CHAPTER 6

Biomass Carbon Removal and Storage (BiCRS)

SUMMARY

Biomass carbon removal and storage (BiCRS) is a major carbon removal pathway that relies on living plants to capture CO_2 from the air. Carbon removal is achieved when the carbon in plant biomass—which would otherwise be re-released to the air through natural decomposition processes—is captured and stored in materials or through geologic storage of CO_2. All integrated assessment-model projections with a reasonable chance of limiting warming to 1.5 °C by 2100 rely on BiCRS as a primary carbon-removal approach [1, 2]. The outsized potential impact of BiCRS (the amount of long-term carbon removal at an intermediate cost (<\$100/tonne CO_2)) lies in the ability to generate a wide range of materials and energy products from plant biomass, thus generating revenue streams while also providing alternatives to fossil-based products in addition to carbon-removal services. Our BiCRS analysis includes biomass drawn from carbon crops, or wastes and residues from forestry, agriculture, and municipal sources. We recognize that BiCRS is not risk free; crops dedicated for CO_2 removal can have negative effects on ecosystem biodiversity, carbon storage in trees and soils, and can put pressure on land needed for food production. Displacing food production creates a risk of indirect land-use change and unforeseen adverse climate impacts. Other major BiCRS risks are associated with its complexity. BiCRS requires collaboration between biomass producers; biorefinery investors, constructors, and operators; and operators of bioproduct and CO_2 distribution and storage systems. Due to the broad scope of BiCRS, this chapter is necessarily wide ranging and addresses land use, biomass availability, biomass conversion pathways, and opportunities for biorefinery siting in the United States.

Key Findings

- In the United States, BiCRS has the potential to exceed 800 million tonnes of CO_2 removed from the atmosphere per year at a net cost less than \$100/tonne CO_2, with no impact on food production.
- Every region has a role to play in BiCRS carbon removal in the United States; interaction between regions is required for the full value chain.
- We found a wide range of potential biomass availability for BiCRS in a mature market—from 0.5 to over 1 billion dry tonnes of biomass per year depending on the approach to land use.
- BiCRS pathways that produce hydrogen are favorable for maximizing CO_2 removal at low net cost per tonne CO_2 due to high CO_2 removal per tonne of biomass and revenue streams from the sale of H_2.

CHAPTER SCOPE

This chapter provides a comprehensive analysis of the impact and cost of biomass carbon removal and storage (BiCRS) for the United States—a set of diverse approaches that useplants to remove carbon from the air. Topics include:

- Baseline biomass availability (wastes and residues) with no land-use change
- In-depth assessment of sustainable biomass supply and costs within a range of approaches, including two different approaches to carbon-crop production
- Distribution of biomass use within 27 unique, technologically mature BiCRS pathways, with detailed technoeconomic assessment (TEA) and life-cycle assessment (LCA), transportation costs and logistics
- Regional and system-level insights for the most promising BiCRS pathways and key drivers of CO_2 removal rate and cost, including energy equity and environmental justice (EEEJ) impacts

- The most influential factors determining cost per tonne of CO_2 are the capital and operating costs of biorefineries and the selling price of co-products, followed by biomass feedstock costs and biomass transportation costs.
- While not the dominant pathways in terms of quantity, production of long-lived carbon products (bio-oil for asphalt, polyethylene, wood products) can play a major role in carbon removal due to low costs per tonne CO_2 and less reliance on geologic storage.
- A wide range of technologically mature BiCRS pathways can serve social, political, regional, and national goals (e.g., production of hydrogen and aviation fuels, reducing the burden of pollution on communities) while providing high-capacity carbon removal; in any approach, hundreds of mid- to large-scale facilities must be built across the United States that link reliable biomass supply, biorefineries, geologic storage, and bioproduct distribution. The complexity and scale of implementation, coupled with the potential for significant climate and regional benefit, requires urgent action.
- With purposeful scale-up that assesses the baseline pollution burdens of each biomass feedstock and the people who are inequitably exposed to them, BiCRS can be used as a tool for restorative environmental justice for a number of environmental pollutants (e.g., PFAS, PM2.5, odorific gases, and excess nutrients.)

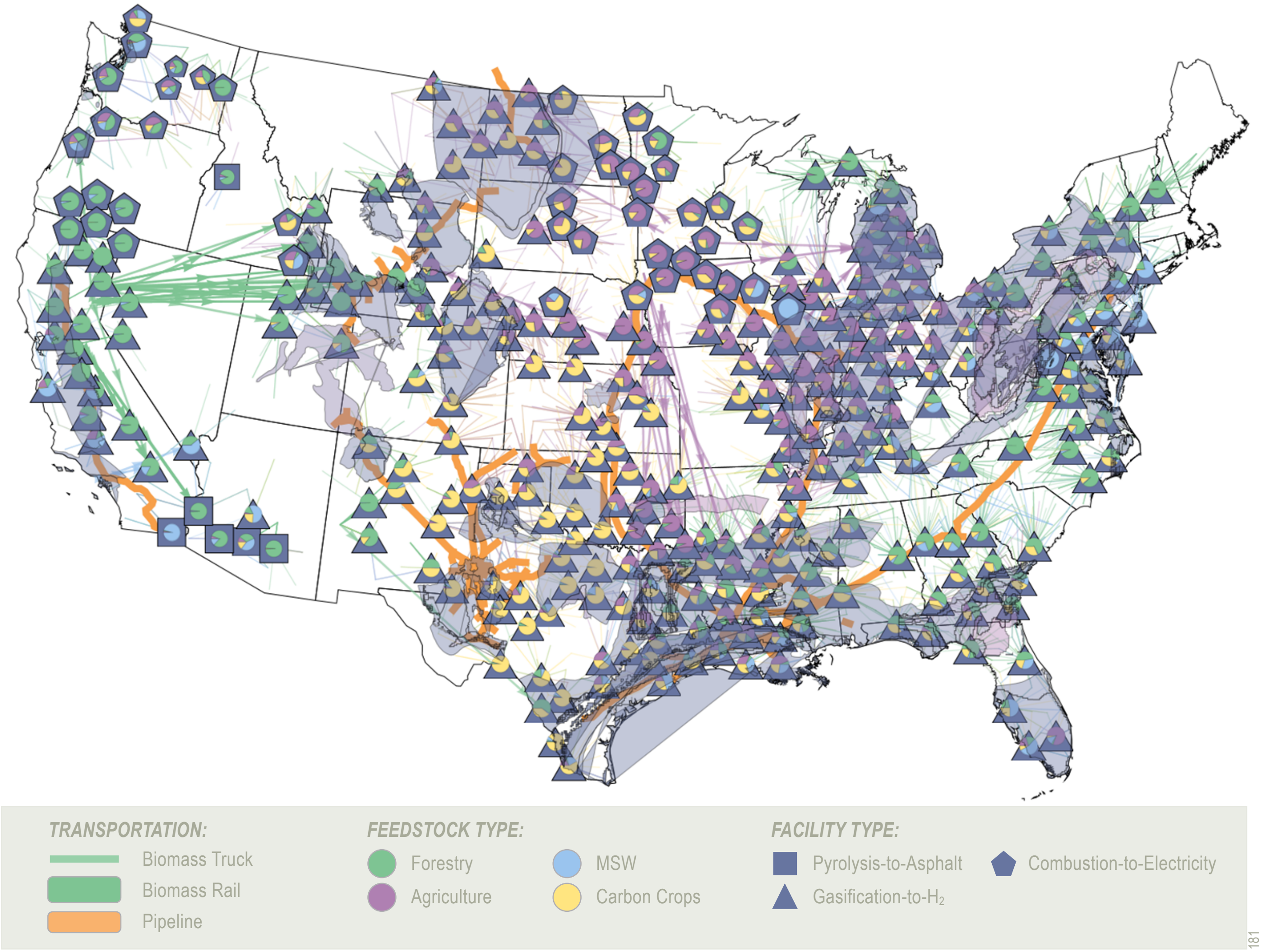


Figure 6-1. *A snapshot of a US BiCRS system that could achieve 90% carbon-removal capacity (related to total biomass availability) at minimal cost ($/tonne CO_2). The symbols represent facility type, and symbol color represents biomass type (forestry, agriculture, municipal solid waste (MSW), or carbon crops). Orange lines represent CO_2 pipelines (current and proposed), thick lines represent biomass transportation by rail and narrow lines by truck. The color of the transportation lines indicates the type of biomass being transported. The total CO_2 removal potential depicted here represents 820 million tonnes/year, with 270 gasification-to-hydrogen facilities and 34 million tonnes of hydrogen production; 46 combustion-to-electricity facilities with 150 TWh of electricity production; and 6 pyrolysis-to-asphalt facilities with 6.7 and 1.4 million tonnes of asphalt and biochar production. Most facilities have a capacity of 5000 tonnes/day of biomass throughput. Shaded areas represent geologic storage availability.*

