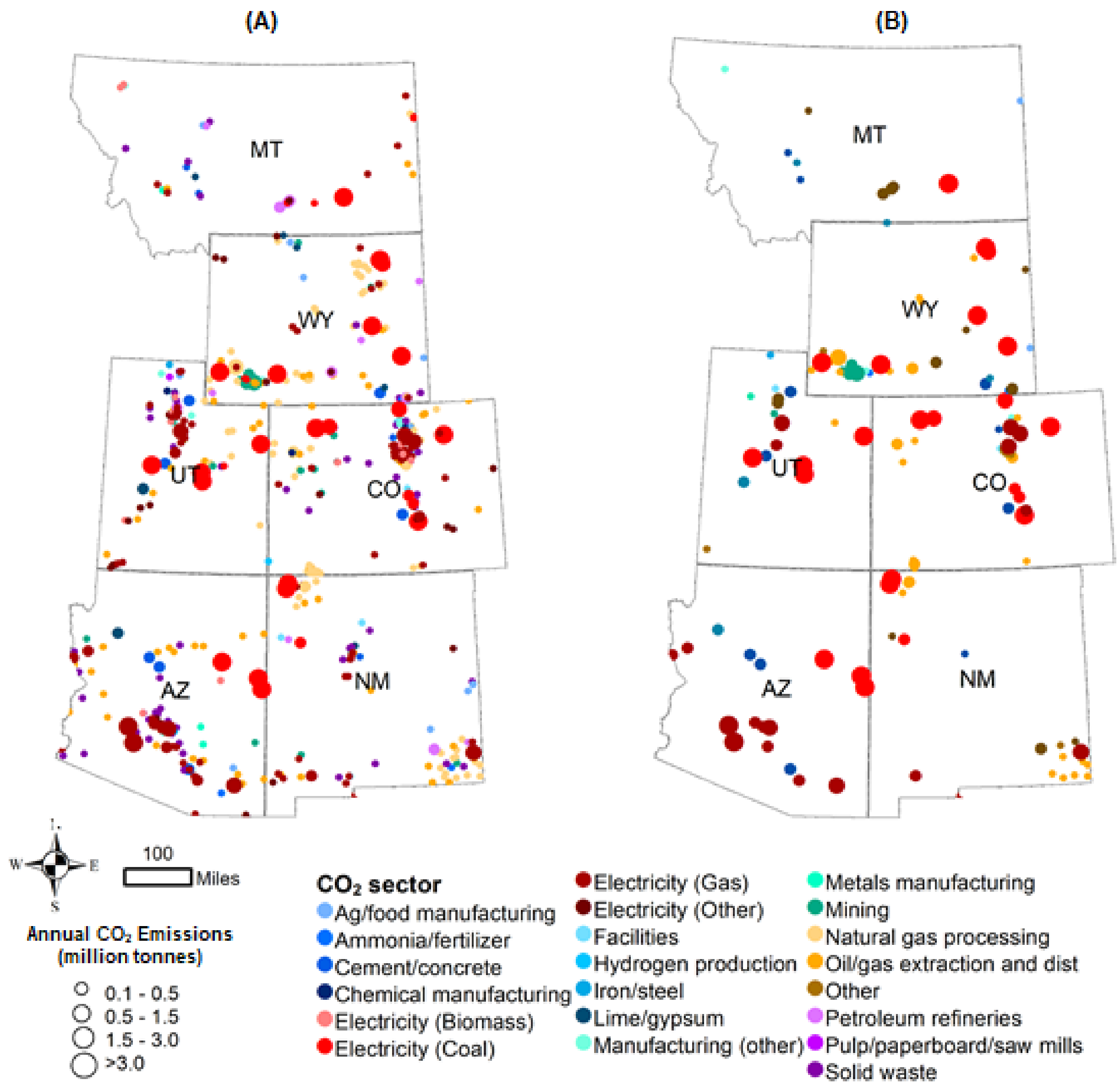

Figure 17. Maps showing all point source CO_2 emitters in the region (A) and those that meet 45Q eligibility (B)

