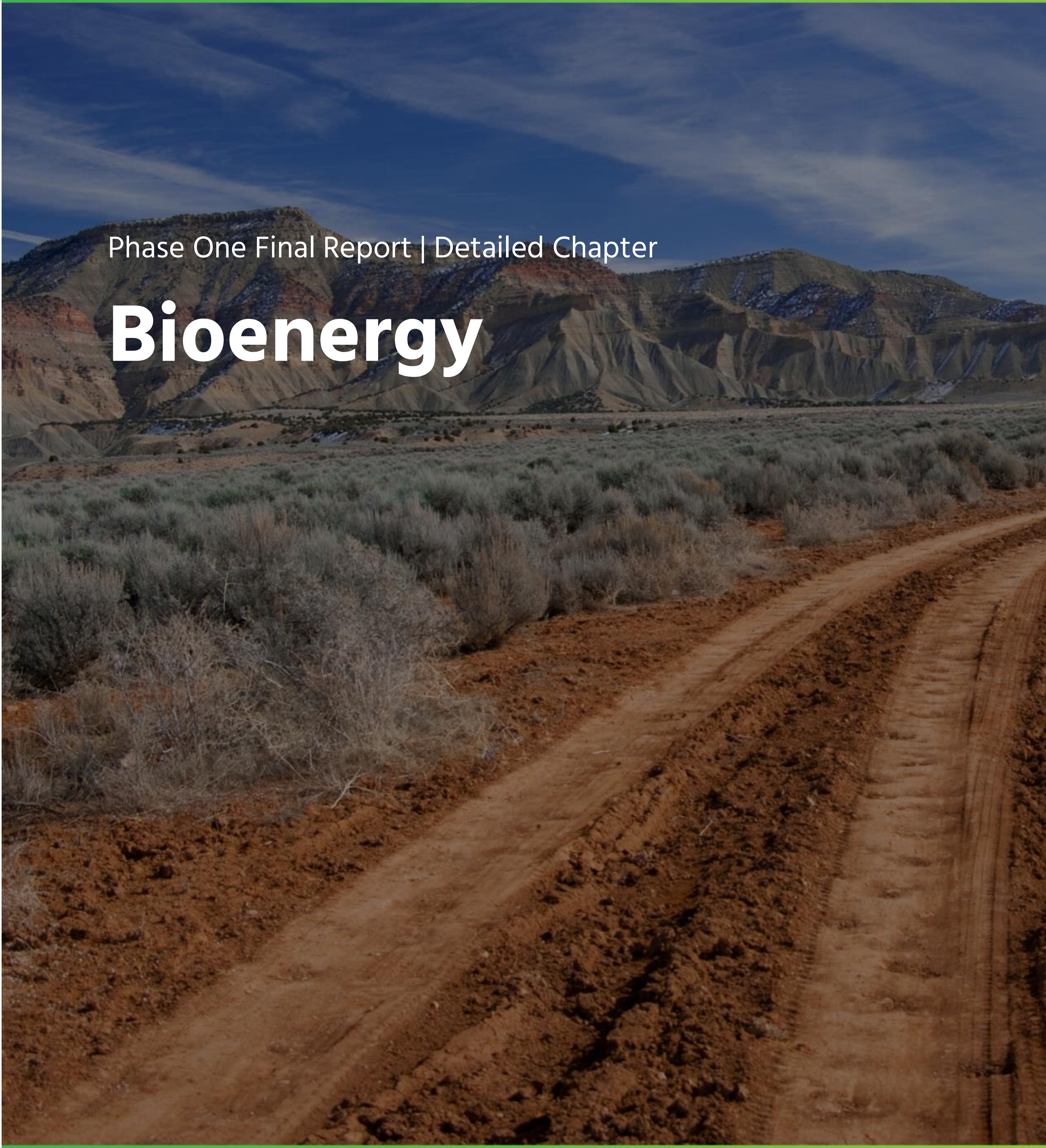
I-WEST



Phase One Final Report | Detailed Chapter

Bioenergy

VERSION 1.0

LOS ALAMOS NATIONAL 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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Summary

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

Key messages

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

Introduction

The bioenergy sector has symbiotic and synergistic relationships with other economies that can bring the Intermountain West to carbon neutrality: biomass and other organic wastes can be converted to electricity; bioenergy production from plants, plant products, and other photosynthetic organisms capture and utilize CO_2 to grow; and hydrogen can be produced by the gasification of biomass, or by microbial synthesis. The bioenergy sector is also synergistic with other economic sectors that are prevalent in the region, specifically forestry and agriculture, both livestock and plant-based crops. This synergy between the bioenergy economy and the agriculture and forestry economies distinguishes bioenergy from the other pathways addressed by I-WEST, but also introduces other factors. For example, growth of the bioenergy economy may compete for natural resources like clean water or land use. On the other hand, utilization of waste plant or forest material may benefit communities by adding value to their crops or reducing the risk of wildfires. Therefore, growing the bioenergy economy in the Intermountain West needs to be done in such a way that local communities and their existing economic interests are considered. Finally, with a large indigenous population in the region, cultural and traditional values may influence the response of the local community to growing the bioenergy economy.

In addition to synergies with electricity, hydrogen, and CO_2 economies, the bioenergy economy is closely linked to agriculture and forestry; for example, food crops, livestock, forests, or algae cultivation (Figure 1).

The production of power and fuels from biomass or waste carbon sources can play an important role as a low carbon source for our energy needs. Biomass or biogas can directly replace fossil feedstocks as a source of liquid transportation fuel or electricity. Biofuels produce 60% lower GHG emissions from light duty vehicles than fossil fuels, while cutting 99% of the most harmful pollutants [1]. Production of electricity from biomass or biogas can also reduce the carbon footprint of electricity production compared to the use of fossil feedstocks. Likewise, the use of biomass or waste carbon feedstocks in production of chemicals or materials can help to lower the carbon footprint of industry and building sectors, respectively. Finally, the agriculture sector can be made less carbon intensive, for example, by capturing and reutilizing biowastes for energy production or applying to soil to restore and sequester carbon.

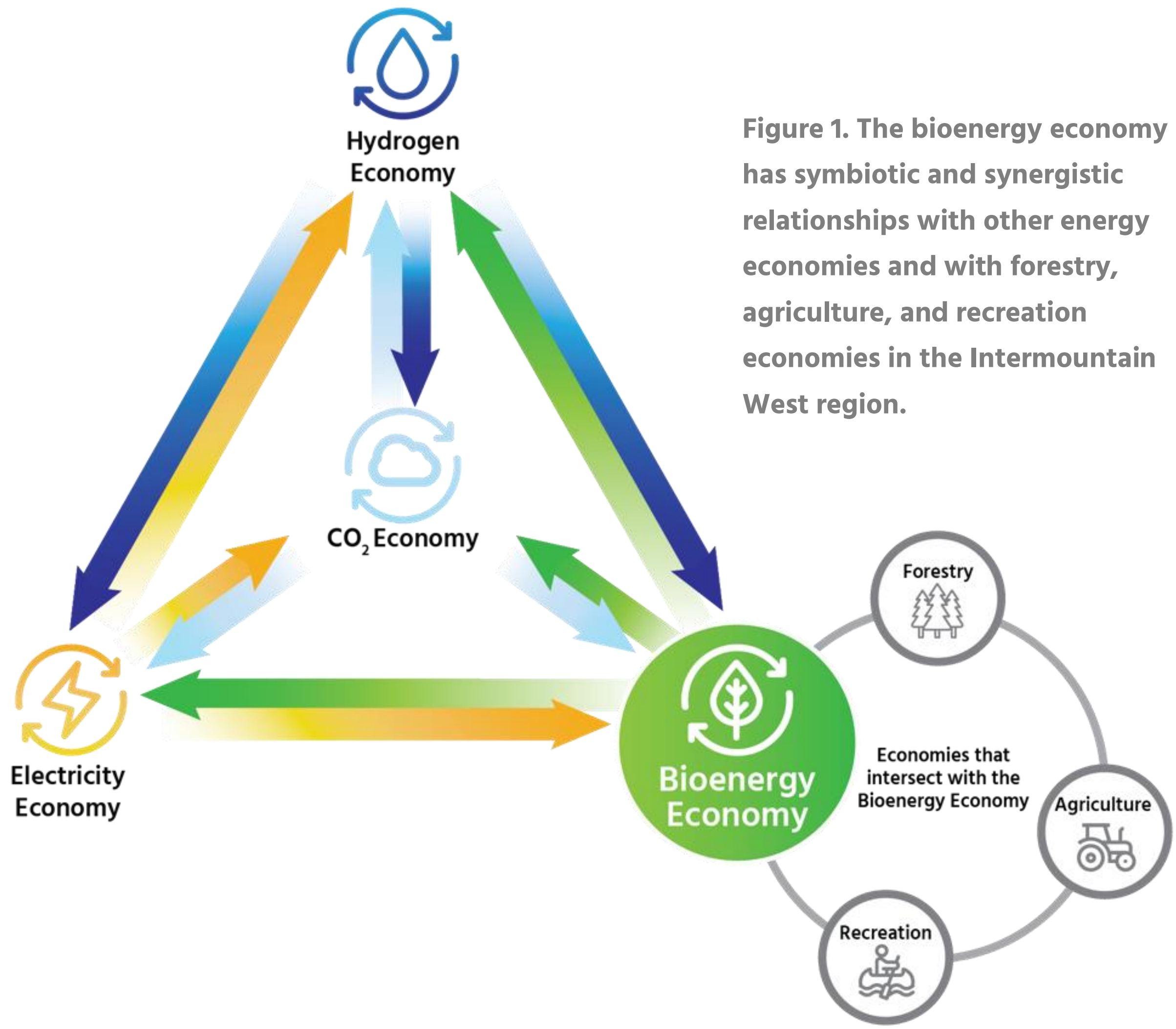

Figure 1. The bioenergy economy has symbiotic and synergistic relationships with other energy economies and with forestry, agriculture, and recreation economies in the Intermountain West region.

Bioenergy feedstocks

There is a wide range of options for feedstocks used for bioenergy: First-generation feedstocks, such as corn, are food crops and directly compete with food production for natural resources, including fresh water. Second-generation feedstocks are crop residues (corn stover), forest residues, mill residues, municipal solid waste, or other waste biomass or carbon sources that can be converted into energy. Third-generation feedstocks are microalgae. Fourth-generation feedstocks are other microorganisms, or genetically modified organisms (Figure 2).

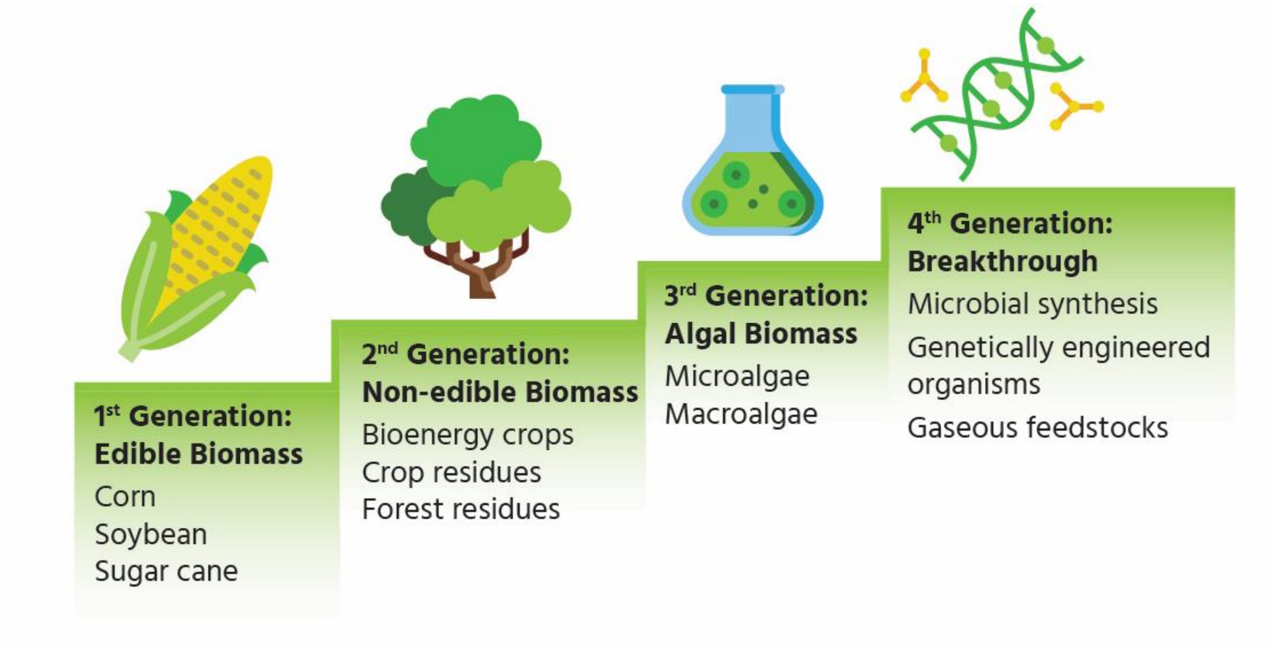

Figure 2. First, second, third, and fourth generation bio-feedstocks used for bioenergy production.

Bio-based energy can be utilized in many economic sectors where it can substitute for fossil-based energy sources and/or can help reduce greenhouse gas emissions in that sector. In transportation, biofuels can directly substitute for fossil fuels in internal combustion engines as drop-in replacements, or as blends with fossil fuels such as bioethanol blended with gasoline. In the electricity sector, renewable natural gas can be produced from organic wastes, such as biogas from manure, and blended with conventional natural gas. Bio-based fuels or biogas can also be used as a heat source for industry processes or for heating or energizing residential or commercial buildings. Finally, byproducts of bioenergy production such as biochar can be important sources of carbon to regenerate soils for agriculture. Our I-WEST analyses focused mainly on bioenergy for the electricity and transportation sectors.