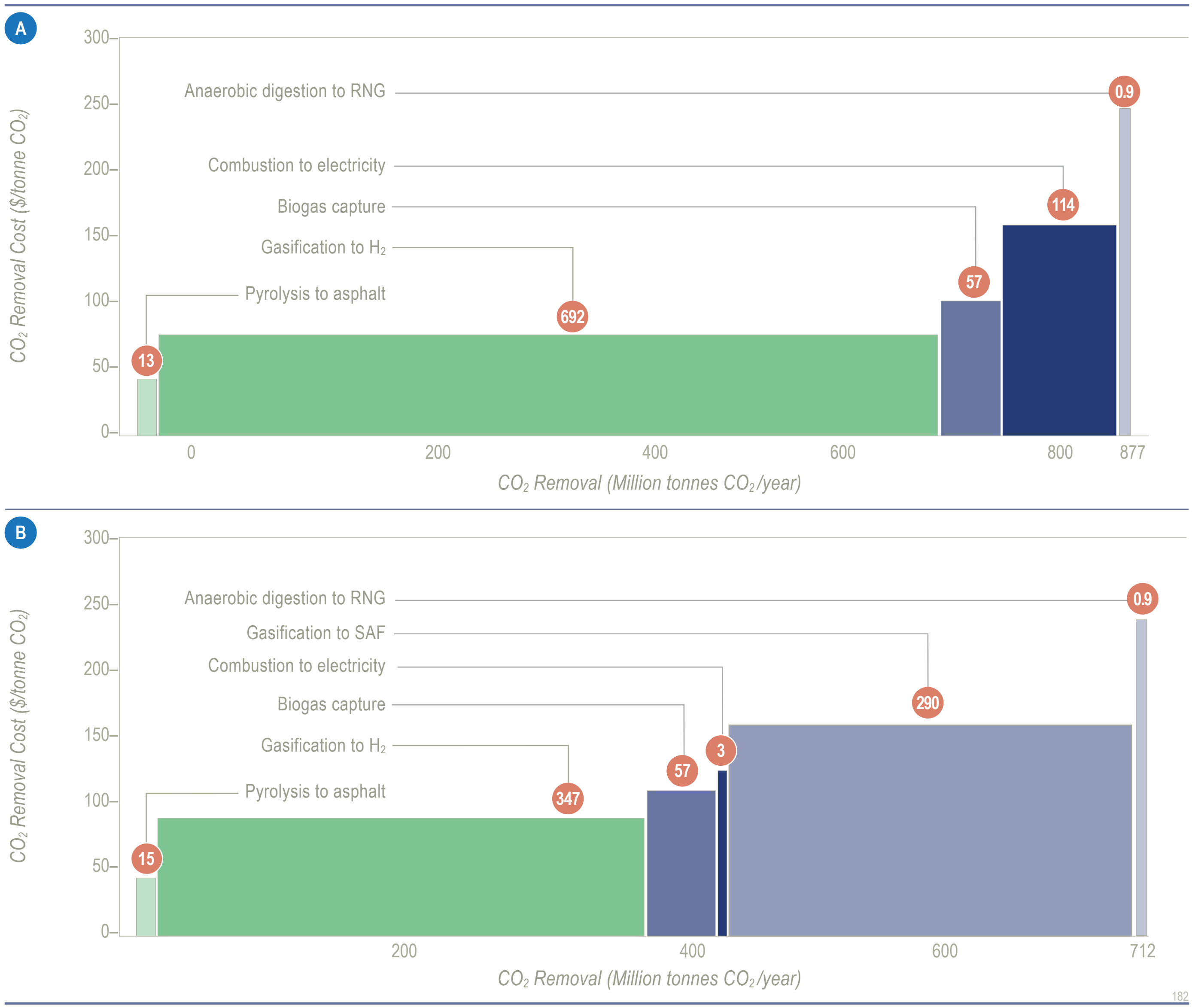


Figure 6-2. *Average CO_2-removal costs and cumulative CO_2-removal potential for US BiCRS system to achieve 90% carbon-removal capacity based on biomass availability. 6-2a shows an optimized result to maximize carbon-removal rate (tonnes/year) while minimizing carbon-removal cost ($/tonne CO_2). 6-2b shows the BiCRS pathways represented in the Executive Summary ES-4, reflecting the BiCRS carbon-removal rate and cost when 17.5 billion gallons of sustainable aviation fuels (SAF) are produced, providing half of DOE's projected SAF demand in 2050. The two supply curves reflect a small subset of potential uses for biomass that could provide bioenergy and bioproducts, including H_2, electricity, and renewable natural gas (RNG), and carbon-removal services. All costs and emissions from biomass collection, transportation, and conversion and CO_2 transportation and injection are included.*

Introduction

Almost all integrated assessment model (IAM) climate-change mitigation scenarios rely heavily on the deployment of bioenergy technologies, and all Intergovernmental Panel on Climate Change (IPCC) Shared Socioeconomic Pathways [3] with a reasonable chance of limiting warming to 1.5 °C by 2100 rely on bioenergy with carbon capture and storage (BECCS) as a primary carbon removal approach [1, 2]. Bioenergy in these scenarios can be used for electricity, liquid fuel, biogas, and hydrogen production, and all can be produced in combination with carbon capture and storage [1] to store a significant portion of biomass carbon as CO_2 in geologic reservoirs.

In this chapter, we assess the potential for CO_2 removal from biomass in the United States, and we broaden our focus from solely bioenergy products to include other end uses for biomass that remove carbon from the air. We use the term BiCRS[4] rather than BECCS to encompasses all approaches that (a) use biomass to remove CO_2 from the atmosphere and (b) store biomass carbon as CO_2 deep underground, as soil carbon, or in long-lived products, while (c) protecting and promoting food security, rural livelihoods, biodiversity conservation, and other important societal values.

Because BiCRS lies at the intersection of land use, agriculture, and biorefinery technologies, implementation barriers can be complex and regionally specific; the risks and benefits depend on implementation details and counterfactual land uses. In this chapter, we illuminate the regionality of BiCRS pathways in the United States, while providing approaches to avoid unintended consequences due to land-use change. The primary risks associated with BiCRS are land degradation, water scarcity, biodiversity loss, and food insecurity, which are primarily attributed to converting lands that provide ecosystem services or food to lands that produce purpose-grown carbon crops [5].

The concept of BiCRS acknowledges a future in which biomass is more valuable for its carbon content than for its energy content due to the potential to remove and store large quantities of atmospheric CO_2. Recent analyses show that biomass carbon-removal revenue can exceed bioenergy revenue at CO_2 prices less than $200/ton [6]. In practice, BiCRS enables and expands the production of a variety of carbon-negative bioproducts that are difficult to sustainably produce by other means, including liquid fuels (especially for long-haul transport and aviation), biochemicals (e.g., isobutanol, hydrogen), bioplastics (e.g., polyethylene), biocarbon (e.g., biochar and bioasphalt), and wood products (e.g., small-dimensional lumber), among others. Some BiCRS pathways produce no bioproducts other than carbon-removal services. We assess a wide range of approaches that have sufficient technological readiness and relevant data for a comprehensive assessment of BiCRS pathways for the United States.

In this chapter, we provide a comprehensive assessment of potential mid-century BiCRS CO_2 removal rate (tonnes CO_2/year) and cost in the United States through synthesis of data

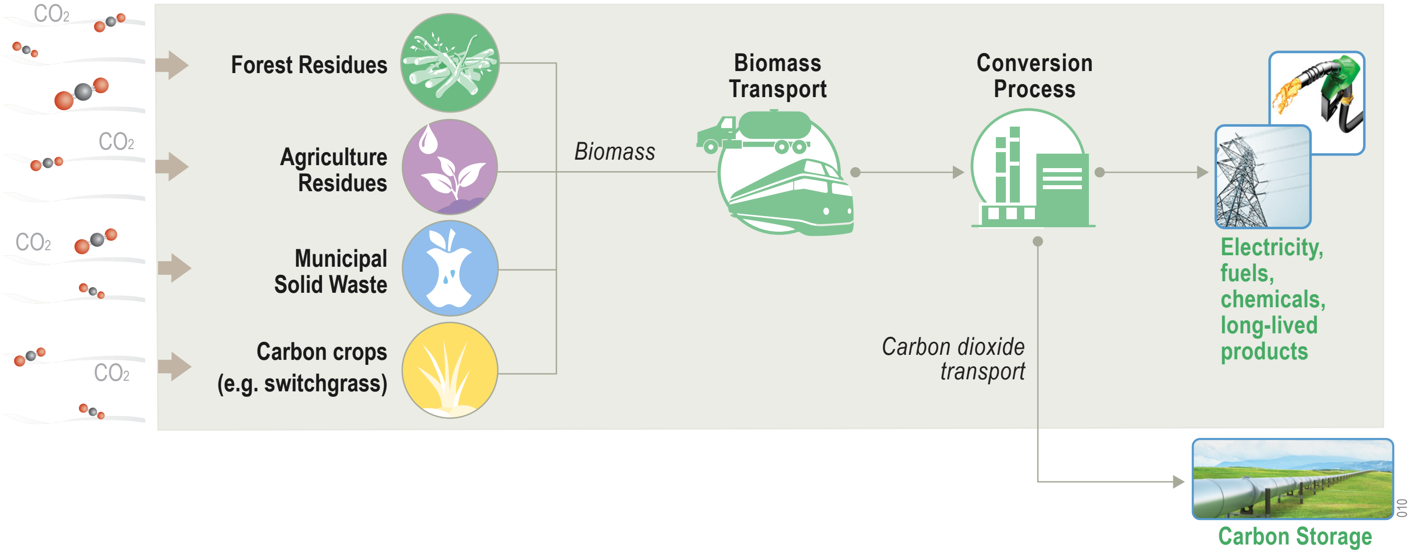


Figure 6-3. *Overview of generalized BiCRS pathway and principles of CO_2 removal. Plants capture and store CO_2 from the air. Carbon removal is achieved when the plants are treated in a conversion process, often to produce valuable products, as well as converting the biomass carbon to a form suitable for high-durability removal, such as geologic storage. "Forestry residues" represents branches, tops, and small-diameter trees (plantations and thinnings). "Agriculture" includes wastes and residues available after accounting for current use. "Municipal solid waste" (MSW) represents biogenic wastes already collected and otherwise destined for landfill. "Carbon crops" represents native perennials planted for carbon removal.*

and new analysis of BiCRS-relevant biomass supply, as well as an extensive assessment of conversion technology pathways and logistics. Our analysis boundaries and an illustration of the BiCRS concept is shown in **Figure 6-3.** Previous studies have expertly aggregated available data and analyzed the potential role of bioenergy in the context of decarbonization and the goal of net zero [7]. Here, we have focused our analysis on the value of BiCRS for carbon removal and do not pursue avoided emissions or decarbonization targets as primary drivers. However, in specific cases, we report the potential avoided-emissions impact of the most prominent pathways. Our focus on carbon removal extends from accounting for the impacts of biomass cultivation on soil carbon to the biomass carbon end-state—where we account for carbon removal with greater than 100-year durability. We avoid carbon leakage through indirect land-use change by implementing sustainability constraints in our biomass supply assessment. We also prioritize land use that (a) does not create long-lived carbon debt, (b) does not adversely impact biodiversity, and (c) agronomic management that requires neither irrigation nor significant nitrogen fertilizer to avoid further carbon costs. We report how US CO_2-removal regions uniquely contribute lands, biomass, biorefineries, and geologic storage for BiCRS and what opportunities emerge for these regions and communities in this build-out.

Major Findings

We find that US BiCRS carbon-removal potential exceeds 800 million tonnes of CO_2 per year at a cost less than \$100/tonne CO_2, with no impact on cropland or commodity prices. Our market-driven "maximum biomass potential" approach, which allows carbon price to dictate biomass producer behavior, predicts yet higher biomass potential and soil carbon storage, exceeding 1 billion tonnes of CO_2 removal per year. These results indicate that BiCRS has the potential to be among the most significant carbon removal pathways in the United States, due to removal rates that exceed those of forests and soils at costs that are lower than direct air capture (DAC) with storage (DACS) (but with significantly more stakeholders, land-use competition, and supply chain challenges). See the CO_2 supply curve ES-4 in the Executive Summary for more context. We identify areas of potential concern (e.g., increased water demand or competition with existing industries), and areas of benefit to communities (e.g., improvement to air and water quality, increased jobs in vulnerable communities). These are neither predictions nor recommendations but are rather assessments of potential and would require buildout of hundreds of facilities in the creation of a robust carbon-removal industry in the United States.

Analysis Approach

Guiding Principles

In our analysis, we prioritized CO_2-removal pathways for which, at time of writing (1) data from demonstrations of technologies (technology readiness level (TRL) 7+) are of sufficient detail to allow calculation of carbon-removal costs and (2) data are available on durability of carbon removed, in which multiple sources indicate >100-year carbon removal from the atmosphere. Our primary analysis objective was to find carbon-removal pathways with the potential for the highest rates of removal (tonnes CO_2/year) at the lowest total-system cost (\$/tonne CO_2), while also prioritizing biodiversity and maintaining existing carbon stocks in trees and soils.

Given these guiding principles and constraints, we excluded several pathways from detailed analysis in this report that may yet play a major role in carbon removal. For example, our objective to rely on pathways with extensive published data providing evidence of durability meant that we excluded emerging carbon removal pathways involving biomass burial. (Note that we provide descriptions of emerging pathways in Box 6-4 later in this chapter.) Further, as described in Box 6-1, we highlight but do not analyze the role of carbon capture from corn ethanol biorefineries for BiCRS, due to lack of data on how these pathways can achieve net carbon removal and challenges in estimating the cost of retrofitting these facilities. However, we do analyze and describe the role of cellulosic ethanol pathways, as they could provide additional benefits of increasing biodiversity and increasing soil-carbon storage and soil water-holding capacity if a small fraction of current low-productivity corn ethanol cropland is converted to native perennial carbon crops, as described in **Chapter 3 – Soils**.