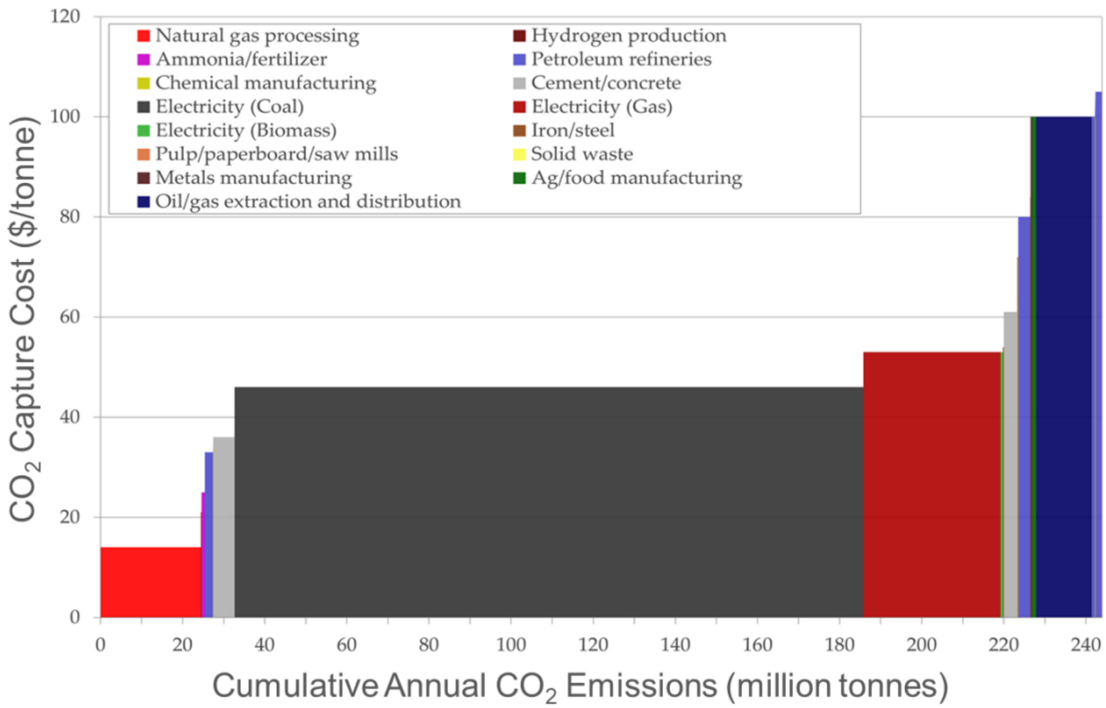

Figure 18. CO_2 supply curve for the CO_2 sources and associated costs of capture in the region

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.