The Intermountain West has high solar irradiance, which is essential for production of natural biomass resources. The region also has an abundance of unused land, including land that has been degraded by mining or oil and gas extraction or is otherwise non-arable. These unused lands may provide opportunities for growth of the bioenergy economy. For example, algae ponds or greenhouses could be built on such lands, and bioenergy byproducts such as carbon biochar or anaerobic digester solids could be used to restore soils for agriculture.

Existing bioenergy economy

Commercial production of bioenergy, biofuels, and related bio-waste or carbon-waste producing industries in the Intermountain West are shown in Figure 3 and Table 1.

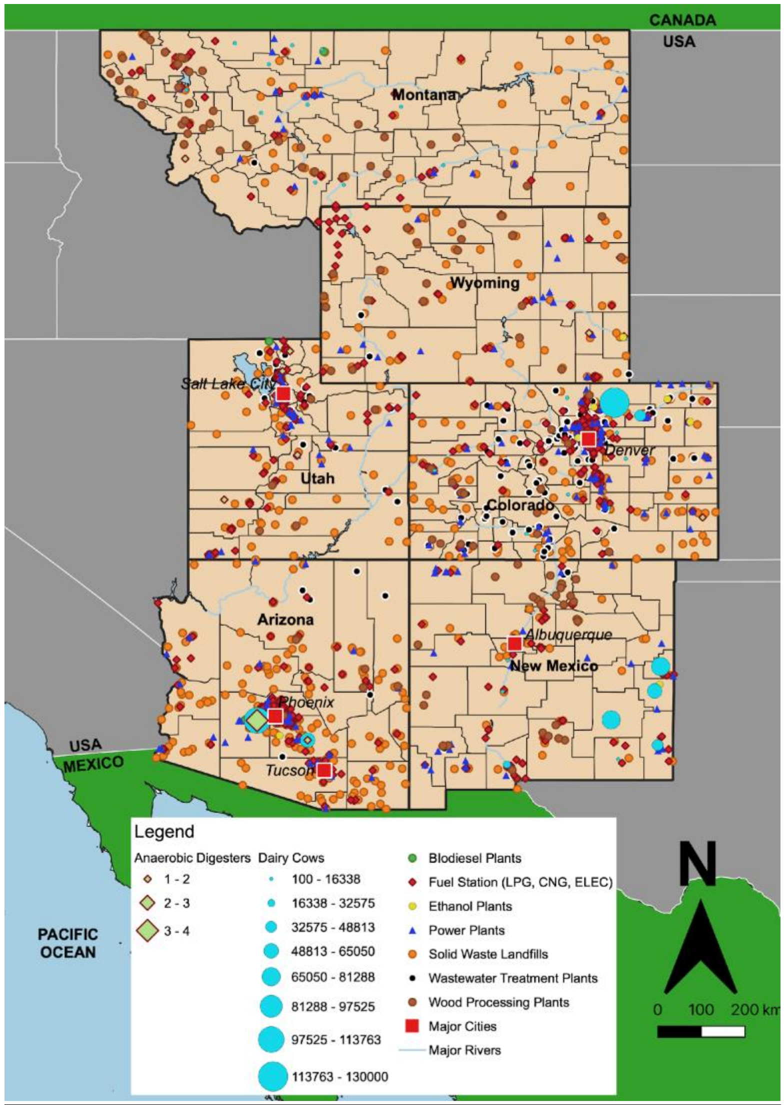

Figure 3: Industry locations in the region relevant to bioenergy and biofuels. Dairy cow and anaerobic digester data come from the U.S. Department of Agriculture [2] and the U.S. Environmental Protection Agency AgSTAR database [3], respectively. All other data comes from the U.S. Department of Homeland Security Homeland Infrastructure-Level Data (HIFLD) database [4].

Table 1: Data from Figure 3 tabulated by state and by industry								
State	**Anaerobic Digester Facilities**	**Dairy Cows**	**Ethanol Plants**	**Bio-diesel Plants**	**Alternative Fuel Stations (CNG, LPG, Electric)**	**Power Plants**	**Solid Waste Landfills**	**Wastewater Treatment Plants**
Arizona	5	194000	1	4	509	42	235	7
Colorado	1	202000	4	0	344	82	168	129
Montana	1	11000	0	1	59	24	66	2
New Mexico	0	292000	1	2	98	30	48	7
Utah	4	0	0	2	184	30	101	43
Wyoming	1	0	1	0	55	25	54	3

Regional biomass resources

Energy crop yield

For most of the region, the total energy crop yields are projected to increase when viewed at the county scale. At the state scale, when viewed as individual crops, the yields of grain crops appear to be slightly increased over time, whereas hay yields appear to decrease slightly over time. Figures 4-7 show crops and crop residue yields from the 2016 Billion Ton Report [5], projected for 2022, 2027, 2032, 2037 in map form for the Intermountain West. These data represent baseline scenario estimates, where the energy crops represented within each county are the same crops shown for state-level estimates in the bar graphs that follow in Figures 8-13.

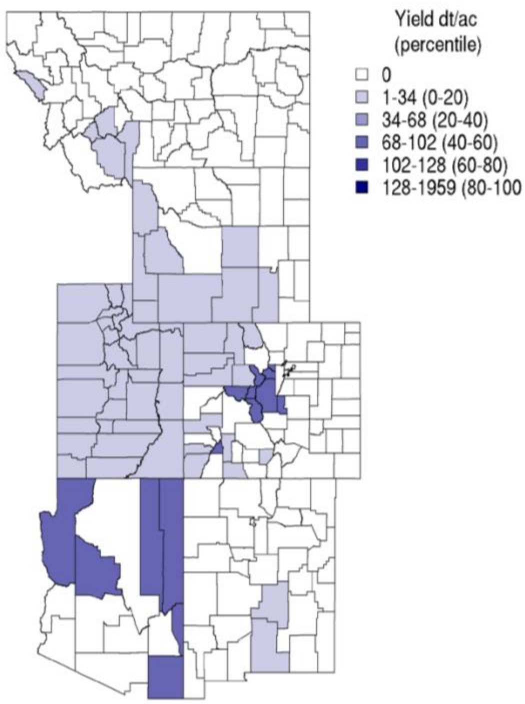

Figure 4. Total energy crop yield in 2022.

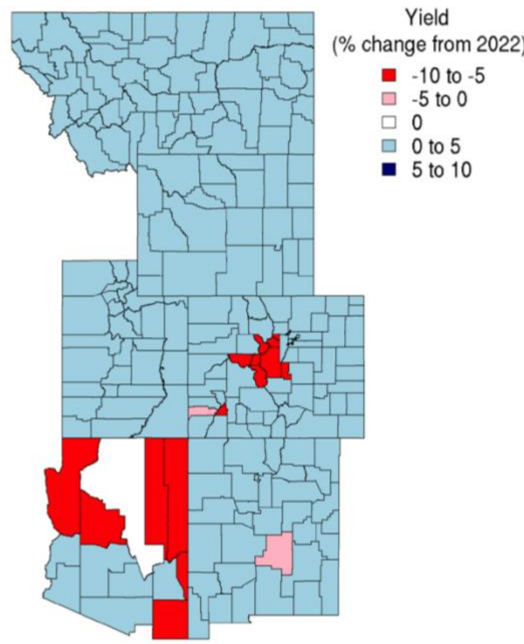

Figure 5. Total energy crop yield in the region projected in 2027.

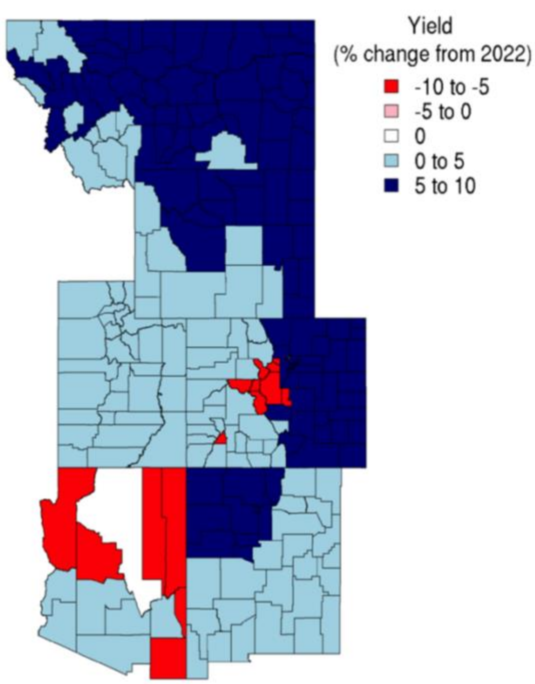

Figure 6. Total energy crop yield in the region projected in 2032.

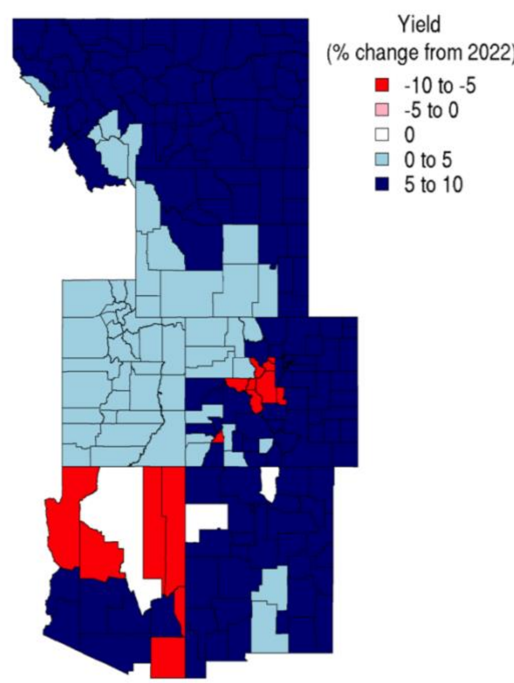

Figure 7. Total energy crop yield in the region projected in 2037.

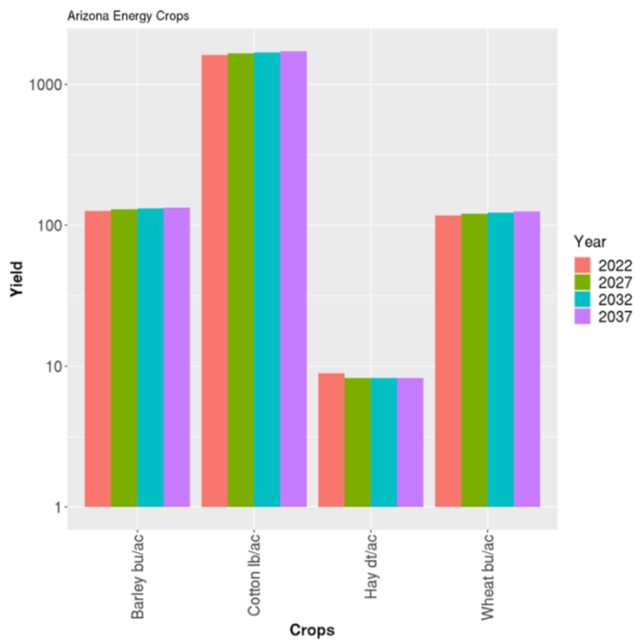

Figure 8. Energy crop yields in Arizona by type and by year.

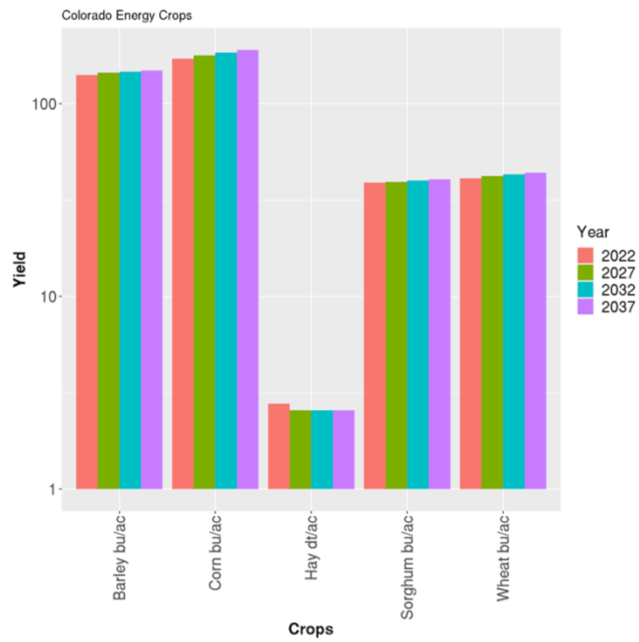

Figure 9. Energy crop yields in Colorado by type and by year.

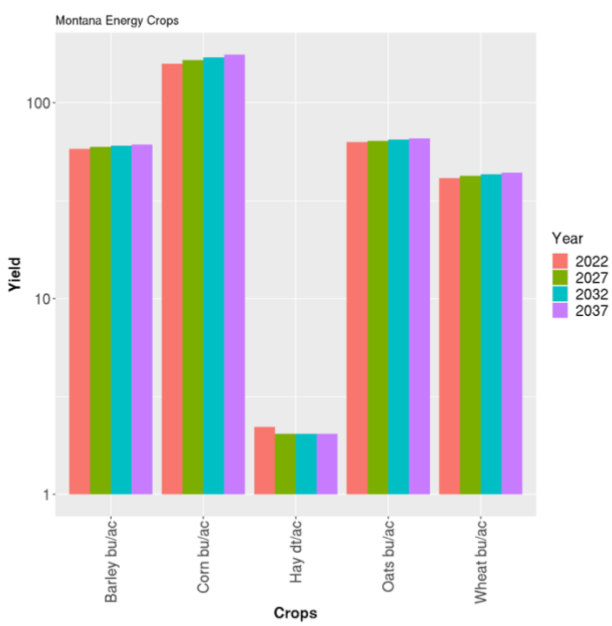

Figure 10. Energy crop yields in Montana by type and by year.