Of note, we found major economic benefits to producing a salable product. While our assumptions of product revenue were conservative (we assumed only historical averages of fossil-based product prices with no incentives), we found that bioproduct revenue played a significant role in reducing overall CO_2-removal costs.

Finally, we acknowledge that there are numerous competing uses for biomass in a carbon-constrained future, and we do not purport to know which uses will be the most beneficial—this question must be answered by communities, stakeholders, and policymakers. However, we do provide information on how biomass carbon-removal pathways influence other goals. For example, we note that production of biofuels (e.g., hydrogen, sustainable aviation fuels, renewable natural gas (RNG)) and products (e.g., bio-asphalt, bio-ethylene, wood products) can contribute significantly to decarbonization by offering a path to avoiding fossil fuel production and emissions, in addition to removing CO_2 from the air.

Workflow

We conducted biomass assessments based on two time periods—2025 and 2050—to quantify how changes in biomass supply, grid decarbonization, CO_2 transportation infrastructure, and markets for BiCRS products influence supply and cost for CO_2 removal (see workflow, as shown in **Figure 6-4**). The 2025 assessments provide a benchmark, giving the most conservative removal rate based on the biomass supply, bioproduct market demand, grid carbon emissions, and CO_2 transportation infrastructure that exist today. However, realizing the full scope of BiCRS pathways (biomass sourcing, conversion, and CO_2 storage) using these resources will require build-out of hundreds of facilities; we do not attempt to project the rate of that build-out in this chapter. The 2050 assessments include a range of potential biomass supply and assume a zero-emission energy grid, the existence of a major CO_2 trunk pipeline, and a bioproduct market-demand potential in 2050. **Table 6-1** summarizes the biomass sources included in our three assessments of potential biomass supply in 2050. Throughout this chapter, we refer to purpose-grown biomass crops as "carbon crops" to emphasize the value of this biomass for carbon removal. The 2050 biomass assessments include a new analysis of potential supply from carbon crops and the associated soil-carbon impacts described in the **Section 6.2** and **Chapter 3 – Soils**.

In **Section 6.3**, we describe methodology for linking biomass to conversion technologies of sufficient technological readiness according to key biomass suitability characteristics. Additionally, we conducted cradle-to-gate (BiCRS co-products) and cradle-to-grave life-cycle assessments (LCAs) of each of 27 unique pathways, alongside technoeconomic assessments (TEAs). We used biomass supply at the county level, LCA and TEA, geologic storage location and costs, and road and rail information as inputs into an optimization tool that enables biorefinery siting to minimize CO_2 removal costs. We explore key implementation and regional questions that cannot be answered through simply linking biomass supply to conversion technologies in a gate-to-gate TEA. Optimization results are highly dependent on our input assumptions; for this reason, we provide these assumptions and sensitivity analyses to find the most important parameters. We report US regions where biomass may be stranded or underutilized due to high biomass density or limited transportation infrastructure or geologic storage capacity. Additionally, we report how BiCRS cost drivers and key pathways vary from region to region.

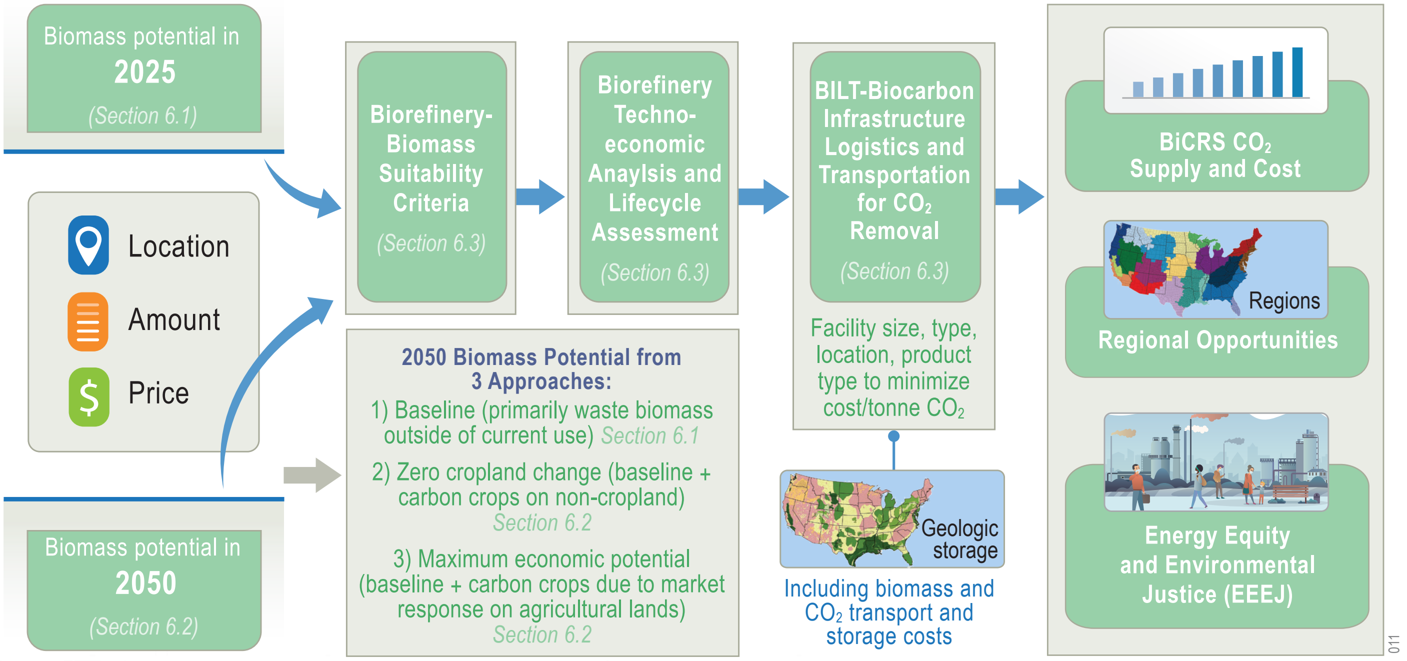


Figure 6-4. *Biomass assessment and workflow to generate understanding of BiCRS supply, costs, regional supply, and Energy Equity and Environmental Justice (EEEJ) impacts in the United States. The Zero Cropland Change biomass assessment includes native perennial grasses grown on the following lands: Conservation Reserve Program (CRP) lands, marginal and abandoned lands, and lands that become available due to decline in corn ethanol demand.*

Table 6-1. *Summary of three 2050 assessments of biomass potential described in this report. The three distinct approaches provide a range of potential biomass supply. The baseline includes wastes, residues, and Western Forest Restoration biomass. Zero Cropland change adds perennial grasses on non-cropland to the baseline biomass. Maximum potential includes baseline biomass, maximum potential agricultural residues, and maximum potential carbon crops based upon an economic response to biomass price with sustainability constraints. The biomass quantities according to each approach (and their locations) are described in sections 6.1 and 6.2 and applied to different conversion technologies in 6.3.*

Biomass Type Included In Each Assessment		
2050 Baseline	**Zero Cropland Change**	**Maximum Economic Potential**
Wet Waste (Manure + Food)	Wet Waste (Manure + Food)	Wet Waste (Manure + Food)
Agricultural Residues	Agricultural Residues	Maximum Potential Agricultural Residues
Forestry Residues	Forestry Residues	Forestry Residues
Western Forest Restoration	Western Forest Restoration	Western Forest Restoration
Municipal Solid Waste (MSW)	Municipal Solid Waste	Municipal Solid Waste
–	Restored Prairie on CRP lands	Maximum economic potential switchgrass
–	Switchgrass and restored prairie on marginal lands	Maximum economic potential willow
–	Switchgrass on former corn ethanol lands due to vehicle electrification	Maximum economic potential poplar

6.1. Current and Baseline 2050 Biomass Assessment

The purpose of our current (2025) and baseline (2050) biomass assessments is to understand potential BiCRS biomass supply (primarily wastes and residues) without the addition of purpose-grown carbon crops or land-use change, thus avoiding the primary BiCRS risks described in the Introduction. In all cases, we selected a subset of biomass types from the entire available biomass supply for their suitability for BiCRS and in almost all cases the biomass was available nationally at >1 million dry tonnes per year (with the exception of food waste, oat and barley straw, and primary mill residue). We summarize all biomass types, categories, and data sources, including those in our baseline assessment, in **Figure 6-5.**

The baseline 2050 biomass supply is available in five primary categories: biomass associated with (1) agricultural residues and processing wastes, including manure; (2) forestry residues, processing wastes, thinnings from wildfire mitigation, and small diameter trees from thinnings and increased productivity on current plantation lands; (3) municipal solid waste (MSW), including food waste; and (4) biogas from landfills, manure management, and wastewater treatment. In **Section 6.2**, we describe the potential biomass supply from additional carbon crops according to two distinct approaches: a land-use-constrained approach and a market-driven approach.

We have categorized biomass by industry sources rather than by end-state (e.g., wastes, residues) or composition (e.g., herbaceous, woody, high moisture, etc.) in order to better identify land and processing needs. We intended the categorization according to industry to help enable understanding of regional industries that can play a role in carbon removal. All biomass in our baseline assessment is technically available outside of current use , and we connect the biomass to conversion technology according to a specific subset of biomass characteristics as part of our workflow.