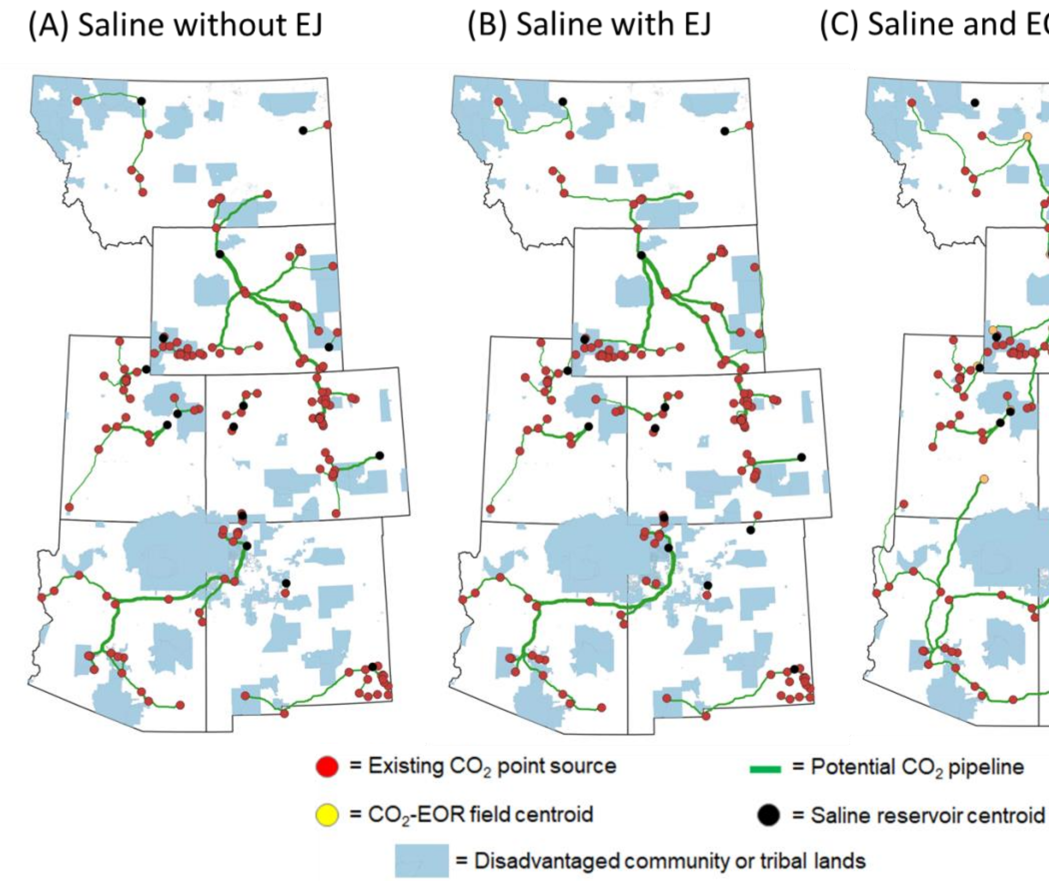

Figure 19. Pipeline network outlook connecting point sources and sinks under the three single phase scenarios

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.