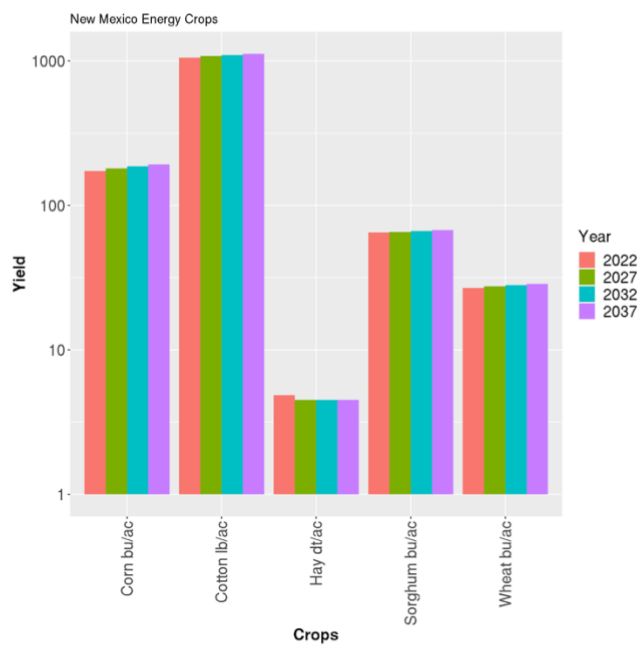

Figure 11. Energy crop yields in New Mexico by type and by year.

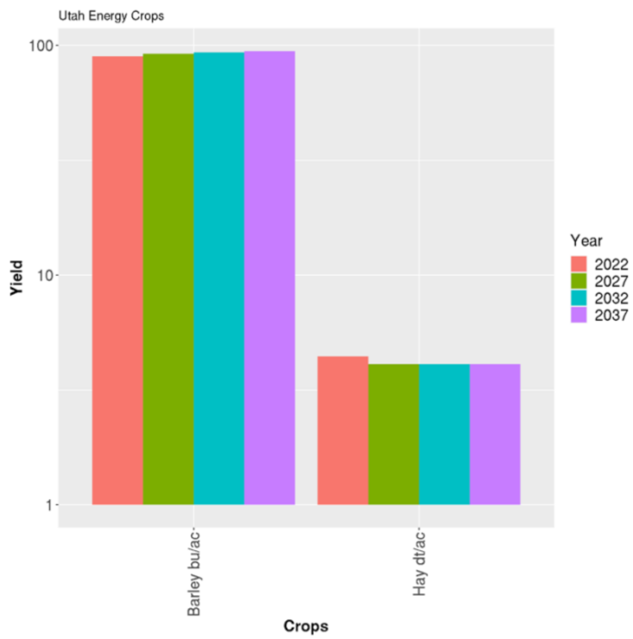

Figure 12. Energy crop yields in Utah by type and by year.

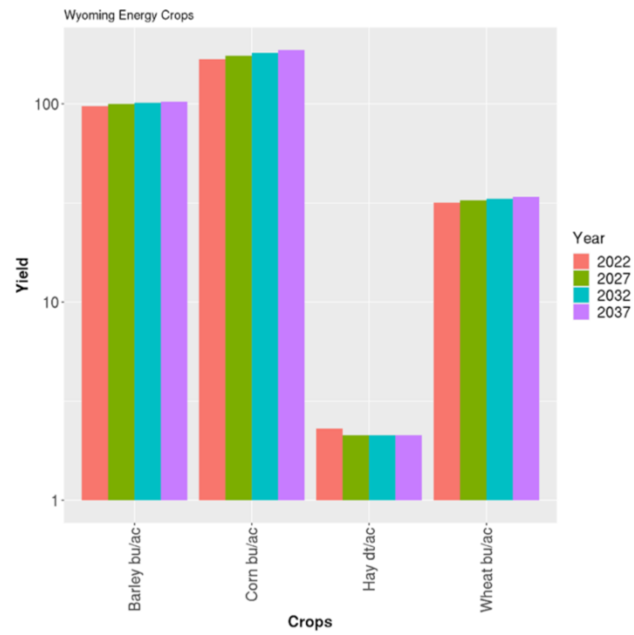

Figure 13. Energy crop yields in Wyoming by type and by year.

Forest Productivity

Forest residues, when viewed at the county or state level, appear to have variable production potential over time. Some areas in the Intermountain West are projected to have stable or slight net increases; other regions are projected to have decreased production potential over time. Figures 14-17 show forest residues from the 2016 Billion Ton Report [5], projected for 2022, 2027, 2032, 2037. These data represent "medium housing, medium energy demand" scenario estimates that assume a biomass price of $30. The forest resources represented within each county are the same resources shown for state-level estimates in the bar graph plots that follow in Figures 18-23.

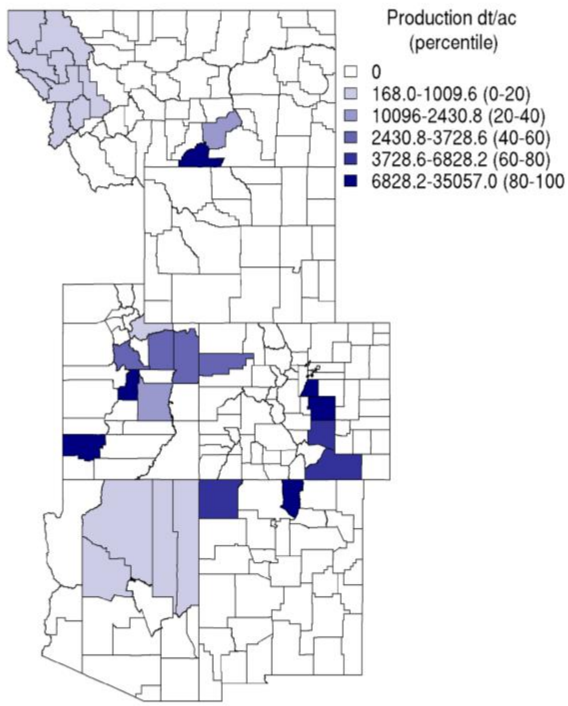

Figure 14. Total forest productivity in the region, by county, in 2022.

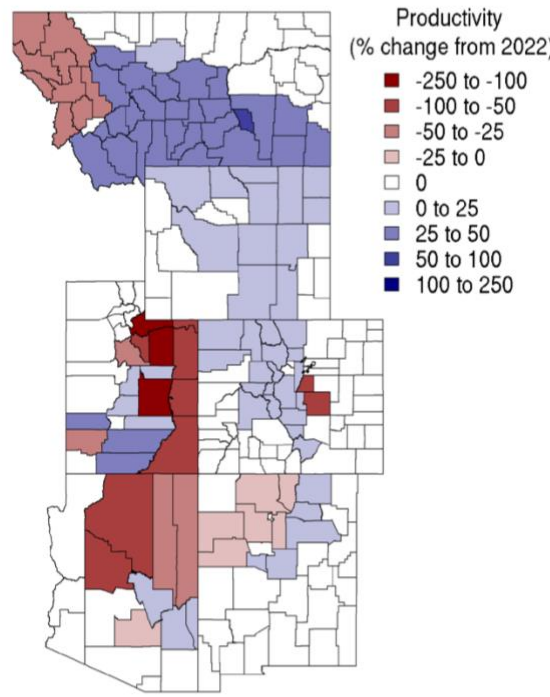

Figure 15. Total projected forest productivity in the region, by county, in 2027.

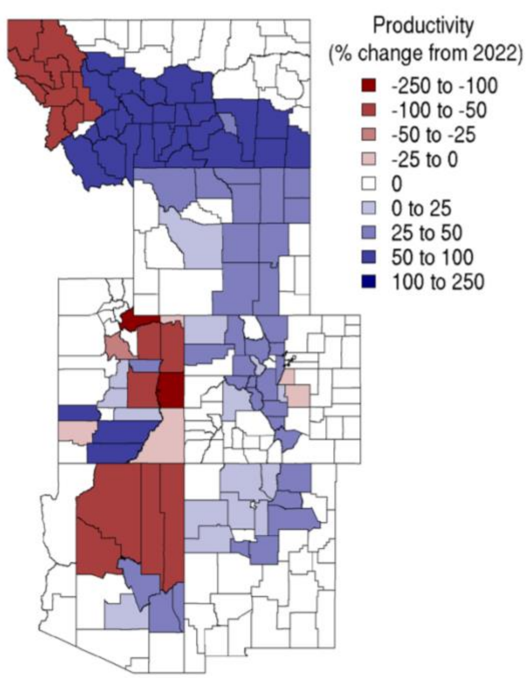

Figure 16. Total projected forest productivity in the region, by county, in 2032.

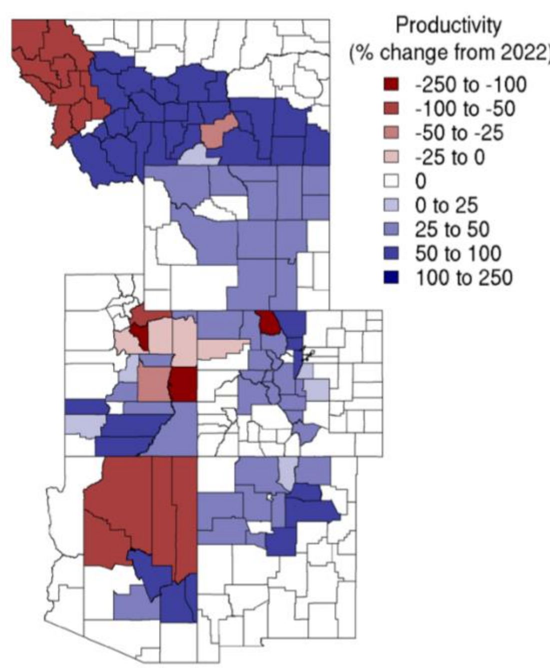

Figure 17. Total projected forest productivity in the region, by county, in 2037.

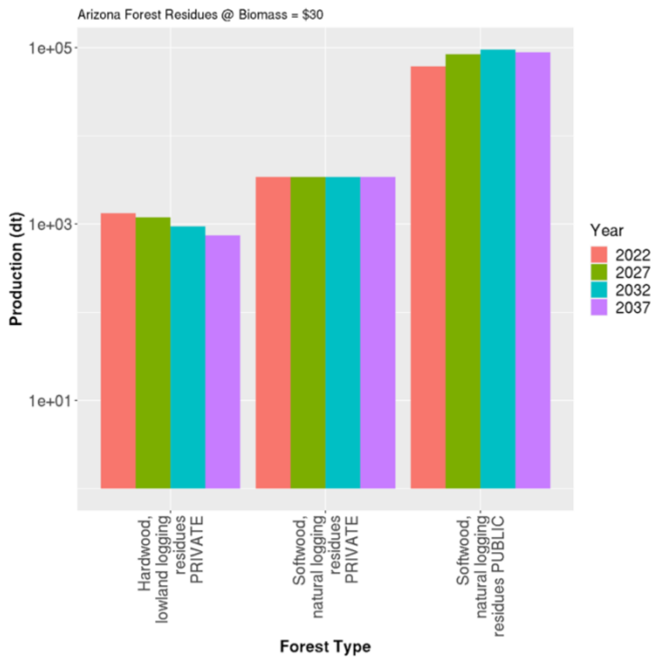

Figure 18. Total projected forest productivity in Arizona, by type and by year.

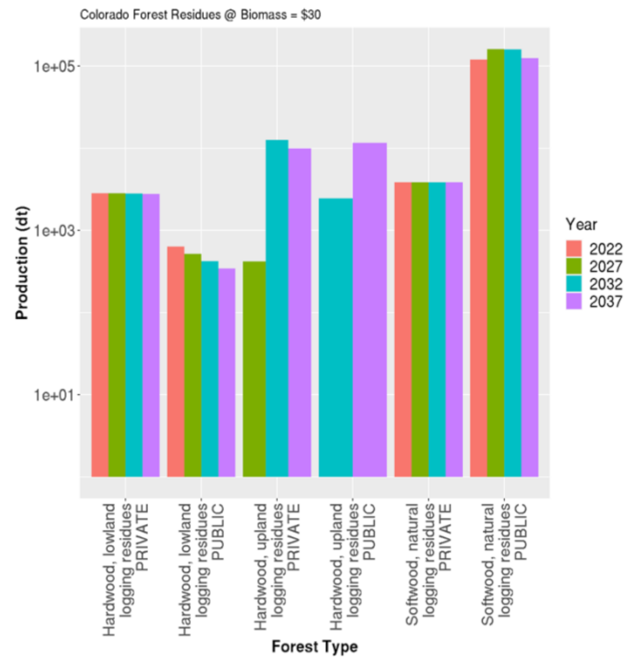

Figure 19. Total projected forest productivity in Colorado, by type and by year.

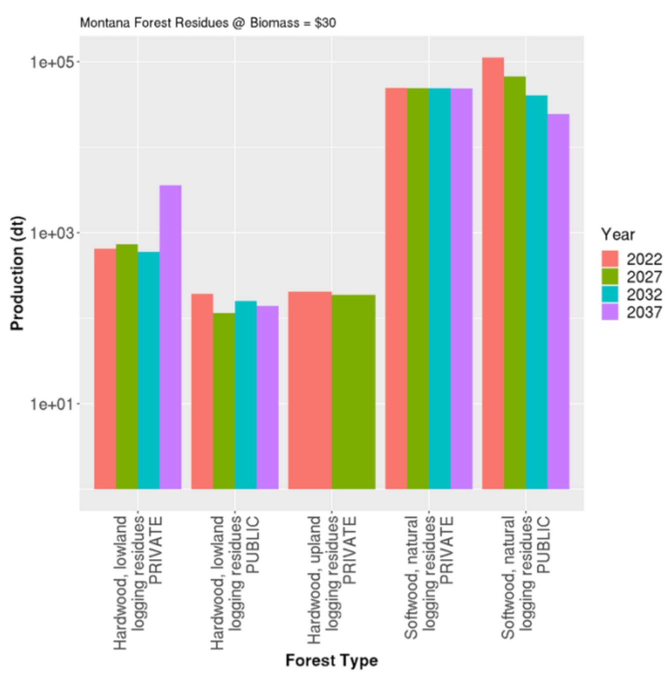

Figure 20. Total projected forest productivity in Montana, by type and by year.