We sourced the majority of the feedstocks in our 2025 and 2050 baseline assessments from the 2016 Billion Ton Report [8] and the National Wet-Waste Inventory [9] but leveraged multiple databases; we describe the predominant types of biomass in each region in **Chapter 10**. To extend the estimate of supply from current (2025) to 2050, we made assumptions according to the source of biomass. For data sourced from the National Wet-Waste Inventory, we extended the supply of available biomass to mid-century based on the US Census Bureau's predicted population growth of 13% [10]. We used this same methodology to extend supply from current to mid-century for paper and paperboard. We extended the data

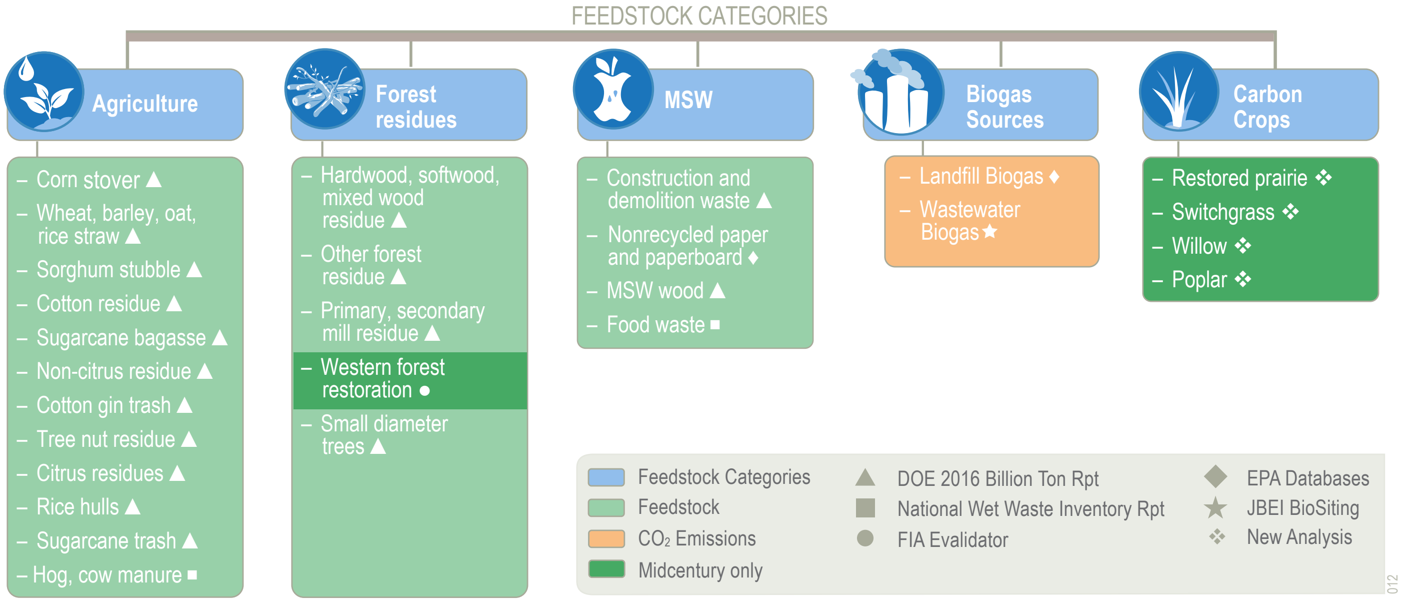


Figure 6-5. *Summary of biomass types and categories included in our analysis. Current (2025) biomass includes all agriculture, forestry, municipal solid waste (MSW), and biogas sources except for western-forest restoration biomass. Baseline (2050) biomass is identical to 2025 but includes slight increases due to yield and population projections, as well as inclusion of western-forest restoration biomass.*

sourced from the 2016 Billion Ton Report [11] to mid-century by applying the most relevant scenarios (medium housing demand and low energy demand for forestry biomass, and 1% base-case scenario for agricultural biomass) in the year 2045. Below, we spotlight paper and paperboard, as well as western-forest restoration, for in these categories we provide additional compilation or modeling of supply and cost outside of existing databases. In **Figure 6-6,** we show (aggregated) biomass supply across the United States for our 2050 baseline assessment and biogas sources.

Agricultural Biomass

Agricultural biomass results from existing agricultural operations: crop residues, such as corn stover and cereal straws; processing wastes, such as cotton gin trash and sugarcane bagasse; and wet waste, such as manure from livestock and dairy operations. The predominant source of agricultural biomass in the United States is from corn stover concentrated in the Great Lakes and Upper and Lower Midwest regions; indeed, this is one of the most significant sources of biomass across all categories. We constrain residue removal to avoid erosion and soil-carbon loss as recommended by the US Department of Agriculture's (USDA's) Natural Resource Conservation Service (NRCS) [12]. Utilization of agricultural residues for BiCRS can represent an additional source of revenue for farmers, avoid disposal costs, and improve air and water quality. In the case of manure, there are additional benefits in terms of odor control. These air, water, and odor impacts are described in the Energy Equity and Environmental Justice (EEEJ) final **section 6.3** of this chapter and in **Chapter 9 – Energy Equity and Environmental Justice.**

Dairy and swine manure from concentrated animal feeding operations (CAFO) provide a second important agricultural source. Here, modeled manure prices can include disposal costs or a price that a farmer might pay to a biorefinery or landfill to accept the manure waste. Prices of waste resources will vary with supply, demand, and policy factors, creating the possibility that negative prices may become positive as markets develop and demand increases for wastes. For purposes of a scenario evaluation, we assume a range of prices for manures from confined animal feeding operations that can be as low as $-50/dry tonne (costing the farmer to dispose of the waste). Our results may deviate from waste prices that will be reported in an update to the Billion Ton Report in preparation at this writing and warrant additional research.

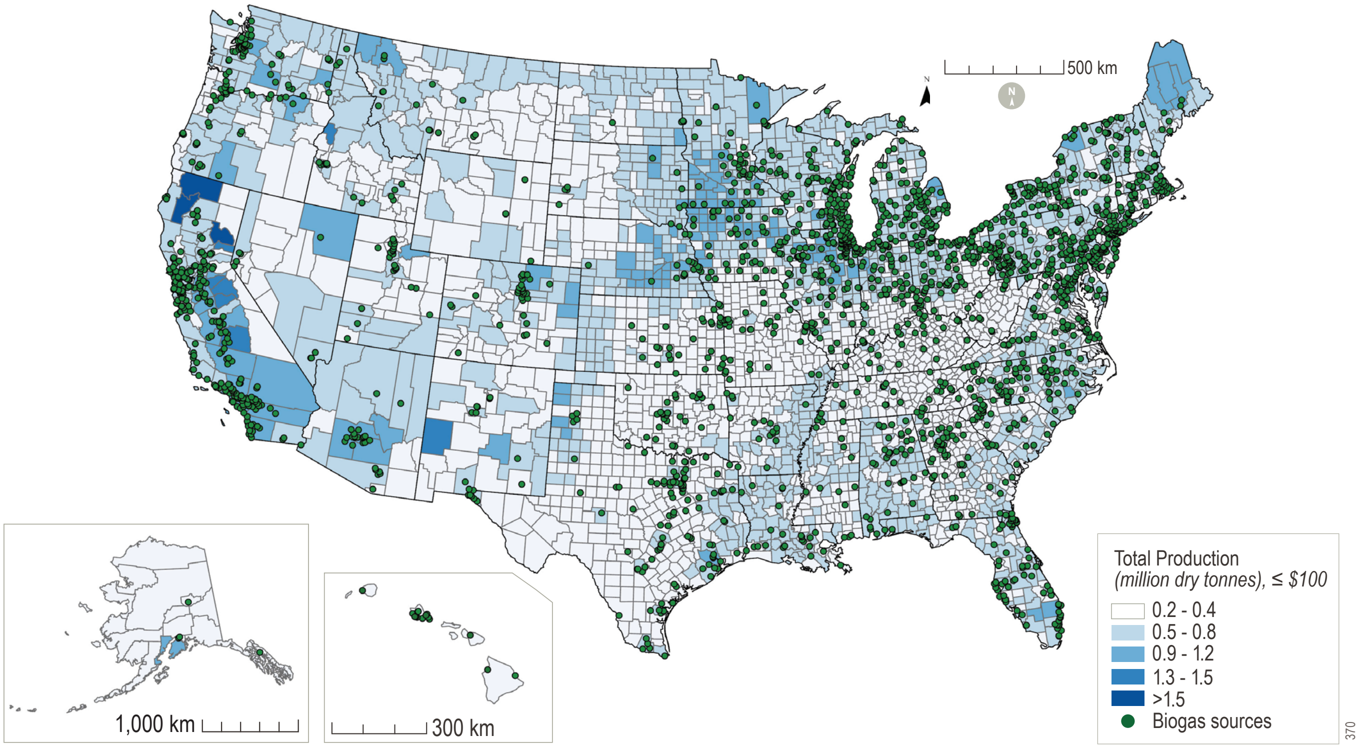


Figure 6-6. *Biomass production and locations of biogas sources for the 2050 baseline biomass assessment with no additional carbon crops or land-use change. Only wastes and residues from current agriculture, forestry, and municipal solid waste (MSW) is included. The total biomass represented here is 494 million tonnes per year.*

Forestry Biomass

The forestry biomass quantities reported here for our 2025 and baseline 2050 biomass assessments are primarily sourced from the 2016 Billion Ton Report [8]. The baseline 2050 forestry biomass quantities in our analysis also include western-forest restoration biomass quantities resulting from thinning operations to reduce wildfire risk, as described below. The forestry biomass supply accounting in the 2016 Billion Ton Report includes (1) the unused fraction of primary and secondary mill residues and logging residues from existing conventional harvests and (2) small-diameter trees (<11 inches DBH; diameter at breast height) that could be available within environmental and sustainability constraints. Sustainability constraints for forest biomass include exclusion of wetlands and other protected and sensitive areas, accessibility with no forest-road building, leaving at least 30% of residues on site [13, 14], restriction of harvest levels to ensure that timber growth always exceeds harvest at the state level, and others as specified in section 3.1.5 of the 2016 Billion Ton Report. All forest removals are modeled from timberland portions of forestlands (USDA Forestry Service definitions), though whether these were intact or not was not technically a modeling constraint. To deconflict forestry biomass in the western states, we compared forestry biomass quantities from thinning operations on a county level between the 2016 Billion Ton Report [8] and our western-forest restoration analysis and selected the greater quantity. **Chapter 2 – Forests** in this report also describes in detail the diverse types of forests and special considerations for using these forests for CO_2-emissions reductions and removal. Here we assess only the biomass availability from forestry, which is concentrated most prominently in the Southeast, Appalachia, Northeast, and Northwest.

Forestry biomass is of high value to BiCRS due to its applicability to a wide range of conversion technologies and consistent feedstock characteristics. However, there is also the danger of substantial carbon debt if the forest carbon content and accumulation rate exceeds the carbon storage and capture of the harvested material. The opportunity cost of leaving the forest intact is a crucial consideration.

Subtopic: Western-Forest Restoration Biomass for Wildfire Mitigation

To address the wildfire crisis in the American West, the US Forest Service (USFS) has proposed a 10-year wildfire-crisis strategy to conduct forest thinning on 28.3 million hectares (ha) of USFS lands (57%; 16.2 million ha) and other federal, state, tribal, and private lands (43%; 12.1 million ha). In **Chapter 2 – Forestry** of this report we include a separate but complementary analysis of forest carbon-emissions-reduction potential—in the context of catastrophic wildfire—from managing fire-prone forests in the western United States that are adjacent to or within human population centers (the "wildland-urban interface"). In this BiCRS chapter, we prioritize managing forested regions of the West to maximize available biomass (within policy and operational constraints), while **Chapter 2** prioritizes forest-management regions where wildfires risk human settlements. Because the analysis in **Chapter 2** reports emissions reductions from avoided wildfire (as opposed to carbon removal), we avoid double counting carbon.

Given the large scale of forest restoration required beyond USFS commitments, we set 2.8 million ha per year as the rate of restoration in 2050. However, as current forest-restoration activities are well below this rate, we remain conservative in our 2025 assessment, including only reported values from the 2016 Billion Ton Report [8]. For the 2050 assessment, we quantify the amount of non-merchantable low-value forest residues that will result from treatment across 11 states (California, Idaho, Nevada, Oregon, Washington, New Mexico, Arizona, Wyoming, Utah, Colorado, and Alaska). We include counties in order of decreasing wildfire hazard, such that biomass will be accumulated in the highest risk counties first, with lower risk counties included until 28.3 million ha is achieved, with 57% from USFS land and the remaining 43% from other federal, state, tribal, and private lands. We then calculate the average amount of low-value biomass generated in this 2.8 million ha as a representative value for 2050. For both scenarios, we sub-divide the biomass into six accessibility categories based on slope and distance to existing roads and assign these values different economic costs of acquisition [15, 16].