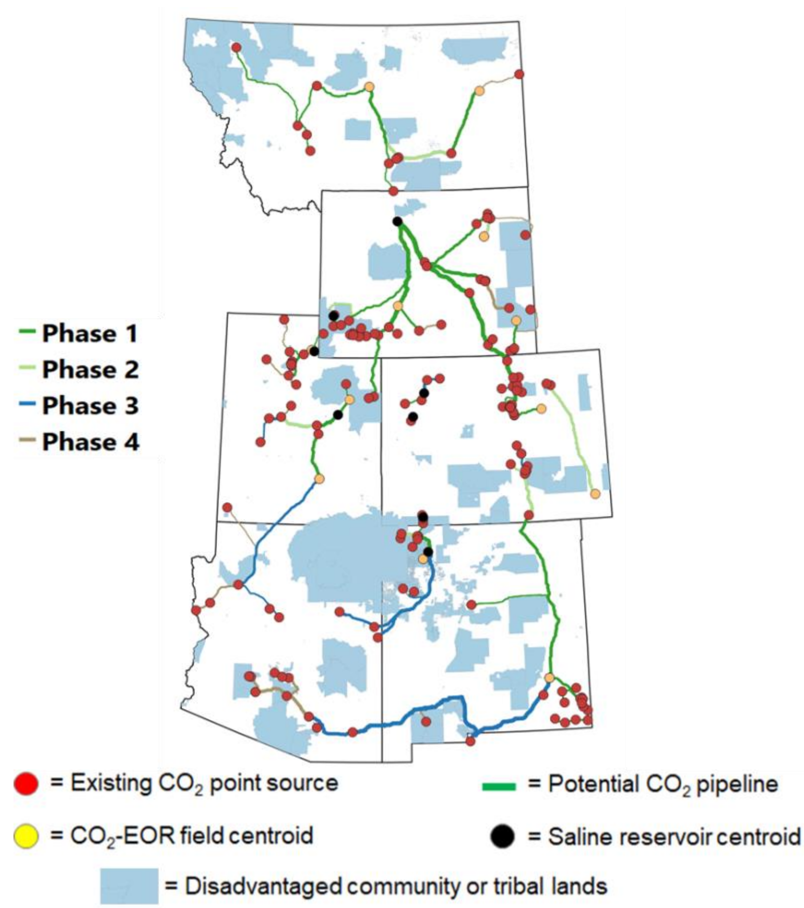

Figure 20. Phased pipeline network buildout connecting point sources and sinks

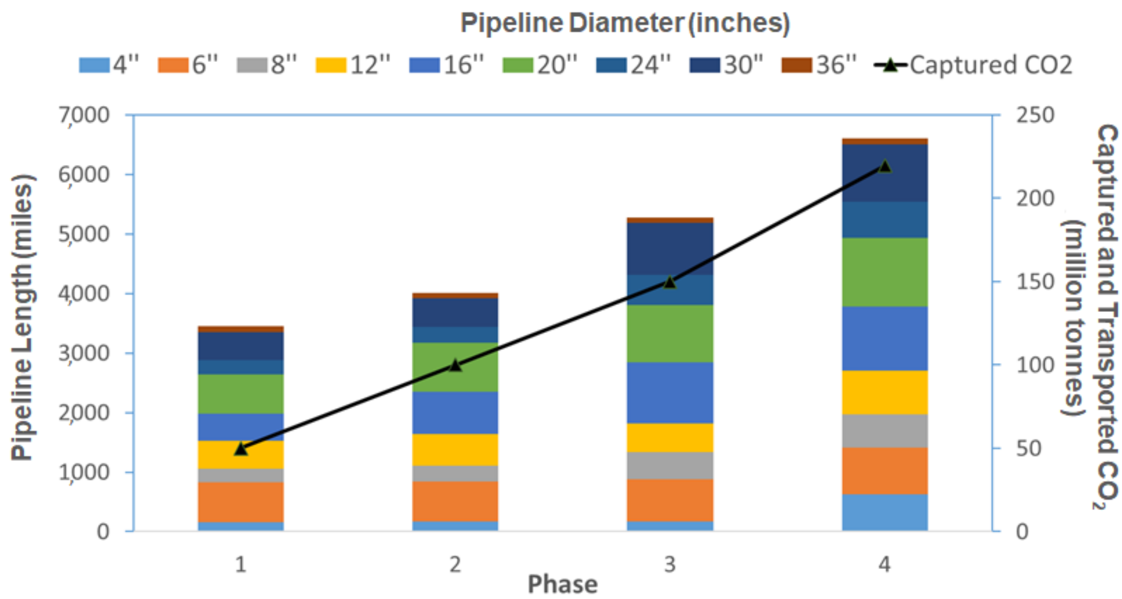

Figure 21. Pipeline length and annual CO_2 capture volume for each buildout phase

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).

$$E_t = E_p \frac{C_t S_t}{C_p S_p}$$ ***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.

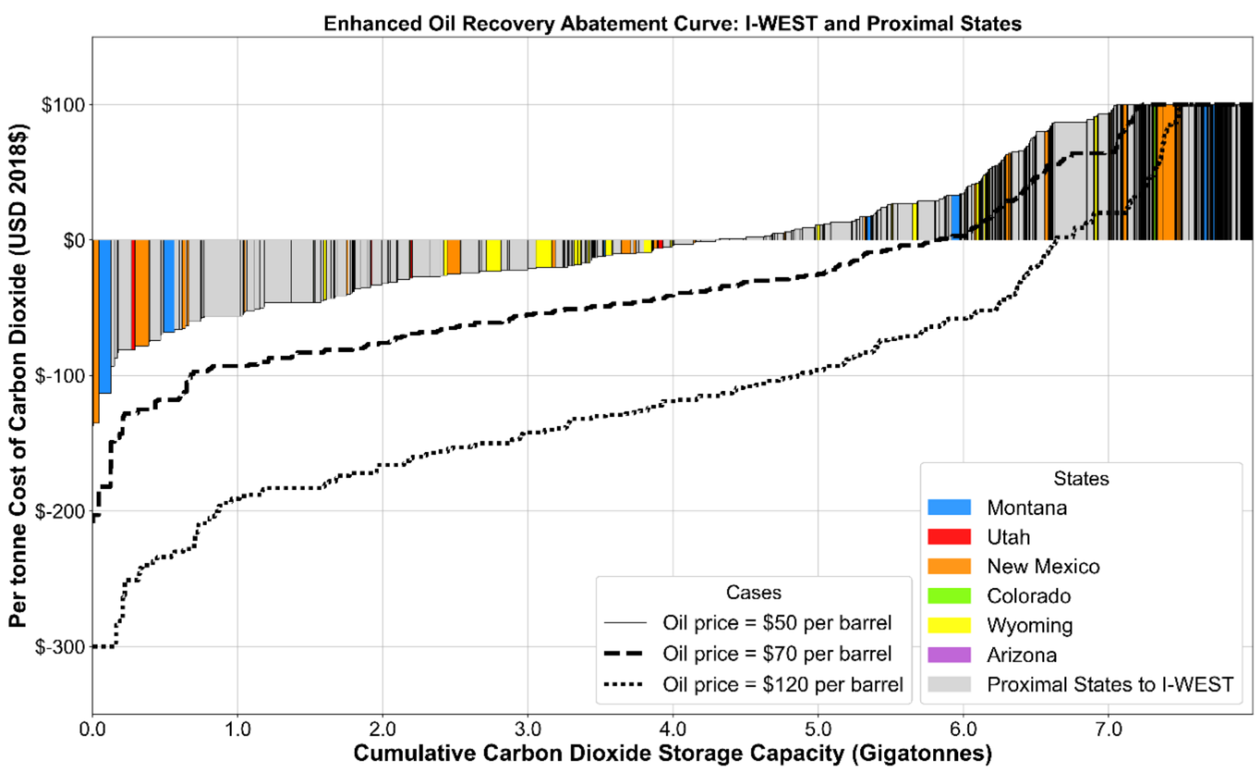


Figure 22. CCUS abatement curve applicable to CO_2-EOR in the region and proximal states