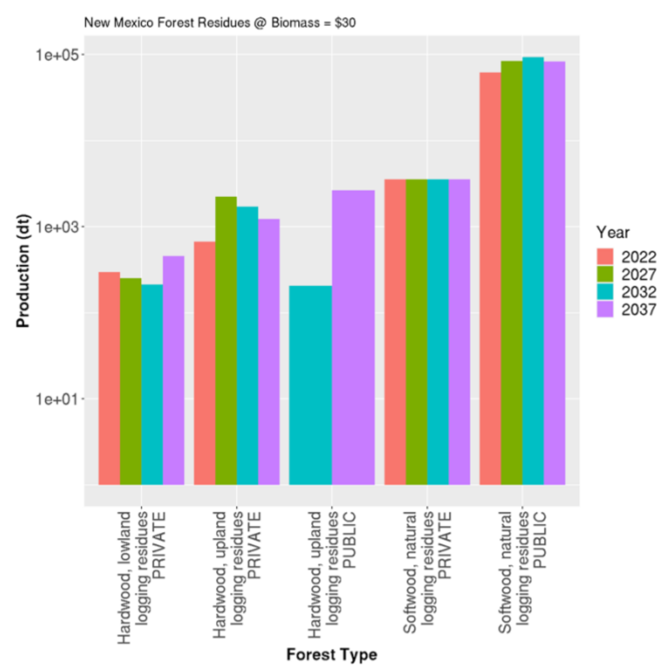

Figure 21. Total projected forest productivity in New Mexico, by type and by year.

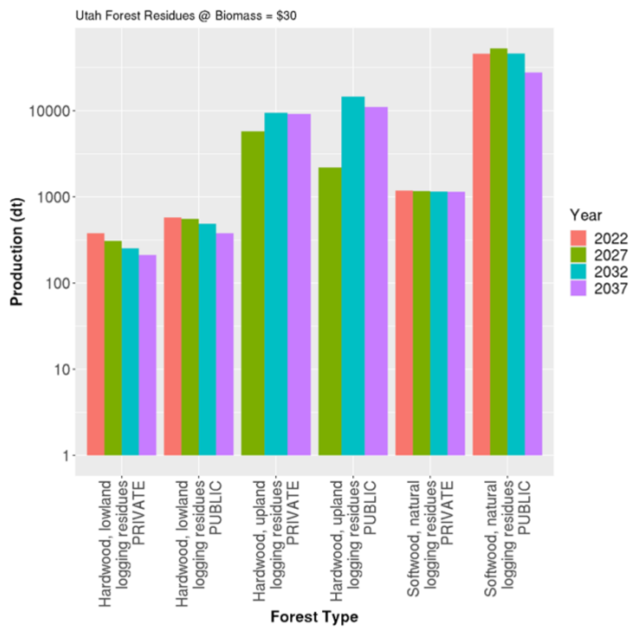

Figure 22. Total projected forest productivity in Utah, by type and by year.

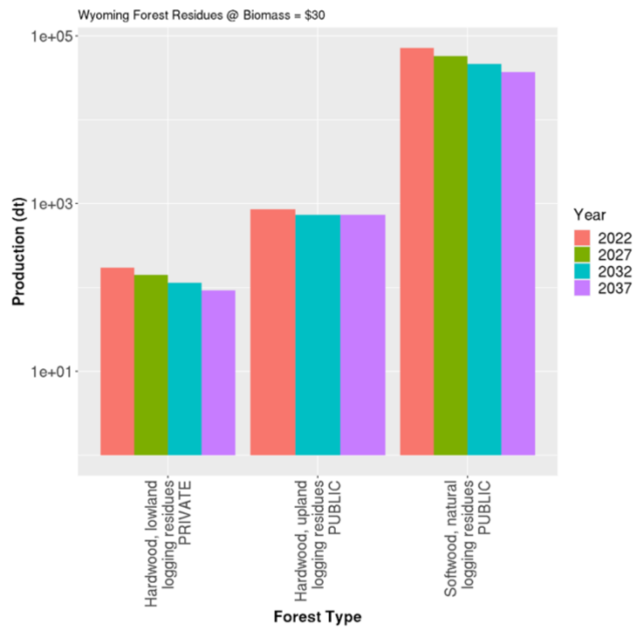

Figure 23. Total projected forest productivity in Wyoming, by type and by year.

Taking a closer look at forest residues available for bioenergy production across the Intermountain West, we would only want to consider the forest materials that are already disturbed (e.g., dead trees from natural events or from harvesting for land development or industry) rather than harvesting old, healthy growth.

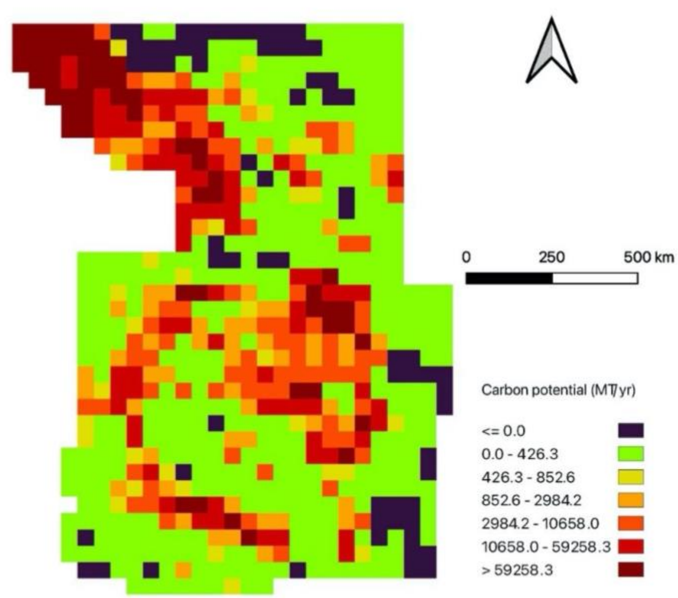

Figure 24. Distribution of forest residue (carbon potential) from all types of disturbances and forest management in the region.

Carbon potential from different types of disturbances is estimated based on data from 2000-2014 remote-sensing-based canopy cover loss [6]. We attributed disturbances to four categories (anthropogenic, fire, drought, and other) by combining multiple datasets from different sources and of various native spatial resolutions [7]. The drought and fire categories mainly refer to potential carbon availability from standing dead trees. For the anthropogenic category, the carbon availability could result from either selective harvesting, land use change, or forest management (e.g., thinning). The carbon potential is estimated based on the aboveground biomass for canopy trees. Using the attributed carbon potential, we clipped the national map to the Intermountain West region and estimated the carbon potential for energy use. The map shows a high potential for the northwest and central region with high forest carbon stocks. Figure 25 shows the distribution of the forest carbon potential by type of disturbance. Standing timber dead from fire has the highest carbon potential. If we assume only the zone with 100 meters radius accessible from roads, 35% of these disturbance forest carbon sources are accessible. The total potential accessible carbon for energy use from disturbed forest biomass is about 60 million tons per year for the region.

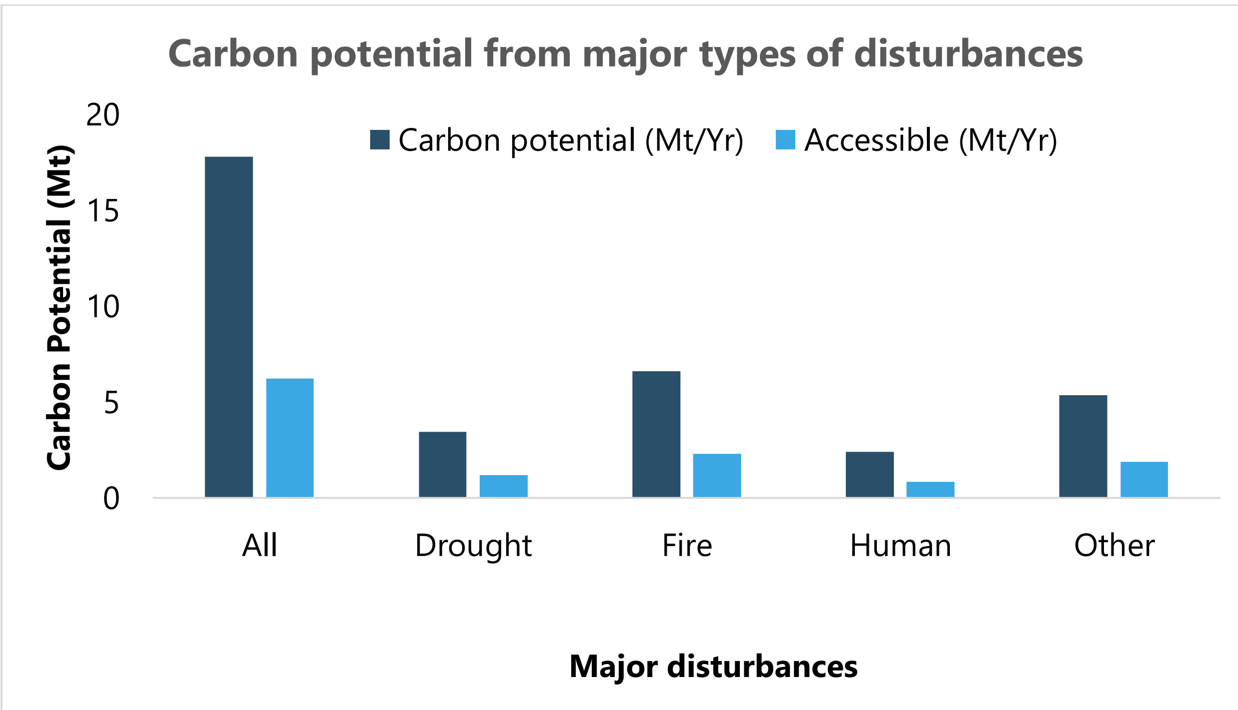

Figure 25. Summary of carbon potential (Mt/Yr) from different types of disturbances and forest management sources in the Intermountain West and the accessible potential (Mt/Yr) assuming a 100-meter radius accessible from roads.

Analysis of electricity potential and CO_2 emissions reduction potential from biomass

The Intermountain West has untapped potential for energy production based on biomass. We conducted an analysis on the potential for energy production (electricity production from biogas [8,9]) and CO_2 emissions reduction using actual observations—our results offer a projection of energy consumption and CO_2 emissions in 2030 and 2050. We did not take into account the effects of climate change on the availability of biomass. We also did not account for the efficiency of scale and GHG emissions of the transformation technologies utilized to convert the feedstocks to electricity, which varies by technology. For this analysis, we assumed that there is only one technology for each transformation pathway, and the yield is scale independent.

Biomass and bio-derived feedstocks considered in the analysis

Crop Residues. This includes harvested crop residues from corn, wheat, soybeans, cotton, sorghum, barley, oats, rice, rye, canola, dry edible beans, peanuts, safflower, sunflower, sugarcane, and flaxseed by county. The crop residues were estimated using total crop production , crop to residue ratio, and moisture content. It is assumed that only 35% of the total residue could be collected as biomass. The remaining portion is to be left on the field to maintain ecological and agricultural functions.

Urban Wood. Urban wood waste by county - wood material from MSW (wood chips and pallets), utility tree trimming and/or private tree companies, and construction and demolition sites. Data used is in dry metric tons/year.

Primary Mill. This field contains data on primary mill residues by county. Primary mill residues include wood materials (coarse and fine) and bark generated at manufacturing plants (primary wood-using mills) when round wood products are processed into primary wood products, such as slabs, edgings, trimmings, sawdust, veneer clippings and cores, and pulp screenings. This data illustrates the total amount of primary mill residues (used and unused) by county. Note that most of this resource is currently utilized. Data used is in dry metric tons/year.

Secondary Mill. Data for secondary mill residues by county (wood scraps and sawdust from woodworking shops — furniture factories, wood container and pallet mills, and wholesale lumber yards). Data used is in dry metric tons/year.

Forest Residues. This category includes logging residues and other removable material left after carrying out silviculture operations and site conversions, as well as harvesting timber for industrial products and domestic fuelwood. Logging residue consists of unused portions of trees, cut or killed by logging and left in the woods. Other removables are the unutilized wood volume of trees cut or otherwise killed by cultural operations (e.g. pre-commercial thinning) or land-clearing to non-forest uses. This data illustrates 65% of logging residues and 50% of other removals could be collected as biomass. The remaining portion is to be left on the field to maintain ecological functions. Data used is in dry metric tons/year.

Data sources used were from USDA census, 2012[10] and USDA Forest Service, 2012 [11].

Sources of biogas data used in the analysis

Methane generation potential from industrial, institutional, and commercial organic waste (in metric tons/year). This analysis estimates the methane generation potential from food manufacturing and wholesalers (e.g., fruit and vegetable canneries, dairy creameries, meat packing and processors, etc.), as well as institutional facilities such as hospitals, nursing homes, educational and correctional facilities. Data sources were the U.S. Census Bureau's County Business Patterns 2012 [12], and the Homeland Security Infrastructure Program (HSIP) 2012 [13], which is further processed to estimate the amount of these resources by county that were used.