We estimate that 1.21 billion tonnes of low-value forest-biomass residues will be generated if the 28.3 million most at-risk hectares are treated in the American West. If we assume that the rate of forestry restoration is constant through 2050, we estimate that the annual available forestry residues from wildfire mitigation activities applicable in 2050 will be 121 million tonnes. The geospatial distribution of the biomass from Western Forest restoration is shown in **Figure 6-7.**

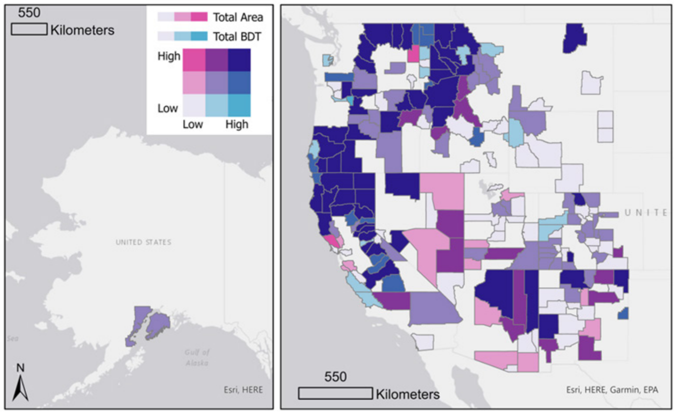


Figure 6-7. *Bivariate graphic of mid-century, 28.3-million-ha western-forest restoration biomass supply. Low-to-high hectares per county (gray to bright pink) and low-to-high tonnes per county (gray to bright blue) are shown. Counties with high hectares and high tonnage are represented in dark blue. BDT = bone-dry tonnes.*

Municipal Solid Waste (MSW) Biomass

MSW includes biogenic wastes that are in most cases already collected and destined for landfill. The wastes in this category are paper and paperboard (for which we conducted new analysis to update and refine collection and separation price estimates); construction, demolition, and other urban wood wastes; and food waste. MSW is attractive for BiCRS because it is already collected, and the alternative fate is landfilling, which can incur disposal costs and methane emissions from anaerobic decomposition in landfills. However, MSW is highly variable and separation costs are uncertain; for this reason, we assumed that a subset of the MSW with high ash composition was only suitable for combustion. We used data on MSW quantities for the contiguous United States from the 2016 Billion Ton Report and for Hawaii from the academic literature [17].

Subtopic: Paper and Paperboard

We considered availability of only non-recycled paper and paperboard as feedstocks for BiCRS to avoid unintended impacts on the recycled paper and paperboard market found a potential supply of 22 million tonnes per year at a price less than $50 tonne. Using these feedstocks can avoid landfill methane emissions and take advantage of pre-existing collection and sorting infrastructure (though additional infrastructure is likely required for sorting higher volumes of material). Our reported county-level availability is based on 2018 US Environmental Protection Agency (EPA) national estimates [18], allocated to counties by population, and excludes (subtracts) estimates of recycled material. To estimate prices, we added sorting costs (a range of $60–$80) based on population density and tipping fees (which can be negative) [19]. Densely populated counties typically result in lower delivered feedstock costs because sorting and collection costs are lower and avoided landfill tipping fees are higher. However, contamination will be a crucial challenge to overcome, particularly in regions where sorting infrastructure is limited or nonexistent. A limitation of prioritizing non-recycled paper/paperboard material is that there is a reason why it is not utilized. For example, some may not be captured in recyclable streams either because no curbside recycling program is available or because a materials recovery facility is rejecting it in bales that are contaminated. We do not know how future demand for this material will impact its recovery rates, if at all. By prioritizing county-level estimates of non-recycled material, our report likely sources paper/paperboard feedstock in regions where infrastructure/curbside recycling programs are currently insufficient to recover it. Further understanding of collection and sorting costs and investment in sorting infrastructure will be needed to capture this important resource for BiCRS.

Biogenic CO_2 Emissions: Focus on Biogas

Biogenic CO_2 emissions present a near term opportunity for CO_2 removal from current biomass-conversion facilities—here we included biogas from wastewater-treatment facilities and landfills in our primary analysis, but several other sources exist today, including paper mills and corn ethanol fermentation facilities. We discuss additional sources of biogenic CO_2 in

BOX 6-1

CO_2 Capture from Corn Ethanol and Pulp/Paper Industries:

The United States has a robust industrial bioeconomy currently emitting over 220 million tonnes of biogenic CO_2 per year [21, 22]. Ethanol fermentation and wood pulping are two existing industries with potential for carbon removal but are not included in our modeling study due to lack of granular LCA and TEA data along their respective supply chains.

The carbon intensity (CI) of producing ethanol from corn grain decreased by 23% over 15 years (2005 to 2019), largely due to an increase in grain yield with constant fertilizer input, an increase in ethanol yield during fermentation and downstream purification, and a reduction in energy consumption onsite at the ethanol refinery [23]. In addition, the generation of co-products that avoid fossil-carbon emissions have helped to decrease the CI for corn ethanol, including dried distillers grain and corn syrup for use in animal feed, corn oil for use in various products, and CO_2 used in food processing and beverage production. The ethanol industry emits ~45 million tonnes of biogenic CO_2 in a highly concentrated form (>90 mol%), which makes it amenable to low-cost capture. Approximately 60% of CO_2 emissions from ethanol refineries could be captured and compressed for under \$25/tonne CO_2 [22]. Several US industrial ethanol companies are currently capturing and storing CO_2 in geologic formations, including Archer Daniel Midlands [24].

We did not include corn grain–derived ethanol as a BiCRS pathway for modeling due largely to its inability to achieve a negative CI without substantial retrofitting of existing corn-ethanol facilities. LCA of corn-grain conversion to ethanol shows a positive CI score even when capture and sequestration of CO_2 and utilization of carbon-free electricity are included [25]. Retrofitting existing corn-ethanol facilities—including adding operations to capture post-combustion CO_2 from onsite boilers and replacing natural gas with clean fuels—has the potential to enable negative CI scores. We deemed including such retrofits into our modeling infeasible due to the complexities, variations, and uncertainties of mass and energy flows and economic metrics specific to existing corn ethanol sites across the United States. Future work should address these uncertainties on a granular, national scale. The co-production of cellulosic ethanol from corn stover has the potential to substantially enhance the carbon-emoval potential of the ethanol industry [26].

The pulp and paper industry is the largest bioenergy producer in the United States and annually emits ~115 million tonnes of biogenic CO_2 in various forms from multiple unit operations, including the recovery boiler (~13 mol% CO_2), multi-fuel boiler (~9 mol%), and lime kiln (21 mol%) [21]. Particular pulp mills have low-cost, high-quality thermal energy available onsite from the combustion of excess biomass waste streams that could be supplied to amine scrubbing technologies for CO_2 capture [21, 27].

Future work will develop detailed TEA and LCA data for the ethanol and wood pulp industries to understand the cradle-to-grave cost and overall impact of carbon removal in these two promising bioeconomy industries.

Table 6-2. *Summary of CO_2 fraction of biogas produced in the US (current and projected).*

Year	Wastewater and Existing Dairy Digesters (Tonnes $C0_2$/yr)	Landfill (Tonnes $C0_2$/yr)
2025	27 million	11 million
2050	31 million	7 million

Box 6-2. Biogas is a mixed gas stream derived from anaerobic fermentation of organic materials, with approximately equal volumes of CO_2 and methane composing about 95% of the total volume. Because of the relatively high CO_2 composition of biogas, separation of the CO_2 is straightforward and technologically mature, and hundreds of sites produce biogenic CO_2 suitable for BiCRS from biogas across the country today. Separation of CO_2 and other constituents from biogas—or "biogas upgrading"—results in pipeline-quality RNG that can be readily integrated into existing infrastructure as a drop-in replacement for natural gas. We show the supply of CO_2 from biogas that we used in our analysis in **Table 6-2**. We assumed that wastewater biogas sources increase over time due to projected population increases, and that the landfills are closed to new waste in 2025, resulting in an estimated decline in biogas production of 2% per year [20]. We made this assumption to avoid double counting biogenic carbon because we account for a signification fraction of (assumed) diverted biogenic wastes in our MSW assessments, though we acknowledge that the assumption that landfills would be closed to new organic waste in 2025 is highly conservative.

We regard separation and storage of CO_2 from biogas, with use of the resulting RNG to displace fossil-derived natural gas, as a near-term BiCRS carbon-removal opportunity. We assumed a price of $0/tonne for the biogas from these sources since it is already being produced and collected. However, in **section 6.3,** we assign costs to the separation of CO_2 from biogas as part of the BiCRS pathway.

Supply curves (**Figure 6-8**) for 2025 and 2050 baseline biomass assessments show distribution of biomass according to supply and cost for the three major types of baseline biomass described in the text (excluding biogas CO_2). For the near term (2025) baseline biomass, we find that the lowest price feedstocks are dominated by manure (shown at negative prices) and MSW. The majority of agricultural wastes are available at intermediate prices of $40–$60/dry tonne. The total baseline biomass available in the near term is 387 million dry tonnes per year. The mid-century (2050) baseline biomass potential cost curve shows the addition of 107 million tonnes per year from western forest restoration biomass, for a total of 494 million dry tonnes per year.

Baseline Biomass Distribution in the United States

In **Figure 6-6** above, we show the baseline biomass distribution across the United States from the combination of the three feedstock sources (agriculture, forestry, and MSW), with existing biogas-producing facilities shown as green points. Biogas facilities are located around major population centers. Biomass suitable for BiCRS is available in every state. High annual production regions include (but are not limited to) the Midwest and Great Lakes, central and northern California, the Pacific Northwest, and the Southeast. In **Section 6.2**, we will show the biomass distribution in each of 22 CO_2-removal regions in the United States.