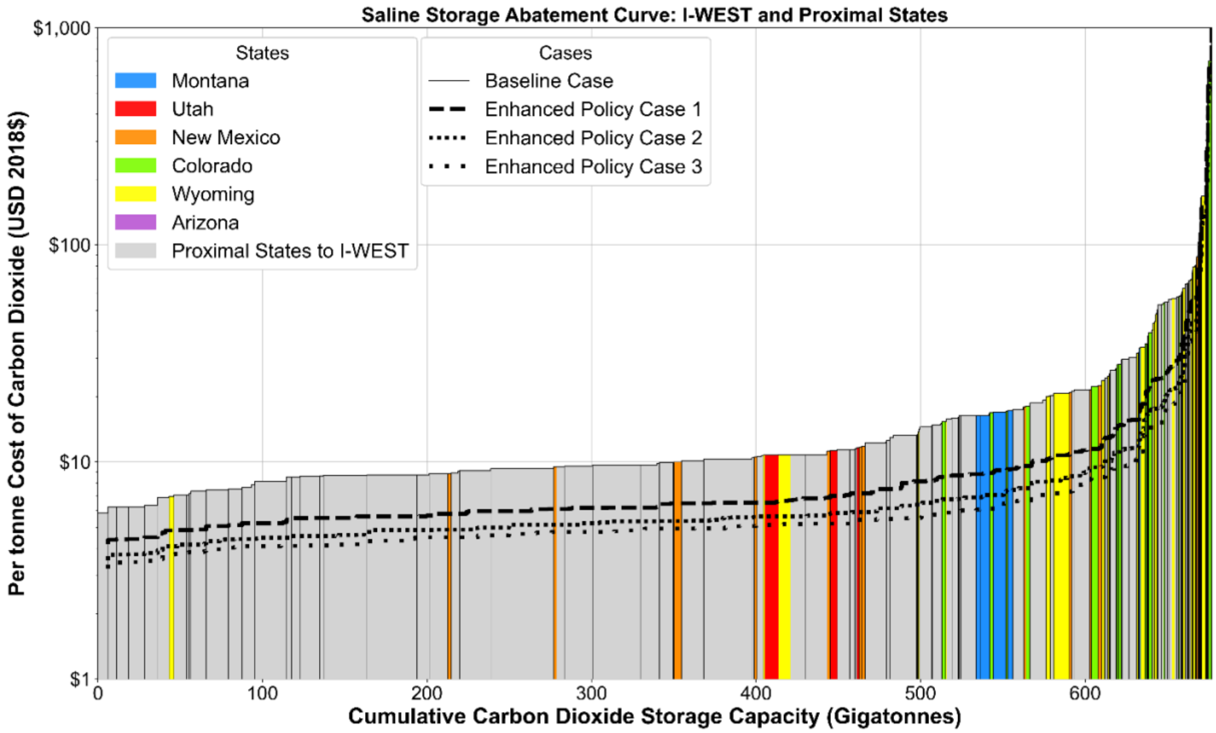


Figure 23. CCUS abatement curve applicable to saline storage resources in the region and proximal states