Methane generation potential from animal manure (in metric tons/year). The following animal types were included in this analysis: dairy cows, hogs, and chickens (broilers). The methane generation potential was calculated by animal type and manure management system at the county level using data from the USDA, National Agricultural Statistics Service 2007 Census [10].

Methane generation potential from wastewater treatment (in metric tons/year). This analysis estimates the methane generation potential of wastewater treatment plants using methodology from the EPA's Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2011 [14], and data from the EPA Clean Watersheds Needs Survey (2008) [15].

Methane emissions from landfills (in metric tons/year). Methane emissions are estimated at each landfill considering total waste in place, status (open or closed), and waste acceptance rate using data from the EPA's EMOP database (as of April 2013) [16], and then aggregated to the county level. Note: this analysis includes "candidate" landfills only. EPA's Landfill Methane Outreach Program (LMOP) defines a candidate landfill as one that is accepting waste or has been closed for five years or less, has at least one million tons of waste, and does not have an operational or under-construction project; candidate landfills are also designated based on actual interest or planning.

Table 2: Total energy potential in the Intermountain West by state

(Biomass comprises crop, forest, mills, and urban landscaping residues.
Biogas is derived from manure, industrial/organic waste, wastewater, and landfills.)

State	total MWh	MWh from biomass	MWh from biogas
1 AZ	198.00	174.24	23.75
2 CO	358.85	349.36	9.49
3 MT	419.09	415.02	4.07
4 NM	71.33	53.82	17.51
5 UT	80.66	74.04	6.62
6 WY	42.62	40.62	2.00

Figures 26-34 below show the total electricity production potential from all types of biomass and biogas sources used in this analysis; followed by individual biomass and biogas sources, by county. Bio-feedstocks are crop residues, forest residues, urban wood, mills residues, and landscaping residues, as well as manure, industrial waste, wastewater, and landfill methane.

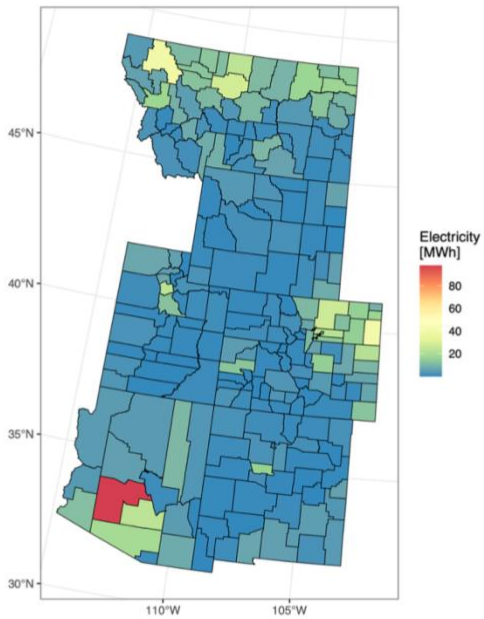

Figure 26. Electricity production potential from all types of biomass and biogas sources described above.

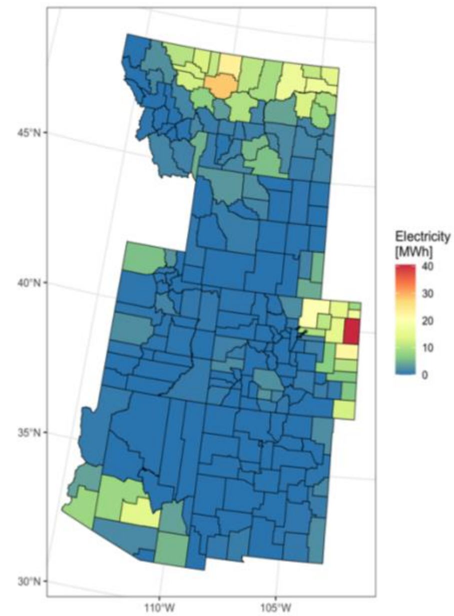

Figure 27. Electricity production potential from crop residues.

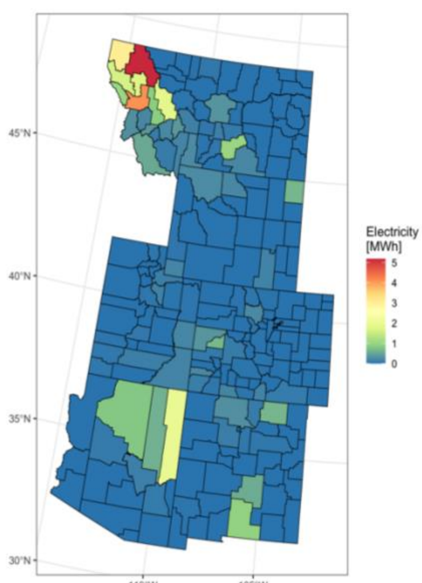

Figure 28. Electricity production potential from forest residues.

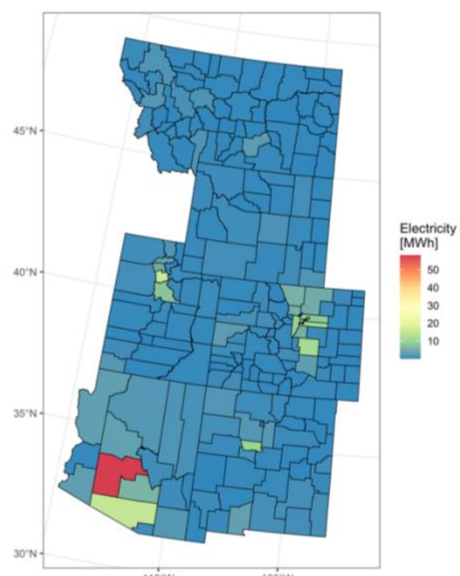

Figure 29. Electricity production potential from urban wood residues.

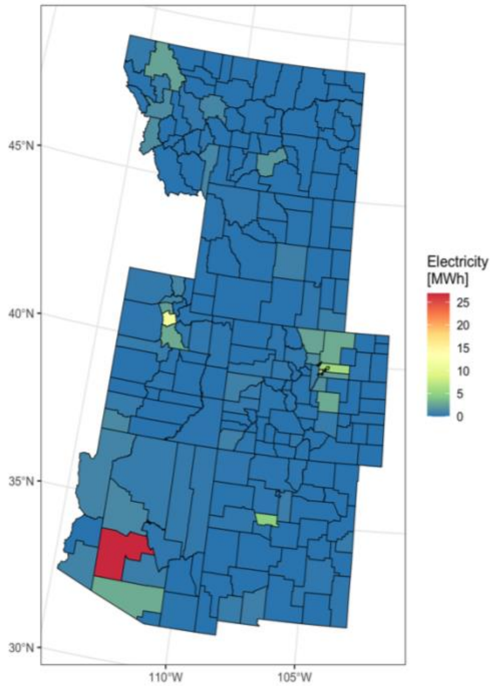

Figure 30. Electricity production potential from primary and secondary mills residues.

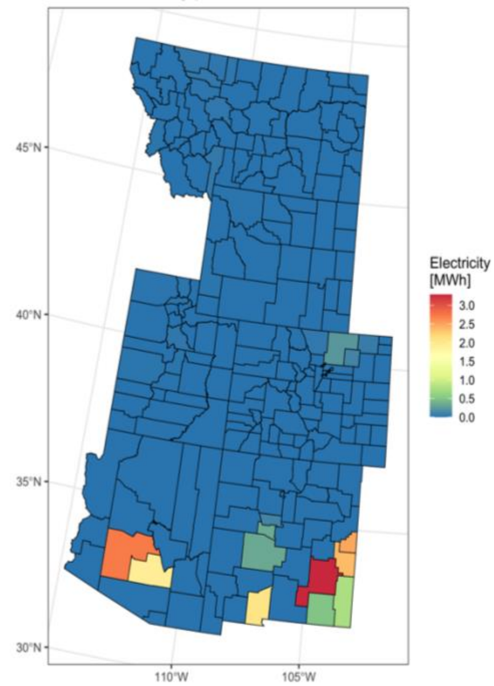

Figure 31. Electricity production potential from biogas sourced from manure.

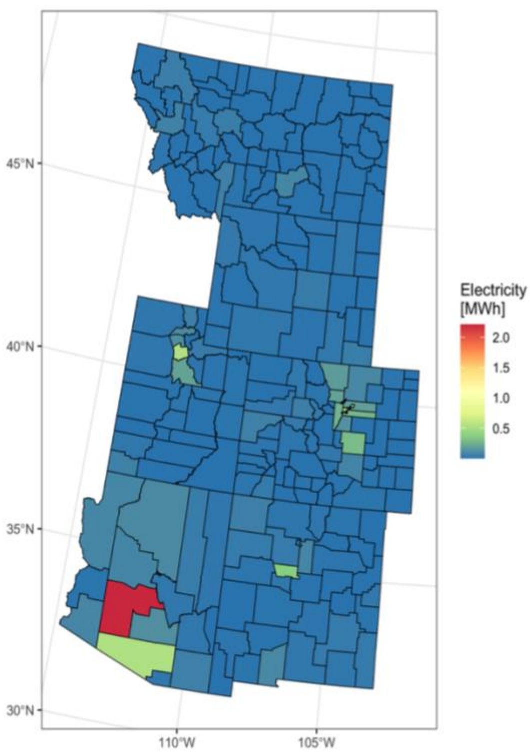

Figure 32. Electricity production potential from biogas sourced from industrial organic waste.

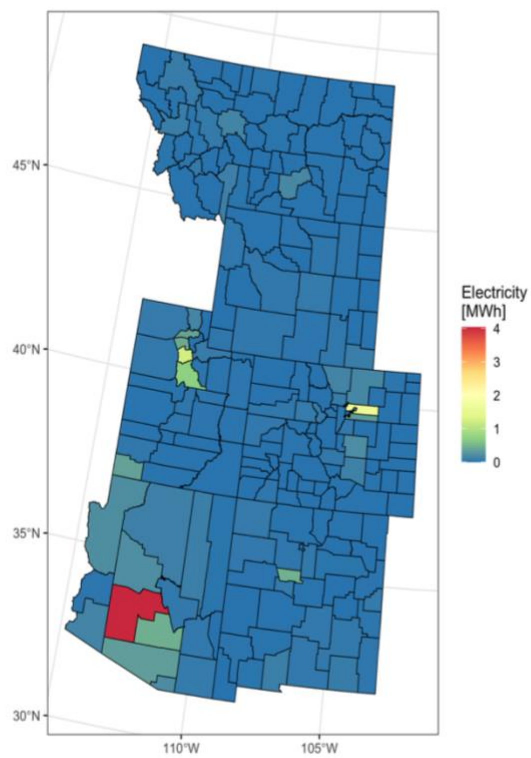

Figure 33. Electricity production potential from biogas sourced from wastewater treatment plants.

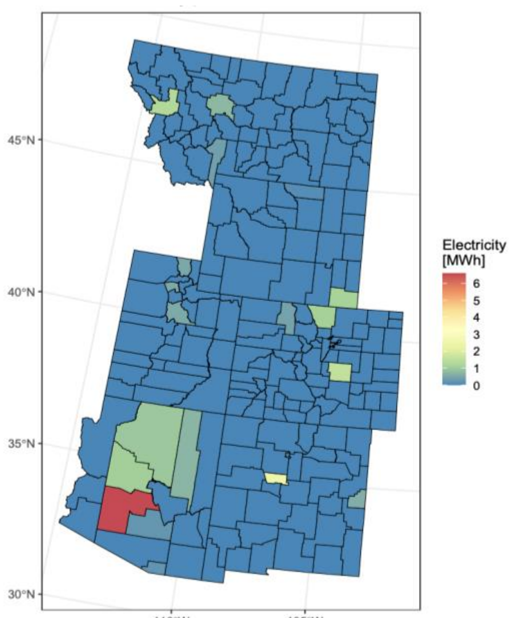

Figure 34. Electricity production potential from biogas sourced from landfills.

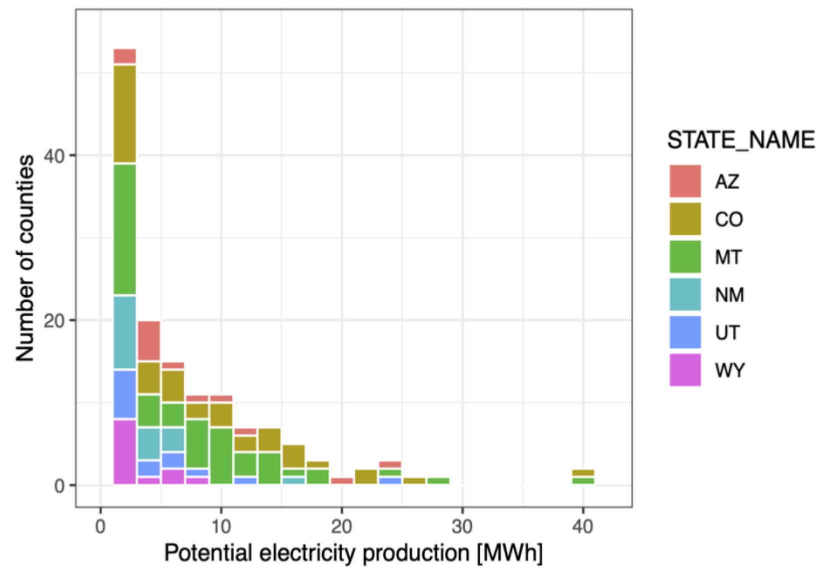

Figure 35: Bio-feedstock energy production potential by county. Maricopa county, Arizona, is not included in the plot for readability (97.6 MWh of energy production potential from bio-feedstocks).