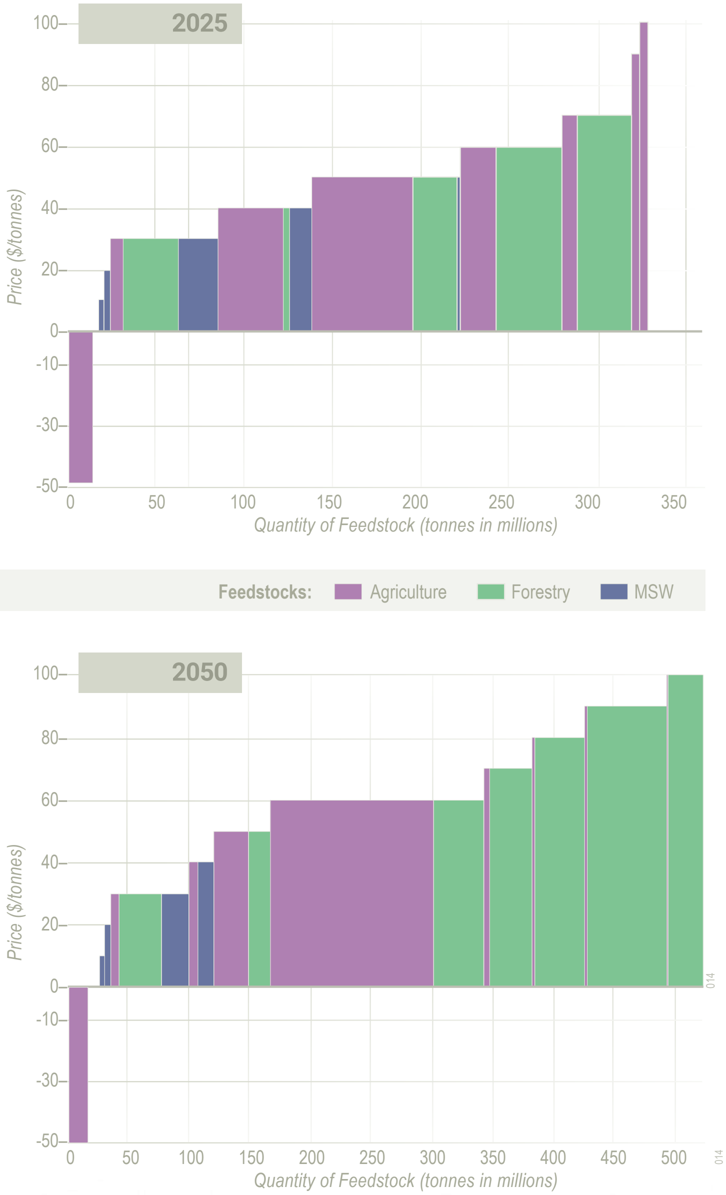


Figure 6-8. *Biomass supply curves representing the baseline (primarily wastes and residues) biomass supply and cost for 2025 and 2050 that we use in subsequent sections to estimate carbon removal rate and cost with no carbon crops or land-use change.*

Biomass Not Included in this Analysis

The above categories and subcategories do not represent all current or potential sources of biomass or biogenic carbon that could be used for BiCRS in the United States. Notably, we did not include some low-volume and challenging-to-separate feedstocks, such as leather or textiles; nor did we include fats oils and greases (FOGs) that are in high demand for conventional refining toward liquid fuel production. We also did not include an assessment of potential for micro- or macroalgae production, due to uncertainties in supply, cost, and technological readiness of appropriate conversion technologies.

6.2. 2050 Biomass Supply Potential with Additional Carbon Crops

BiCRS relies on biomass—and the associated lands on which it is grown—for the capture of atmospheric CO_2. Understanding biomass supply, price, and land-use impacts in a biomass-constrained future is central to understanding the role that BiCRS can play in carbon removal. Increasing biomass supply may provide higher levels of carbon removal, but impacts on other biomass uses, biodiversity, soil-carbon storage, and EEEJ must also be considered. In this section, we describe a new analysis of options to produce additional carbon crops in the United States. In **Section 6.3** we describe how biomass described in **Sections 6.1** and **6.2** can be used to create fuels and products and to durably store CO_2.

Carbon-Crop Supply Modeling Approach

In all carbon-crop approaches, we modeled biomass supply in a way that prioritizes biodiversity and carbon removal. To avoid creating carbon debt, we avoided lands with large existing carbon stocks. Thus, we excluded forests, wetlands, and soils with high carbon contents (such as Histosols). In order to avoid the potential negative biodiversity impacts of monocultures or non-native invasive species, we assessed only native perennial grasses (e.g., switchgrass) and trees (e.g., poplar, willow) for carbon-crop supply and assessed only native restored prairie on CRP lands and recognized biodiverse regions (e.g., the Flint Hills area in Kansas and Oklahoma).

For our “zero cropland change” and “maximum potential” assessments, we compared to baseline agricultural practices to calculate the change in soil carbon and input emissions. We use national economic models to track land-use and commodity-price changes—with commodity-price change as an imperfect metric to identify potential risk of carbon leakage. While we did not analyze how to avoid leakage, in a hypothetical leakage scenario, price increases of corn, soy, and wheat could lead farmers to increase the planted area of these crops elsewhere in the world at the expense of carbon stocks in native vegetation. The exact magnitude of this hypothetical effect is subject to discussion among academics, policy makers, and stakeholders. By assessing the carbon-crop supply from lands that are not used for food and other commodities, we designed our “zero cropland change” assessment to minimize such leakage.

BOX 6-2

Three 2050 Biomass Supply Options

To understand the impacts and opportunities for BiCRS biomass supply in 2050, we describe three primary approaches to land use and biomass cultivation in this report:

1) **2050 Baseline** is based on mid-century biomass supply potential under conditions where there is neither new biomass demand nor a carbon price. Only wastes, residues and biomass associated with current land use is assumed and no carbon crops are included. The 2050 baseline biomass supply was described in **Section 6.1**.

2) **Zero Cropland Change** in **Section 6.2** adds carbon crop biomass to the 2050 Baseline biomass supply. The analysis evaluates potential supply of native perennial grasses planted on unused cropland and pastureland, including CRP, marginal and abandoned lands, and land that could become available from widespread vehicle electrification and the potential reduced demand for grain-based ethanol as a gasoline additive.

3) **Maximum Economic Potentia**l in **Section 6.2** represents an economically driven biomass supply with sustainability constraints, including maximum potential for agricultural residues, and carbon crops. This assessment aligns closely with the Billion Ton reports (2011, 2016, and in press).

Instead of simulating a biomass price, which could provide perverse incentives for management practices that increase productivity at the expense of greenhouse gas (GHG) emissions (excess nitrogen fertilizer or irrigation, for example), we simulate a "carbon price" that accounts for input emissions and soil-carbon change in addition to biomass harvested. Under the carbon price simulation, the price received by landowners is equal to the carbon value of the annual biomass production plus the estimated annual amount of carbon stored in soils. The soil-carbon storage calculation also accounts for N_2O emissions from fertilizer application and is described in detail in **Chapter 3**. For reporting purposes, in this chapter we indicate prices in "per dry tonne of biomass" terms, but the equivalent value of carbon is also applied to soil-carbon changes. Biomass is 50% carbon, so biomass prices per dry tonne are 50% of the carbon price, or 183% of the CO_2 price (when multiplied by the molecular weight); a price of \$40/tonne CO_2 is reported here in biomass terms as a price of \$73/dry tonne. We did not assume a carbon market but did assume carbon will likely be roughly equally valued throughout the economy, either through a market or through policy enactment that incentivizes carbon reduction through payments (for example through the USDA Environmental Quality Incentive Program (EQIP)).

To accomplish this analysis, we simulated increasing levels of carbon incentives in each of the defined scenarios in economic models to estimate the quantity and type of lands that grow biomass crops, the quantity of biomass that would be produced on these lands, and the price impacts upon competing crops of any land-use change. We then used the land-use changes to model resulting changes in soil carbon and to estimate the economic cost of transporting the biomass from fields to processing plants to determine the final production cost of unique feedstock to fuel pathways (**Section 6.3**).

The mature-market biomass resource assessment quantifies potential production of dedicated carbon crops for BiCRS. To consider soil-carbon changes and a range of production scenarios that may mitigate carbon leakage from biomass-crop production for BiCRS, we include estimates of biomass-crop production from (1) from CRP lands, (2) so-called marginal lands and former cropland, (3) cropland made available because of reduced demand for corn grain ethanol due to electric vehicle (EV) adoption, and (4) market response on agricultural lands (**Table 6-3)**. These four approaches are combined into two mature-market assessments for biomass crops: (1) zero cropland change and (2) maximum economic potential. **Table 6-3** summarizes the modeling approaches for each mature-market assessment.

BOX 6-3

Restored Prairie: Carbon Crop Supply and Biodiversity

The conversion of abandoned cropland to restored prairie or another type of native plant community provides multiple ecosystem services not available from other feedstock plantings. First and foremost are services related to biodiversity – restoration of the native plant community provides new habitat for native taxa including insects and birds, now in steep decline across North America, and thereby contributes to national conservation targets and enhances the services provided by these taxa (e.g., Werling et al. 2014 [16]). Such services include pollination and the biocontrol of pests to benefit crops in the local landscape, wildlife amenities for recreation and public health, and the cultural value of their intrinsic worth. While restored prairie on infertile soil tends to produce less biomass than monocultures of switchgrass and other native grasses (e.g., Jayawardena et al., 2023 [17]), many landowners may prefer the more diverse assemblages of mixed grasses and forbs, which are also particularly well suited for areas of conservation concern such as the Flint Hills of eastern Kansas and Nebraska's Sandhills region. Life cycle analyses show a negative carbon intensity (g CO_2e MJ-1) for restored prairie that is even lower than that for purpose grown monocultures (e.g., Gelfand et al. 2020 [18]), though the lower productivity of restored prairie means that larger areas would need to be planted to achieve the same degree of climate mitigation.

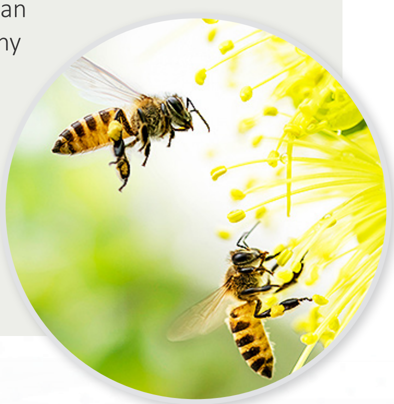


Table 6-3. *Summary of carbon crop modeling lands and categories in Mature Market assessment. Restored prairie is modeled in Flint Hills (Kansas) and Sandhills (Nebraska) areas.*

Category	Model	Biomass Type	Approach to Carbon Crop Assessment
Zero Cropland Change	POLYSYS	Restored prairie	Conservation Reserve Program lands
Zero Cropland Change	POLYSYS	Switchgrass and restored prairie*	Marginal and abandoned lands
Zero Cropland Change	AgModel	Switchgrass	Reduced corn ethanol demand from EV
Maximum Economic Potential	POLYSYS	Switchgrass, poplar, and willow	Market response on agricultural lands

The purpose of our analysis approach summarized in **Table 6-3** is to emphasize carbon accounting across the biomass supply chain and to consider how different carbon-crop production approaches affect the scale of the carbon-removal opportunity for BiCRS. All the biomass crops used in our analysis are native to the United States (to avoid undue biodiversity impacts) and are, to a large degree, generic—switchgrass, for example, can be considered a good representative of native grasses in general and poplar and willow are good representatives of fast-growing woody species. Our exclusion of miscanthus results in minor differences in supplies from the 2016 Billion Ton Report [8], but switchgrass and miscanthus are modeled similarly, from a production perspective, as perennial biomass crops.

Our results give insight into the impacts (carbon-removal potential, commodity-price impacts) of allowing or avoiding displacement of a subset of cropland for food production. All carbon-crop assessments avoid biomass production and prime cropland that is needed to meet projected demands for food, feed, fiber, and exports. The maximum-economic-potential approach results in commodity-crop price increases as reported in the text. Though increases in commodity-crop prices can negatively impact consumers, they can also mitigate historic chronic overproduction and below-cost commodity prices, which, if left unchecked, can have negative consequences for farmers and food security internationally [32]. Readers can consider the range of biomass-production approaches within the context of potential future tolerance for commodity-crop price impacts.