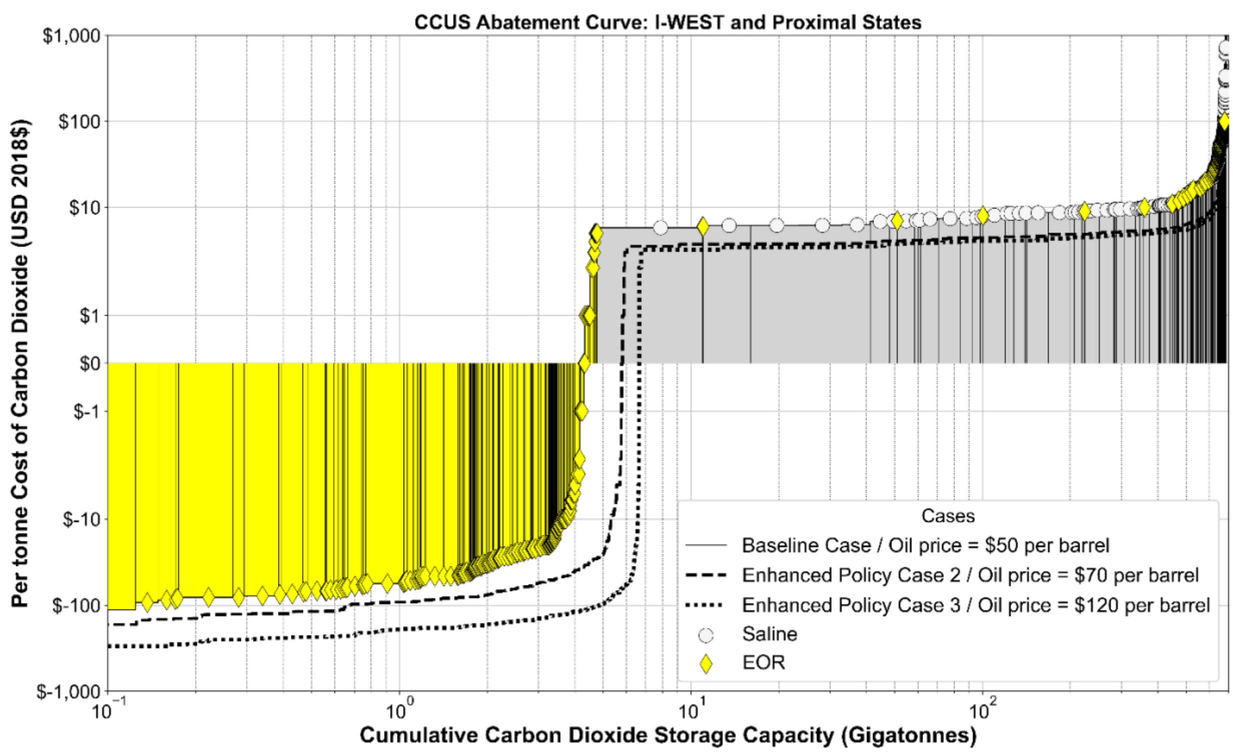
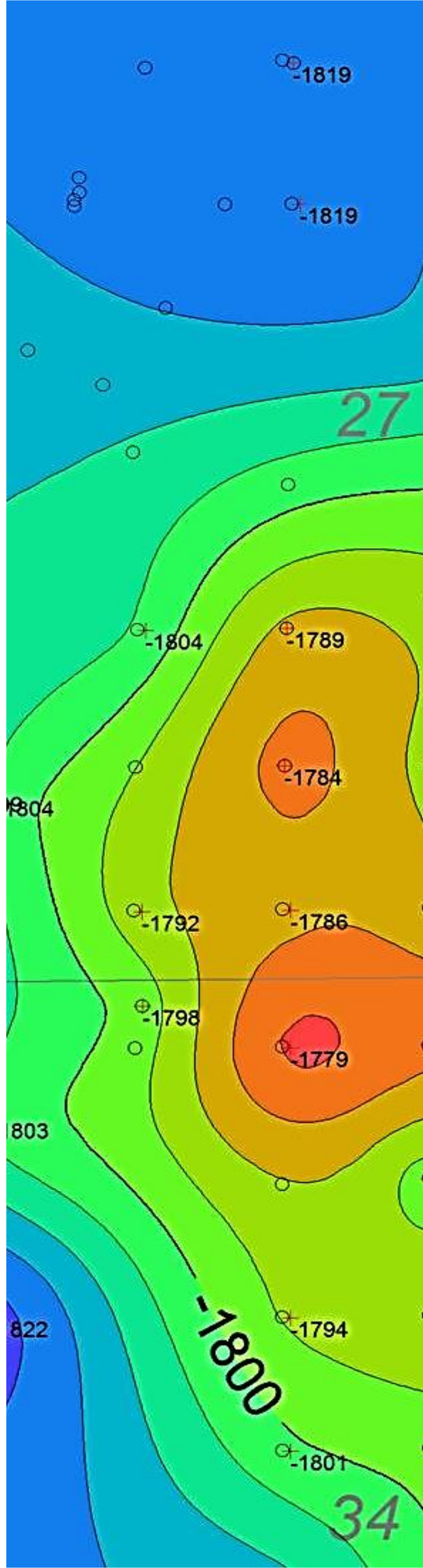


Figure 24. CCUS abatement curve that includes both saline storage and CO_2-EOR in the region and proximal states



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