Table 3. State-level availability of the most abundant bio feedstocks (forest residues of all types, and crop residues), in dry tons per year

State	Crop residues	Urban wood residues	Mills residues	Forest residues	Forest disturbances residues
Arizona	362,771	773,045	210,675	29,127	390,565
Colorado	1,745,954	731,841	260,815	19,557	876,606
Montana	2,301,657	156,792	626,644	191,386	536,442
New Mexico	69,595	253,233	80,136	21,971	397,981
Utah	123,447	333,687	118,522	8885	216,832
Wyoming	149,327	90,721	68,582	12,028	284,202

Microalgae for energy production Outdoor cultivation of microalgae is a viable process in parts of the Intermountain West, particularly in the southern parts of Arizona and New Mexico where the growing season can be longer [17]. A number of studies have analyzed the potential supply of algae biomass and biofuel in different geographic regions of the U.S., with particular focus on water availability [18-20] as well as suitable terrain [5].

Microalgae produce lipids, which can be converted to a "drop-in" biofuel (fuel that is chemically similar to fossil-based fuel). In addition, certain species of algae or cyanobacteria can be very robust in outdoor cultivation systems. They can utilize saline or brackish water, thereby reducing or eliminating freshwater use in cultivation. They also can be grown using point source or direct air captured (DAC) CO_2 as a carbon source. Analysis of co-location potential of stationary CO_2 sources with algae cultivation—ethanol plants, coal electric generating units (EGUs), and natural gas EGU sites in proximity to CO_2 distribution pipelines [21]—were addressed in the 2016 Billion-Ton Report [5] and other studies [22]. Based on temperature and length of growing season alone, southern Arizona and southern New Mexico are the most suitable locations for commercial algae cultivation using open ponds. However, at this time there are only a handful of commercial algae production sites in those states. The theoretical potential for algae cultivation in the region is high Figure 36 illustrates this untapped potential even using currently accepted open outdoor cultivation ponds and marine strains of algae.

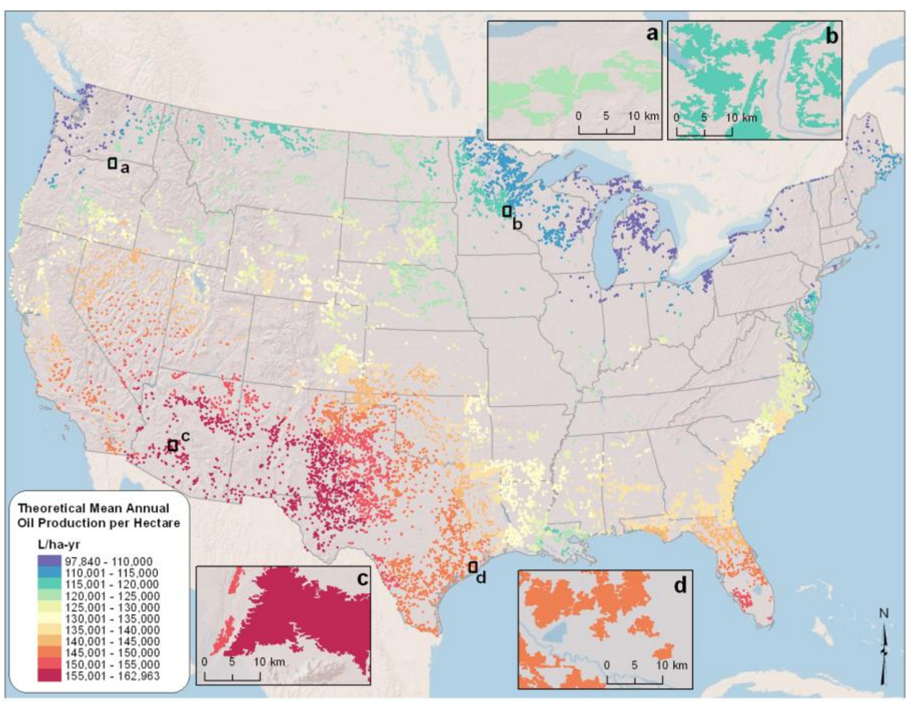

Figure 36. Mean annual theoretical maximum biofuel production (L ha−1 yr−1) plotted at the centroid of each pond facility. Insets illustrate underlying detail at the pond facility (490 ha) scale [18].

Microalgae can also be grown in indoor systems, greenhouses, and specialized photobioreactors that can be temperature and light controlled, much like industrial fermentation systems. The ability to grow algae in indoor reactors allows for algae cultivation systems to be deployed more widely. Attached or biofilm-based [23] growth systems are also possible and are used to efficiently filter water in wastewater treatment facilities. The company Clearas in Montana uses microalgae as a “filter” to treat municipal wastewater. The algae biomass can be harvested periodically and sold to companies that process the biomass for use in materials such as polymers.

Analysis of reducing CO_2 emissions from bioenergy production with biomass and biogas

In this section, analysis was conducted to project the potential reduction in CO_2 emissions in the Intermountain West from biomass and biogas utilization for bioenergy production: electricity or bioethanol production. Biomass comprises forest, residues, crop residues, urban, and mill residues. Sources of biogas are animal manure, organic waste, wastewater treatment, and landfills.

CO_2 emission reduction by use of biofeedstocks for electricity production

Table 4. State level EPA estimates of CO_2 equivalent emissions in lbs/MWh for electricity production

State	CO_2 2015	CO_2 2030	CO_2 2050
1 Arizona	734.20	903.07	1074.40
2 Colorado	1212.20	1508.62	1952.90
3 Montana	905.70	1014.04	1308.30
4 New Mexico	1252.80	1366.98	1494.03
5 Utah	1554.90	2028.70	2945.58
6 Wyoming	1975.60	2039.41	2244.57

Figures 37-39 show the CO_2 emissions reductions at the county level for 2015, 2030, and 2050 when bio-feedstocks are used for electricity production.

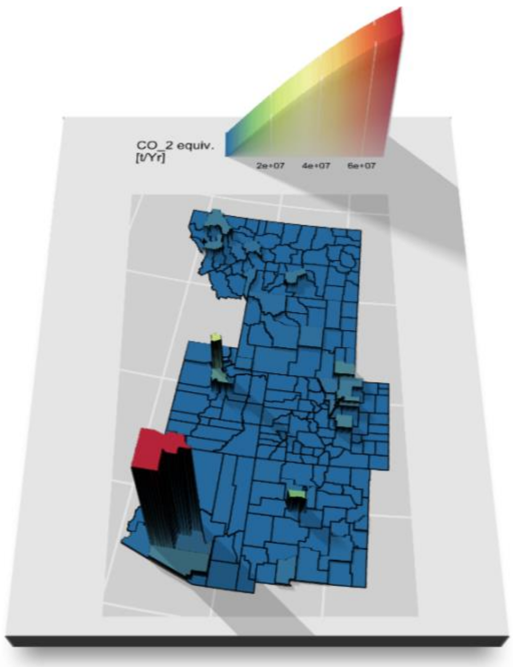

Figure 37. Electricity production. County-level potential CO_2 reduction from the use of biomass and biogas, using 2015 electricity consumption levels.

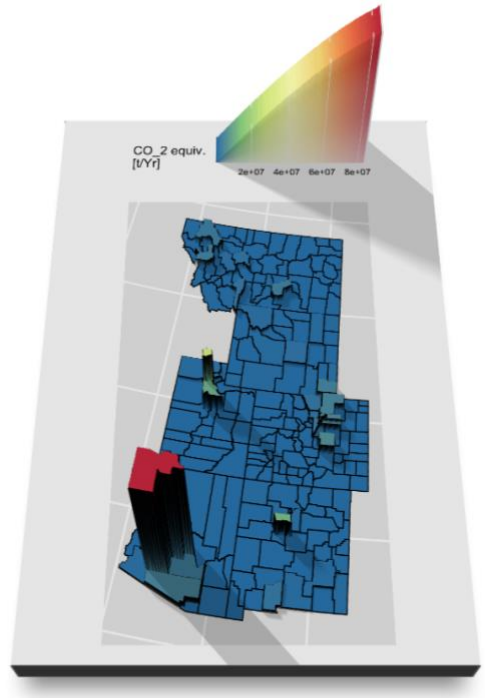

Figure 38. Electricity production. County-level potential CO_2 emissions reduction from the use of biomass and biogas, using 2030 electricity consumption levels.

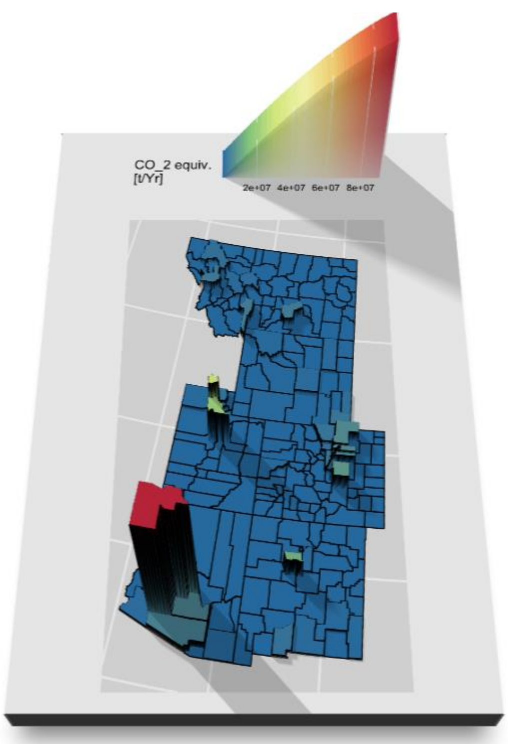

Figure 39. Electricity production. County-level potential CO_2 reduction from the use of biomass and biogas, using projected 2050 electricity consumption levels.

Table 5 shows the top 20 counties in the region with the highest potential for CO_2 reduction by using biofeedstocks for electricity production. The growth potential represents the increase of CO_2 reduction in 2050 relative to 2015. A positive growth value indicates a likely higher return on the investment.

Table 5. Counties with highest potential for CO_2 reduction from biofeedstock use in electricity production			
County	**State**	**Reduction growth**	**CO_2 Reduction 2015**
1 Maricopa	AZ	0.31	15883219.36
2 Salt Lake	UT	0.34	5016676.17
3 Bernalillo	NM	0.20	2361439.42
4 Utah	UT	2.47	1341675.47
5 Laramie	WY	-0.34	904949.08
6 Adams	CO	0.42	900272.08
7 Denver	CO	0.11	843157.08
8 El Paso	CO	1.38	827050.57
9 Pima	AZ	0.41	771329.40
10 Arapahoe	CO	0.63	688987.20
11 Flathead	MT	-0.43	677968.40
12 Missoula	MT	0.22	630611.06
13 Weld	CO	1.31	615262.35
14 Yellowstone	MT	0.60	517068.32
15 Jefferson	CO	0.14	483802.61
16 Davis	UT	0.63	450605.71
17 Pinal	AZ	2.29	369951.74
18 Dona Ana	NM	0.52	311068.33
19 Cascade	MT	-0.18	281017.71
20 Larimer	CO	0.84	279932.66

Table 6: CO_2 equivalent reduction from offsetting electricity produced using fossil fuel with electricity produced from biomass and biogas			
State	CO_2 2015 [t/Yr]	CO_2 2030 [t/Yr]	CO_2 2050 [t/Yr]
Arizona	75936897	92112367	103315691
Colorado	22842477	29169142	38370793
Montana	12211033	13519026	15994909
New Mexico	14521818	16581623	18132568
Utah	32520079	42064782	57664288
Wyoming	8282999	8236355	8264697
IWEST Total	160 MillionMT/y		
Cumulative: 2022-2050= 6000 MT (6GMT) 6x 10^9			

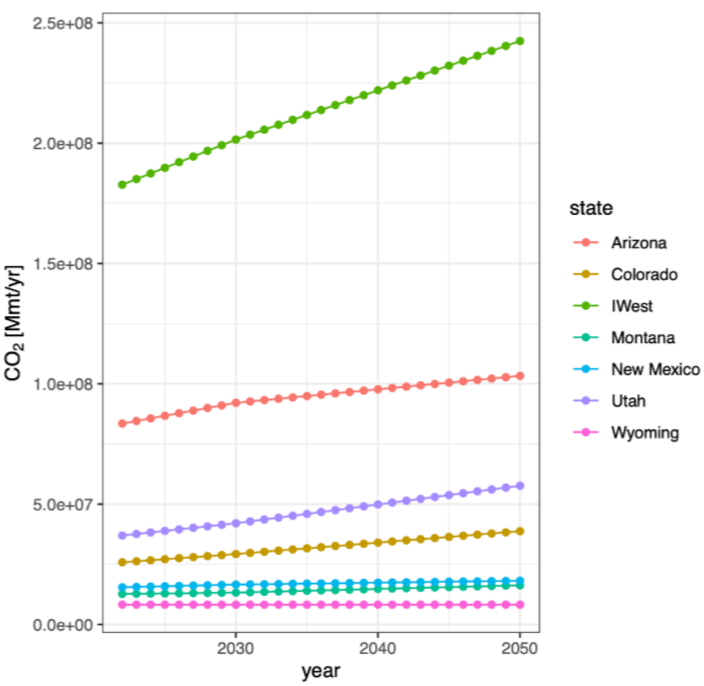

Figure 40. Potential CO_2 reductions by year and state from using biomass and biogas to produce electricity (t/yr).