Zero-Cropland-Change Assessment: *Carbon-Crop Potential from Cultivation on Conservation Reserve Program (CRP) Lands, Marginal Lands, and Lands Spared Due to Vehicle Electrification*

Zero Cropland-Change: Assessment of Conservation Reserve Program (CRP) Lands

We evaluated restored prairie as carbon-crop sources on CRP lands as part of our zero-cropland-change assessment. This conservative approach assumes no current agricultural lands are converted to bioenergy-crop production, avoiding any potential for carbon leakage while making 7.4 million ha of CRP lands available for carbon crop production. Lands enrolled in the CRP provide wildlife, water quality, erosion prevention, and carbon benefits to the nation. A potential approach following CRP regulation for forage harvest is to allow lands that remain enrolled in CRP to be harvested for biomass every year if a percentage of biomass is left for wildlife. Currently, CRP can be harvested every three years with a 25% reduction in payment from the Farm Service Agency. To explore this approach, we compared the land-use transition under a mature biomass market with and without a biomass-harvest option. The results provide insight into how much biomass production can occur on CRP lands and to what extent the policy could maintain enrollment in CRP and preserve environmental benefits. We assumed that conversion of CRP to biomass harvesting does not lead to a net change in soil-carbon sequestration because the land remains in perennial cover (see **Appendix 6** for our economic-modeling approach and more details on methodology)

Results: Biomass Supply on Conservation Reserve Program (CRP) Lands

Our results indicate that up to 16.1 million dry tonnes of biomass can be harvested annually from CRP lands under a policy allowing biomass harvesting, and 10.9 million dry tons at a median reference price of $73/dry tonne (**Figure 6-9**).

In the status quo projection, about half of current CRP lands (3.8 million ha) return to conventional annual crops rather than renew (3.6 million ha re-enroll in CRP). Under the biomass-harvest policy and beginning at biomass prices over $73/dry tonne, more land is re-enrolled and harvested for biomass.

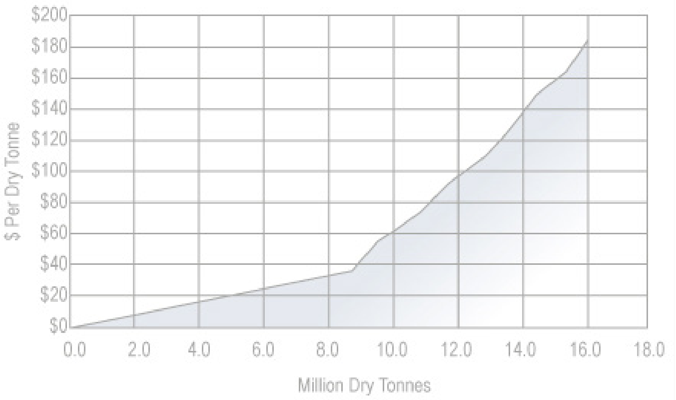


Figure 6-9. *Supply curve of biomass from Conservation Reserve Program (CRP) lands under a policy of allowing perennial grass harvest.*

As biomass prices increase, less land is converted to annuals and more lands remain in perennial grasses and are harvested for biomass. At a reference price of $73/dry tonne, conversion to annual crops declines to 2.9 million ha, 4.5 million re-enroll and remain in perennial mixed grasses to be harvested for 10.9 million dry tonnes of biomass, a 1.0-million-ha increase in perennial cover over baseline. At the high price of $183/dry tonne, only 1.2 million ha convert to annual crops and 6.3 million ha remain in perennial cover where 16.1 million dry tonnes are harvested for biomass (**Figure 6-10** and **Table 6-4)**. In **Chapter 3 – Soils**, we describe the loss of soil carbon that will result from land returning to annual crops. **Figure 6-11** shows the CRP lands that are used to grow mixed grasses for BiCRS in our zero-cropland-change assessment.

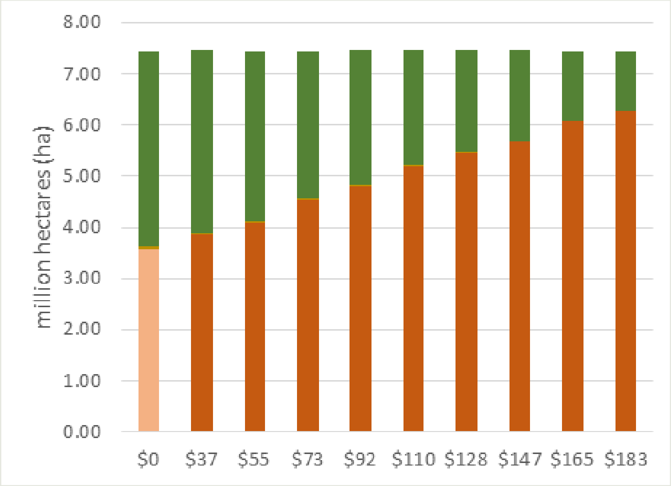


Figure 6-10. *Conversion of current Conservation Research Program (CRP) lands under a policy allowing newly re-enrolled lands to harvest biomass as biomass prices increase.*

Table 6-4. *Conversion of current CRP lands, perennial cover changes, and biomass production under policy allowing newly reenrolled lands to harvest biomass at increasing biomass prices by 2050.*

Biomass Price	CRP to Annual Crops	CRP to Pasture	CRP Re-enrolled	CRP to Established Grass Harvesting	Increase in Perennial Cover Over Baseline	Biomass Production
($/dry tonne)	*(Million ha)*					*(Million dry tonnes)*
$0	3.8	0.0	3.6	0.0	0.0	0.0
$37	3.6	0.0	3.9	3.9	0.3	8.8
$55	3.3	0.0	4.1	4.1	0.5	9.6
$73	2.9	0.0	4.5	4.5	1.0	10.9
$92	2.6	0.0	4.8	4.8	1.2	11.8
$110	2.2	0.0	5.2	5.2	1.6	13.0
$128	2.0	0.0	5.5	5.5	1.9	13.8
$147	1.8	0.0	5.7	5.7	2.1	14.4
$165	1.4	0.0	6.1	6.1	2.5	15.5
$183	1.2	0.0	6.3	6.3	2.7	16.1

*Established grasslands harvested are reenrolled

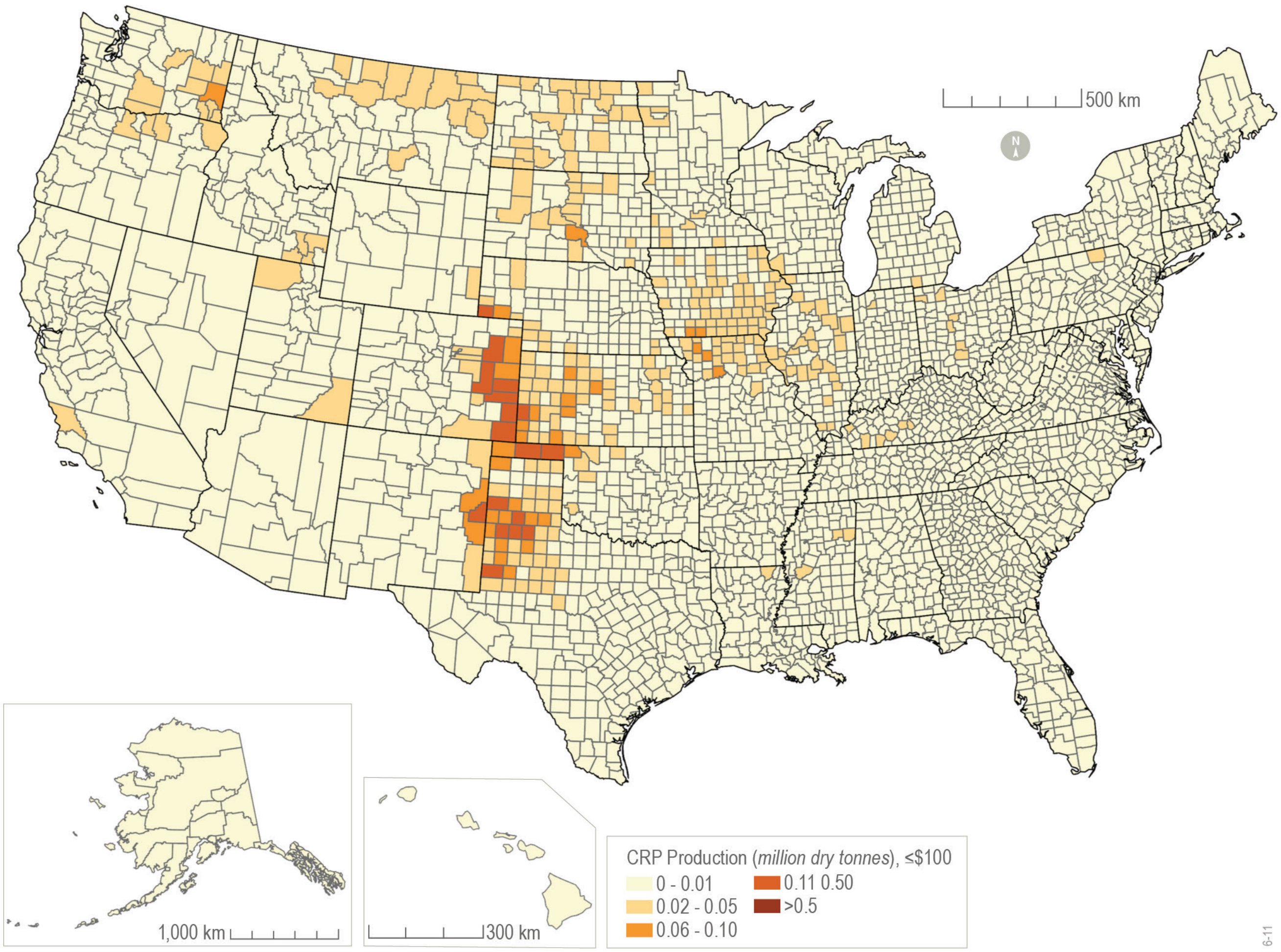


Figure 6-11. *Map of Conservation Reserve Program (CRP)-restored prairie production density under a policy allowing biomass harvest (at $100/tonne biomass).*

Zero Cropland Change Carbon-Crop Supply Potential on Marginal and Abandoned Lands

We define marginal lands for the purposes of this analysis as lands that can sustain production of grasses but are unsuitable for food production due to soil limitations. Marginal-land locations include the National Land Cover Database (NLCD) classes of shrubland, herbaceous land cover, hay/pasture, and barren land and exclude lands used for food crops or biodiversity-conservation areas. We also excluded lands that have trees or soil-carbon stocks that could be lost upon conversion to biomass crops and thus create carbon debts. Because marginal land only includes areas where farming grasses is possible, we excluded sloped lands, arid lands, public-owned lands, and private protected areas.

We used USDA land-capability classes to select land currently not used for food production and the Department of Energy (DOE) Great Lakes Bioenergy Research Center (GLBRC) Atlas of US Bioenergy Lands to further identify agricultural lands that have been abandoned since 1985 . We calculated the relative yield difference between marginal and arable lands at the county level, where the weighted National Commodity Crop Productivity Index (NCCPI) is estimated for county-level marginal and non-marginal lands. We then used the NCCPI estimates to differentiate and adjust crop yields from the reported county averages (see **Appendix 6** for additional methods). With yields differentiated, we used the Policy Analysis System (POLYSYS) model to simulate biomass prices from \$30–\$100/dry tonne to construct supply curves of biomass and associated subcounty marginal land-use changes. The model will also calculate the indirect impact of biomass production on commodity prices.