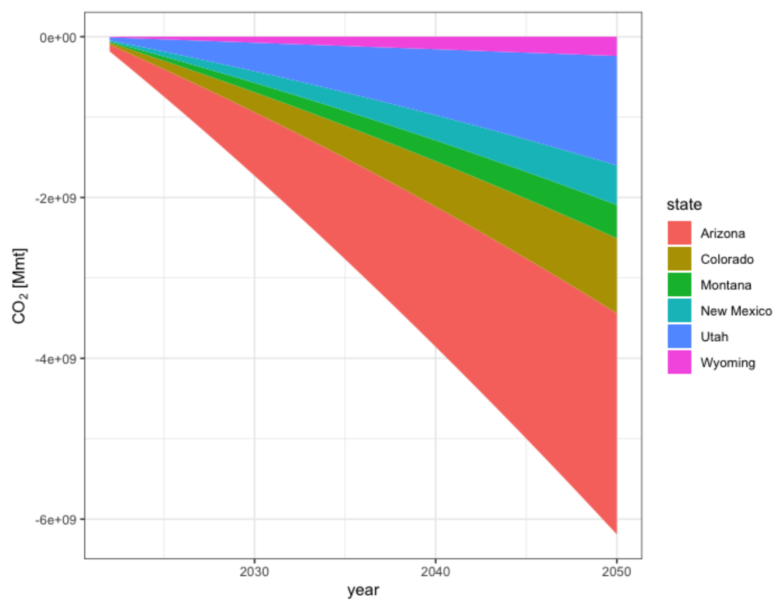

Figure 41. Cumulative potential for CO_2 reductions by year and state from using biomass and biogas to produce electricity (million metric tons).

Conclusion: The plot shows an average reduction of CO_2 of 214MMT per year. That corresponds to 55% reduction of the total 2022 Intermountain West CO_2 emissions of 387 MMT.

CO_2 emission reduction by bioethanol in the transportation sector

In this analysis, biofeedstocks from agriculture, forestry, and mill residues are converted to ethanol. Methane produced from manure, water treatment sludge, landfills, and industrial production is also converted to ethanol. Ethanol is blended with gasoline and used in the transportation sector. Total CO_2 saving was computed by summing the emissions corresponding to the number of liters of gasoline displaced by ethanol. The conversion yields are derived from the literature and are validated, where possible, using the Argonne GREET database [24]. EIA long-term predictions of U.S. gasoline consumption for the transportation sector are almost constant.

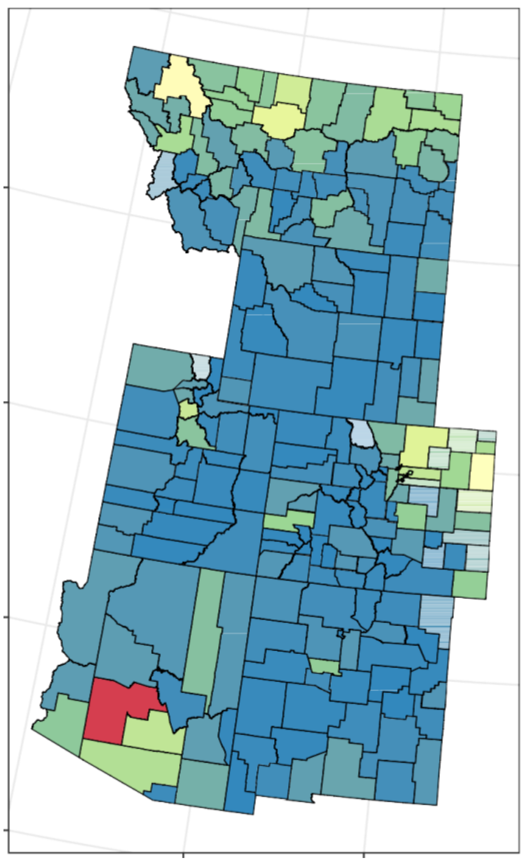

Figure 42. Potential ethanol production from biofeedstocks by county.

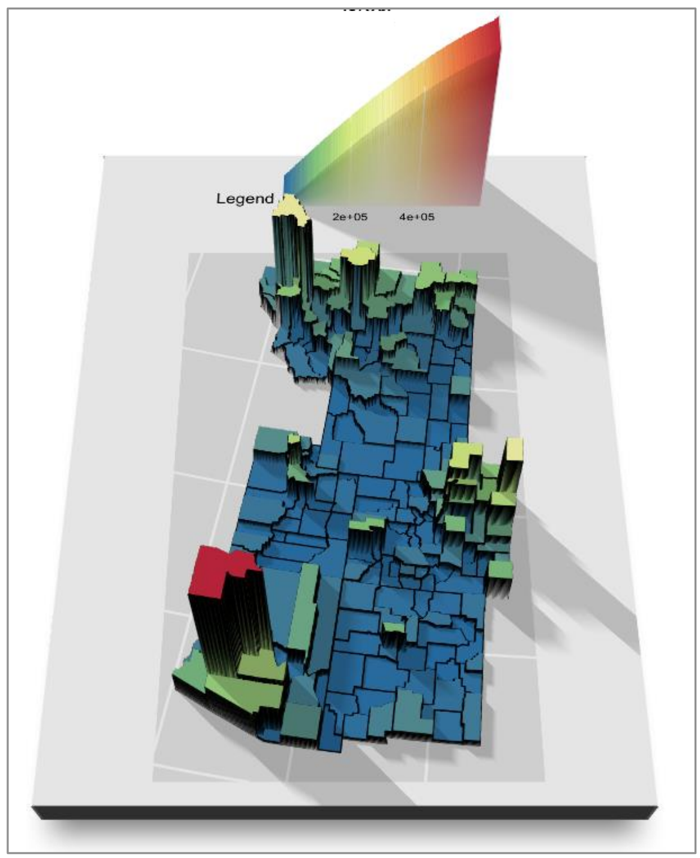

Figure 43. Potential CO_2 reduction from bioethanol used in transportation by county (t/yr).

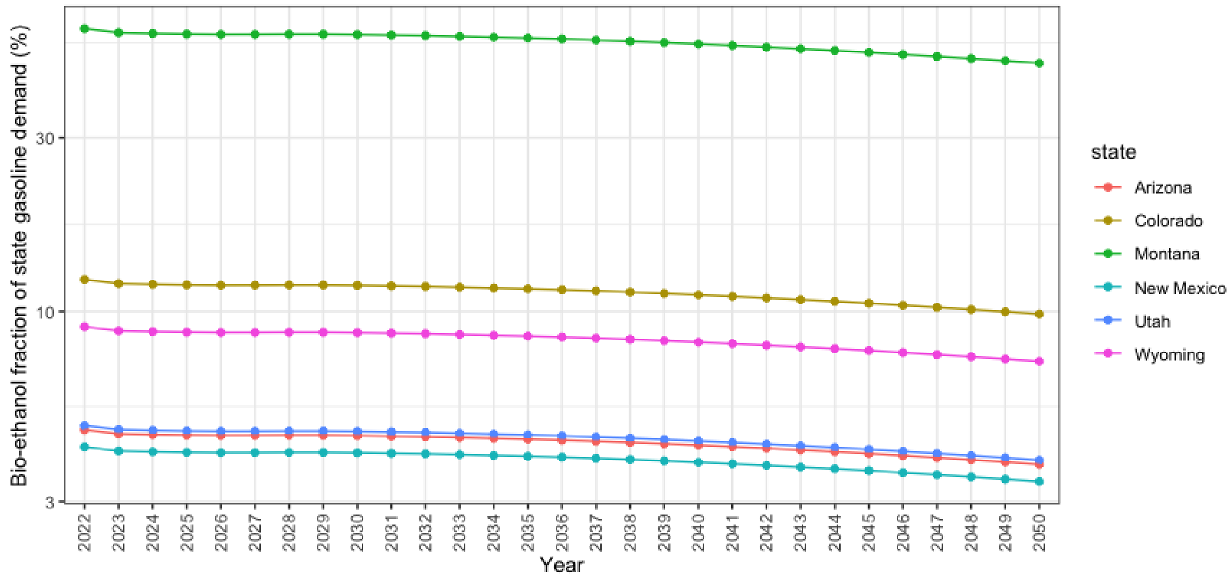

Figure 44. Fraction of state-level gasoline projected demand by year for transportation that can be potentially offset by locally produced bioethanol. Gasoline demand is based on EIA long-term national consumption projections applied to 2021 state-level gasoline consumption data.

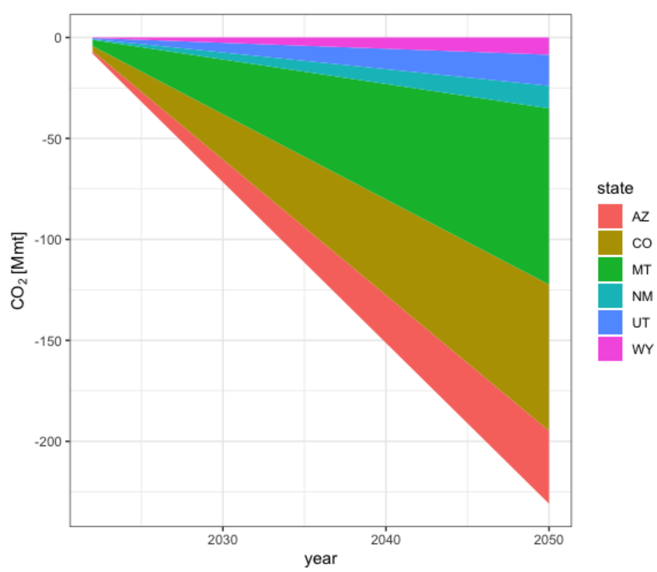

Figure 45. Potential cumulated CO2 reduction from bio-ethanol– a ton of CO_2 equivalent. Bioethanol is produced by biomass and biogas transformation. CO_2 savings are computed as gasoline emissions displaced by bioethanol.

Conclusion: This plot shows that CO_2 reductions can be reduced by 225+ MMt by 2050. The yearly saving is almost 8 Mmt of CO_2 per year.

Overall analysis conclusion: The reduction in CO_2 emissions from use of bio-derived feedstocks to produce electricity is substantially higher than the potential for reduced CO_2 emissions from the transportation sector, using bioethanol.

Bioenergy processing pathways

Conversion technologies/emerging trends and technologies

Just as there are a variety of bio-feedstocks, and bio-derived waste carbon sources that can be converted into bioenergy products or chemicals and materials that would replace fossil-based products, there is a range of technologies and pathways for converting these feedstocks into a product (Figure 46).

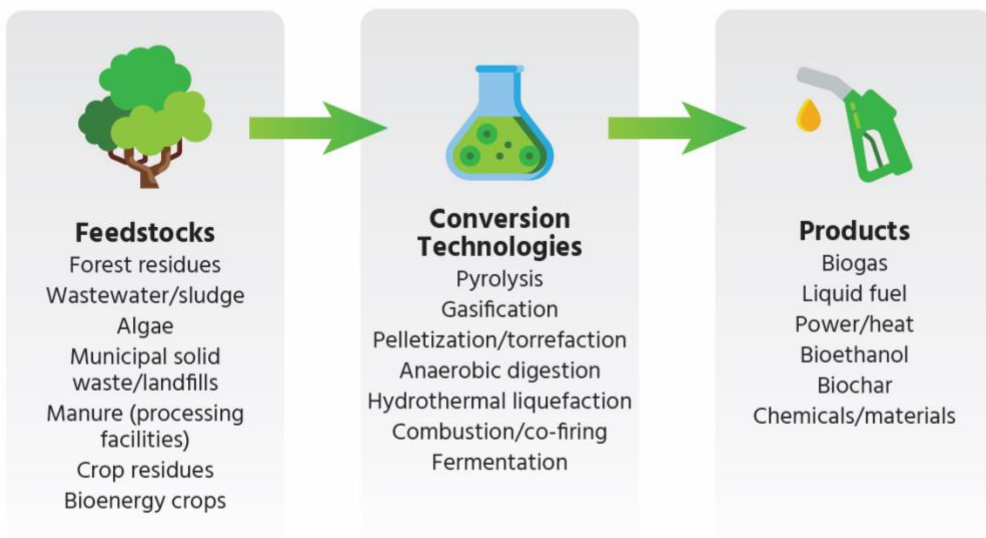

Figure 46. Feedstocks (left) are biomass or bio-derived, and alternative biofeedstocks as considered in this report are highlighted [25]. Some feedstocks may need pretreatment or preprocessing before being converted to improve efficiency; pretreatment or preprocessing technologies are not shown here. Conversion technologies (center) convert the feedstock to a gas, a liquid, or a solid and the composition varies depending on the feedstock. Generally speaking, each conversion route can apply to more than one type of feedstock. The efficiency of conversion and the products will vary. Finally, there are a range of products (right) from the conversion technologies and multiple products (co-products or by-products) can also be obtained from a single feedstock and conversion technology pathway.

Primary conversion technologies

Pyrolysis

In pyrolysis, low-moisture, bulky, lignocellulosic biomass such as forest or crop residues, purpose-grown bioenergy crops, or municipal solid waste are converted at high temperatures and high heating rate in the absence of oxygen to a bio-oil, which can be used as a liquid fuel; or a clean syngas, which can be used for electricity generation or renewable natural gas. A co-product of the conversion is biochar, which can be applied as a soil amendment or as an adsorbent for water filtration. The conversion in the reactor can be optimized by adjusting the processing conditions and by the addition of suitable catalysts. These modifications will also determine the percentage of product (bio-oil, gas, or char) obtained. In pyrolysis, one challenge is the variability in the form and composition of the feedstock. This can be partly solved through pretreatments that partially deconstruct the biomass before sending it to the pyrolyzer [26].

Gasification

Biomass gasification is a mature technology pathway that uses a controlled process involving high heat (>700°C), steam, and oxygen to convert biomass to hydrogen and other products without combustion [26].

Pelletization/torrefaction

Woody biomass can be thermally treated to densify it for use as a replacement for coal. The densification process can also be a pretreatment for the lignocellulosic biomass to make the pyrolysis or gasification process more efficient [27].

Hydrothermal liquefaction

Hydrothermal liquefaction converts wet/high moisture biomass into liquid fuels through a thermochemical process in a hot, pressurized water environment, which breaks down and depolymerizes solid components into liquid components. Hydrothermal liquefaction is still in pre-demonstration scale; but has shown promise for processing of microalgae to biocrude [28]; and for conversion of municipal wastewater sludge [29] and food waste to biofuel intermediates [30].

Biochemical conversion (anaerobic digestion)

Anaerobic digestion (AD) is a technology that is widely used in food processing, wastewater treatment, and on livestock farms. AD technology is based on the natural process by which microorganisms, in a closed system without oxygen, break down organic wastes to produce a gas. Recovered biogas can be an energy source for electricity, heating, or transportation fuel. The compressed biogas can be pumped into existing gas pipelines, from where it can be sold and distributed. The AD process also generates solid and liquid coproducts such as natural fertilizer, compost, and animal bedding. AD technology is mature, but there are still opportunities to improve the efficiency of the technology [31, 32].

Biochemical Conversion (Fermentation)

Bioethanol is produced from biomass through a process involving pretreatment (initial breakdown), then enzymatic hydrolysis (to convert polysaccharides to monomer sugars), followed by fermentation by different microorganisms to convert the sugars into ethanol. Other alcohols like isobutanol can also be generated from biomass. In a different biochemical conversion process, Alder Fuels in Colorado uses microbes to convert food and farm wastes to short hydrocarbons called Volatile Fatty Acids (VFA). The VFAs are then processed further by chemical catalysis to longer hydrocarbons, and selectively separated to become sustainable jet fuel [33].

Future opportunities

Use of produced water to minimize fresh water consumption in bioenergy production

The Intermountain West supports an abundance of oil, gas, and coal resources—water that is co-extracted with these fossil-based resources has the potential to replace some fresh water use in the drought-prone region. In New Mexico, water from oil production is produced in a 10:1 ratio. This "produced water" can be treated or, in some cases, used directly for bioenergy applications such as cultivation of algae for biofuel production [34, 35]. Produced water (PW) reuse has also been suggested for some crop irrigation purposes, but there are some conflicting reports on how safe this would be. Two recent greenhouse studies suggest that plant immune response to pathogens may be suppressed when PW is used for irrigation, along with decreased soil health, wheat yields, and (soil) microbial diversity [36, 37]. However, in California, a panel found no evidence of elevated threat to human or crop safety from use of oil field PW to irrigate crops [38], and this has been supported by field studies using low-saline PW [39]. Whereas the use of PW for irrigation of food crops may continue to be controversial for some time, its use for production of biofuel and bioenergy crops may be less controversial, provided combustion of such feedstocks does not increase toxic emissions and, in the case of bioenergy crops like oil seed crops or switchgrass, there are no adverse effects on soil health or crop yield.

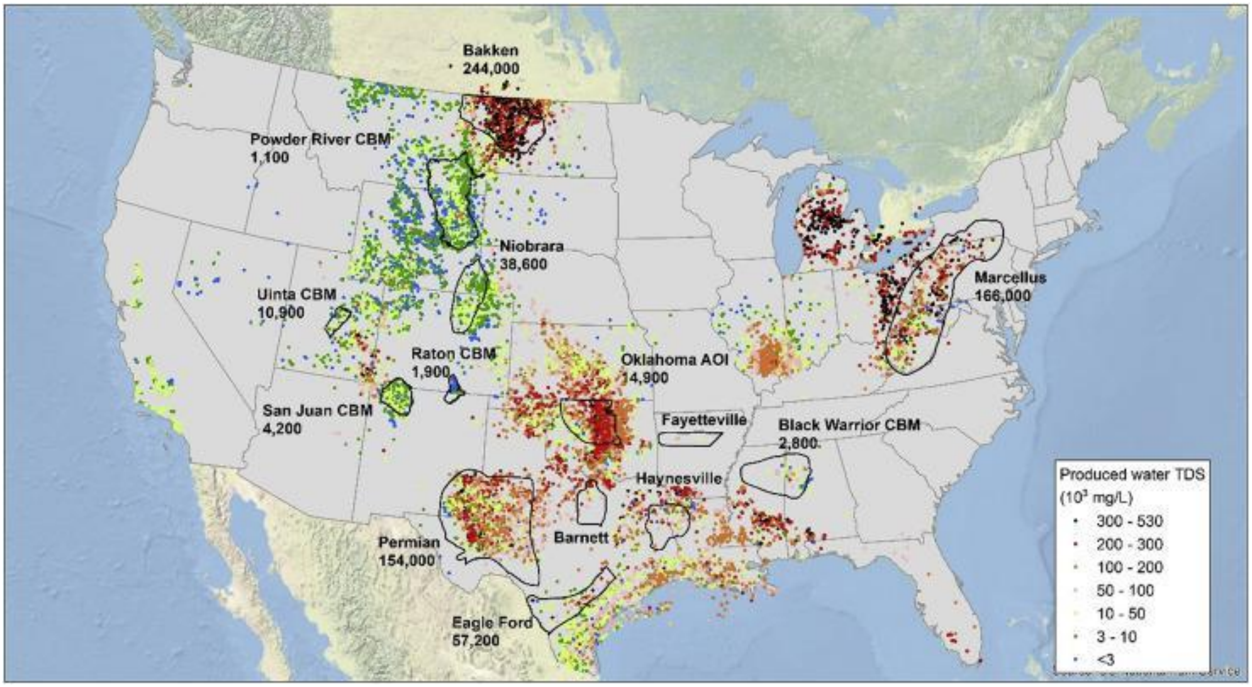

Figure 47: Total dissolved solids (TDS) of produced water from the USGS Produced Waters database (version 2.3) with supplemental data for the New Mexico region of the Permian Basin provided by the New Mexico Institute of Mining and Technology (NMIMT) Petroleum Research and Recovery Center (PRRC) and data from the USGS in the Eagle Ford Play. 2020 [40].

Smaller modular technologies

Small, modular, process-intensification technologies would make bioenergy and bioproduct production accessible to both rural and urban communities for more modest investments than construction of large-scale, central biorefineries. For example, the Trio Renewable Gas (a California based company) fast pyrolysis platform is modular and mobile, meaning operable on a semi-truck. The ability to bring a small portable unit to the site of harvesting to process biomass would be a gamechanger in utilizing alternative biomass feedstocks for conversion into syngas. Likewise, hydrothermal liquefaction systems and anaerobic digesters, if made smaller in scale, could be used on location to process or pre-process biomass into fuel or energy intermediate products.

Use of ML/AI to accelerate process optimization

Several reports have been published recently on the use of machine learning and artificial intelligence (ML/AI) to optimize bioenergy processes. For example, ML/AI tools have been applied to optimize biomass gasification processes [41, 42], hydrothermal liquefaction of biomass [43], and algae cultivation productivity for biofuel production [44]. Application of ML/AI tools could help to accelerate the pace of innovation and new energy technology deployment in the Intermountain West to achieve the needed reduction in GHG emissions in the next decade and beyond. ML/AI tools can be applied to optimize operational practices and can also help equipment manufacturers improve equipment and equipment component design (e.g., catalyst and membrane materials selection).

Synergies of bioenergy with agriculture

Agriculture (livestock, agricultural soils, and food crop production) contributes to about 11% of greenhouse gas emissions in the U.S. (EPA). There are two main areas of synergy between bioenergy production and agriculture that could be exploited in the Intermountain West to reduce GHG emissions.

First, as biomass or waste carbon is processed into energy, there may be solid carbon produced, called biochar. Pyrolysis, gasification, combustion, and even hydrothermal liquefaction will produce biochar as a byproduct. The biochar is used in regenerative agriculture in place of conventional fertilizers to remediate and sequester carbon in soils and help soil retain moisture. Biomass residues from anaerobic digestion (the solid digestate) may also serve as a soil amendment. Regional adoption of sustainable practices in agriculture may enable opportunities to increase bioenergy crop production (e.g., Montana Renewables and Calumet Specialty converting oil seed crops to biodiesel) or increase productivity of food or feed crops (e.g., Navajo Agricultural Products Initiative in the Four Corners region).

Second, agrivoltaics uses land for both agriculture and solar photovoltaic energy. It is an approach that intersects the food, energy, and water nexus, combining the ability to grow various crops on the same land used to generate solar electricity. Solar grazing is a type of agrivoltaics installed where livestock are grazing.

Current efforts to implement agrivoltaics across the region include Jack's Solar Farm in Boulder, Colorado, and Arizona State University's Agrivoltaic Learning Lab (ALL) located at Biosphere 2. Tucumcari Bioenergy and Trollworks, both companies located in New Mexico, are also integrating agrivoltaics into their bioenergy production processes.

Agrivoltaics is an active area of innovation [45]. Design solutions are being implemented to minimize shadows on crops and maximize electric energy generation. Solar panels can be raised to allow animals (e.g., cows) or equipment (e.g., combines) to pass through. These have been implemented over crops such as grapes, raspberries, strawberries, and pollinators. There are additional efforts to improve semi-transparent and transparent panels and light selective photovoltaic devices. For example, the application of photovoltaics in greenhouses is being used by UbiQD, Inc. in New Mexico and Heliene (a Canadian solar panel manufacturer) is using UbiQD's quantum dot glass technology that may allow for a more "optimal" spectrum of light into greenhouses. The sunlight is optimized by converting direct UV/blue light from the sun into an orange/red glow that can improve plant growth.

Bioenergy crops

Another potential area of synergy is cultivation of bioenergy crops, for example oil seed crops such as those used for biodiesel by Calumet Specialty and Montana Renewables. The Intermountain West has an abundance of non-arable land that could be cultivated with bioenergy crops and irrigated by produced water, or have its soil health regenerated with biochar or other waste carbon resources from regional biomass processing operations. Bioenergy crops cultivated with marginal water on restored land, for example from mining operations, presents an opportunity for the region to transition to bioenergy.

Discussion of unused land in the region

Non-arable land, or land that is contaminated from mining may present opportunities for regenerative agriculture and remediation of soil health for growing bioenergy crops, horticulture, or even food crops if suitable water sources can be located nearby and made clean enough for human consumption. Construction of greenhouses on such land may also make sense. Potential water sources may be low TDS produced water, or reclaimed water from a nearby industry.

Other synergistic opportunities

Waste, captured CO_2 as a feedstock in agricultural applications

Carbon dioxide is a carbon source for plants. In photosynthesis, plants use energy from sunlight to combine CO_2 and water to make carbohydrates, which they use as an energy source to grow. All terrestrial plants, as well as aquatic photosynthetic bacteria and algae, need CO_2 to make biomass. Bio-utilization of waste, or CO_2 captured by plants and other photosynthetic organisms, could be an effective way to boost growth while sequestering the captured carbon in the organism [46].

The use of CO_2 enrichment to enhance crop response in greenhouses has been used for many years [47]. Supplemental CO_2 increases net photosynthesis in greenhouse plants, resulting in improved growth and yield of flowering plants, as well as vegetables and forest plants. Use of CO_2 from captured waste sources [48] presents new opportunities for growers to supplement their greenhouses with CO_2 at less cost and hazard than by installing CO_2 generators in the greenhouse, and without adding to greenhouse gas emissions.

Likewise, algae cultivated for biofuels or bioproducts are routinely sparged with CO_2 to maintain biomass growth. For the past decade or more, algae cultivators have experimented with sparging of waste CO_2 collected from the flue gas produced by industrial facilities and power plants (49). Algae grown in either open ponds or greenhouses, or enclosed photobioreactors could benefit from utilization of CO_2 captured from industrial sources. Algae grown with waste CO_2 could be converted into biofuels or turned into a soil amendment to restore nutrients into marginal lands to enhance agriculture. The company Heliae in Gilbert, Arizona is focused on cultivation of algae as a soil amendment in regenerative agriculture. Their product, PhycoTerra® is a sustainably produced soil microbial supplement from algae that "works to restore the natural quality of the soil and balance in the overall soil ecosystem."

Colocation of greenhouses and/or algae cultivation ponds or PBRs with CO_2 emitting industries (e.g., power plants, biorefineries, etc.) would enable utilization of captured waste CO_2 to enhance biomass growth and yield, without the expense of transporting the CO_2 to the site of utilization. An additional benefit may be the use of "free," low-quality heat from the power plants that may be used to directly heat the cultivation environments. Ou et al. [22] reported that an algae site that sources carbon from a high purity waste CO_2 source would achieve a 9-39% reduction in life-cycle GHG emissions, and a 9-37% reduction in life-cycle fossil energy use compared to a similar site using dilute CO_2 for algae cultivation.

Biohydrogen production

Biohydrogen is hydrogen produced biologically from microorganisms (e.g., algae or bacteria). Microalgae are capable of producing high levels of carbohydrates such as starch or cellulose, which are ideal substrates for hydrogen production. Furthermore, a sustainable process can be developed where the production of biohydrogen from microalgae can be integrated with industrial CO_2 utilization, or cultivation in wastewater or produced water [50].

Special intersections with environmental and social justice and bioenergy

One of the unique features of the Intermountain West is the high number of tribes in the region. From the bioenergy workshop I-WEST held in January 2022, we learned that there are strong bonds between indigenous people and nature, and these bonds need to be understood and respected as we transition to new energy sources. In particular, advancing bioenergy and related technologies in the region needs to occur in synchrony with tribal interests and consideration of their land and resources. Agriculture is an important part of indigenous culture. Consequently, there could be competition for resources needed for food vs. energy/commodity crops; for example, arable land and freshwater availability are concerns. Some of the integrated approaches between agriculture and bioenergy technologies may help mitigate these concerns and actually turn them into new opportunities for tribal communities, as well as other rural and/or economically disadvantaged communities.

Training and engagement with local colleges, or community members (co-ops) to build a local workforce is a viable approach to growing bioenergy technologies in the Intermountain West, particularly at the interface of agriculture and bioenergy interests. Developing workforce training and degree and certificate programs in conjunction with local colleges will help to ensure a well-trained workforce locally. Additionally, training programs that offer skills development in the range of new energy technologies will be important to building a workforce that is agile in response to climate change and the portfolio of new energy sources that will be developed and deployed locally.

List of figures and tables

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