The marginal lands assessment assumes only marginal lands not currently used for agriculture will be available for biomass conversion and harvesting. The GLBRC's Bioenergy Lands Atlas estimates that 33.2 million ha of non-forested agricultural lands are poorer quality marginal lands and an additional 10.5 million ha of previously farmed land is not currently used for agriculture. We investigated the potential for this land to convert to switchgrass biomass production given the estimated yields on these marginal lands and the regional costs of production at increasing market prices.

The results give insight into how much biomass production can occur on marginal lands. The use of marginal lands does not compete with agriculture commodities for land and thereby does not impact food production or commodity prices. We assume marginal lands in our analysis are already vegetated in perennial grasses and that planting perennial carbon crops (i.e., switchgrass) will not change soil-carbon stocks significantly relative to baseline conditions.

Results: Biomass Supply on Marginal and Abandoned Lands

Our results indicate that 98.5 million dry tonnes of biomass can be harvested annually from 22.9 million ha of marginal lands at a reference price of \$73/dry tonne (**Figure 6-12**). **Table 6-5** shows the land conversion and switchgrass yield according to a range of biomass prices. Production of biomass from marginal lands reaches a maximum of 129.4 million dry tonnes at prices over \$180/dry tonne. At prices lower than \$50/dry tonne, production of biomass is not economical. There are no commodity-price impacts in the marginal assessment because there is no land-use competition between biomass crops and commodity crops. **Figure 6-13** shows the geospatial distribution of biomass in our marginal-lands assessment.

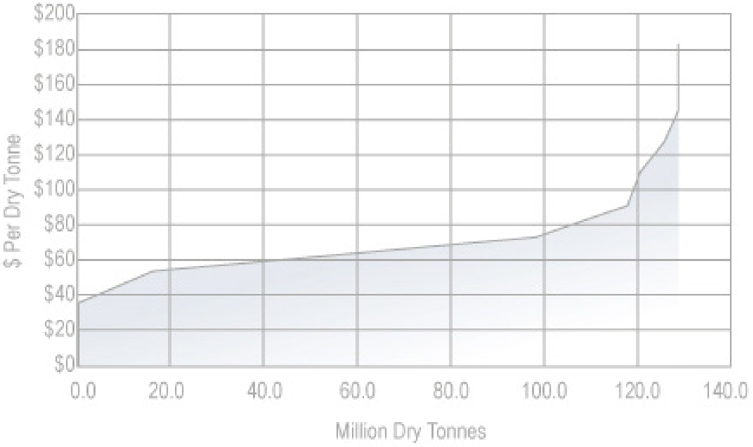


Figure 6-12. *Supply curve of biomass from marginal lands.*

Table 6-5. *Conversion of marginal lands to biomass harvesting and production at increasing biomass prices by 2050.*

Biomass Price	Marginal Lands to Biomass	Atlas Lands to Biomass	All Marginal Lands to Biomass	Biomass Production
($/dry tonne)	*(Million ha)*			*(Million dry tonnes)*
$0	0.00	0.00	0.00	0.0
$37	0.00	0.00	0.00	0.0
$55	2.34	0.97	3.31	16.7
$73	15.38	7.50	22.89	98.5
$92	19.48	9.41	28.90	118.3
$110	20.75	9.61	30.36	120.8
$128	23.85	9.66	33.51	126.4
$147	25.79	9.68	35.46	129.0
$165	25.93	9.69	35.63	129.3
$183	26.05	9.70	35.75	129.4

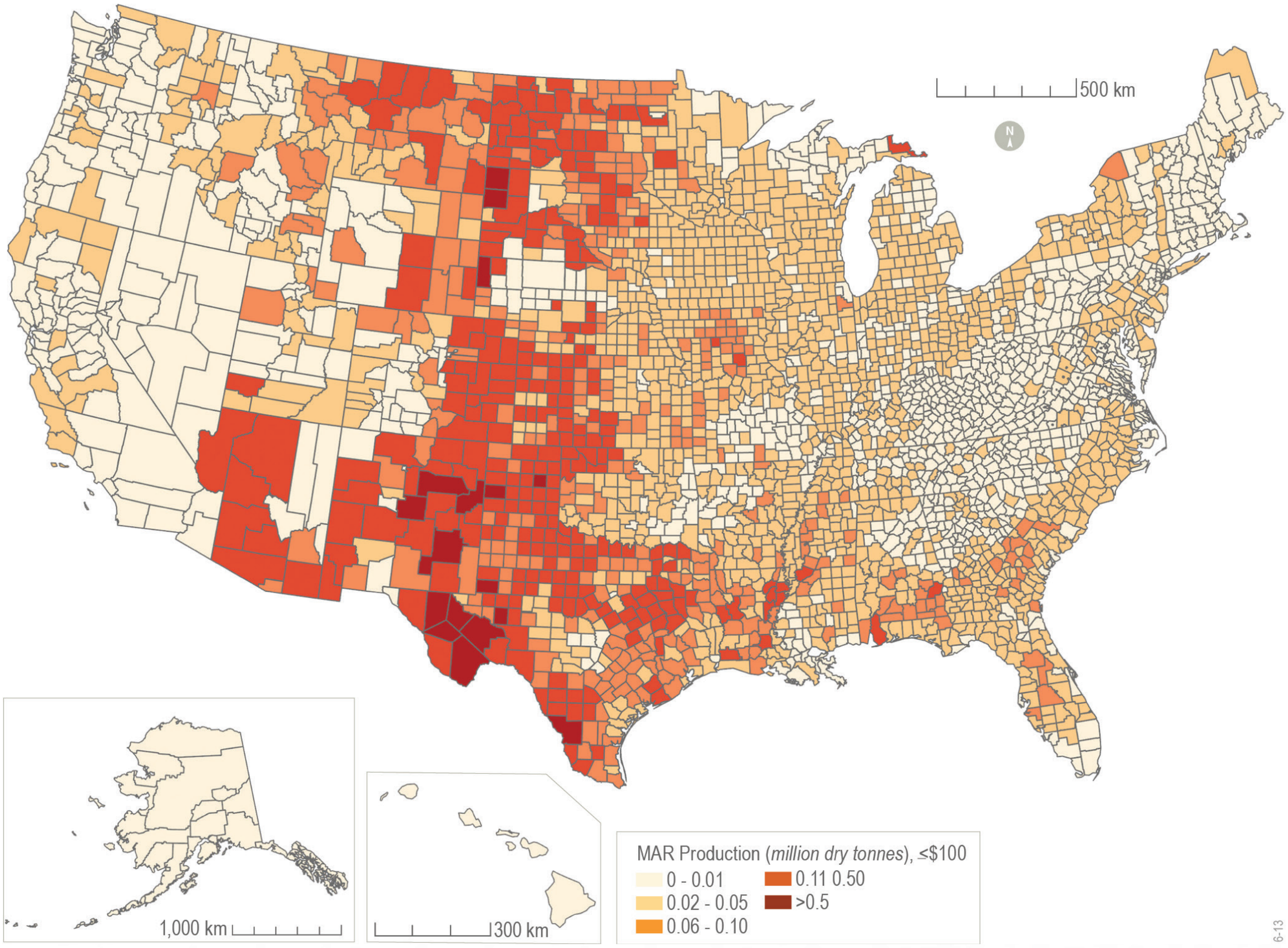


Figure 6-13. *Map of marginal-land biomass production available at less than $100/dry tonne.*

Zero-Cropland-Change: Carbon-Crop Supply on Lands Spared due to Vehicle Electrification

Almost one-third of current US corn-grain production is used for ethanol. Given the likely electrification of the US vehicle fleet over the upcoming decades and a potential reduction in corn-ethanol demand, we assessed the possibility of growing switchgrass on cropland that would be taken out of production from grain and oilseed cultivation. In this scenario, farmers are also paid for the CO_2 removal and subsequent storage in the soil given a positive carbon price. Using former corn-ethanol lands for biomass crops provides the greater climate benefit associated with cellulosic biofuels (including soil-carbon sequestration), with minimal impacts on commodity prices due to an acceleration of EV sales. We couple a road-transportation model with an agricultural-outlook model to assess the area and production of switchgrass after simulating an increase in EVs to nearly 100% of light-duty vehicle (LDV) sales by 2050.[1] The agricultural model also includes the possibility of harvesting agricultural residues (i.e., corn stover and wheat straw).

Specifically, we conducted the following two simulations:

- **Baseline:** We executed a baseline with status quo electrification rates based on the 2020 Annual Energy Outlook (AEO) published by the US Energy Information Administration (EIA). We assumed that prices on biomass and carbon are zero, and thus neither agricultural residues nor switchgrass are harvested or planted.
- **EV Assessment:** We executed a scenario assuming a logistic growth of the EV sales share reaching close to 100% in 2050. In this scenario, corn stover, wheat straw, and switchgrass are harvested and assigned a biomass price of \$73 per tonne and a carbon price of \$40 per tonne of CO_2 equivalent (CO_2e). Switchgrass is grown in the areas that are spared from production compared to the baseline.

Previous research has implemented comparable scenarios at the global level [33-35] . The findings at the global level showed that corn exports increase in the case of falling ethanol demand due to lower prices and not due to an increase in growing world population. The decline in corn demand and price from electrification leads farmers to reallocate land away from corn toward other crops (i.e., barley, rice, soybeans, sorghum, and wheat in this scenario). Due to the increase in production of these crops, prices decline as well. Because farmers allocate land based on the profitability of crops relative to each other and because the profitability of all crops decreases, total crop area declines in this simulation. Given this decrease in crop area, a county-level agricultural production model allocates switchgrass on that spared cropland [36]. **Table 6-6** shows that under an increasing biomass price, agricultural residues are supplied earlier than switchgrass due to lower production cost. **Table 6-7** shows the land area allocated to corn, wheat, and switchgrass. In the description of the results, the focus is put on corn and soybeans because these crops are mostly affected by changes in the ethanol demand, but the crop-area results are the aggregate of all crops covered.

Taking the 2020 AEO baseline vehicle electrification rates, long-term corn and soybeans prices are expected to decline by 47% and 48%, respectively, due to commodity yields increasing faster than demand, gains in fuel efficiency, and vehicle electrification. The long-term price decline for the other crops (i.e., barley, rice, sorghum, and wheat) is smaller, ranging from 17% to 42%. This range is in line with the February 2023 long-term projections by the USDA that indicate a decline of corn and soybean prices by 28% and 29%, respectively, over the much shorter period until 2033. Although these changes are seemingly large, historical year-to-year fluctuations for corn and soybeans have been ranging from-36% to 49%, which puts the long-term changes into perspective.

Corn price is most significantly affected by an increase in EV sales to 100% in the LDV market by 2050 because ethanol demand would decline 74% by 2050. In this scenario, corn prices are 21% lower in 2050 compared to the baseline. Note that although close to 100% EV sales are simulated by 2050, less than 100% of the vehicle stock would be electric and some internal combustion engine (ICE) vehicles would remain on the road due to the longevity of vehicles. Biomass and carbon prices combined with the possibility of harvesting agricultural residue leads to a smaller corn area decrease than in the baseline. The intuitive reason behind this finding is that the incentive to reduce corn area due to electrification would then be countered by the revenue opportunity from harvesting agricultural residues and obtaining incentives for CO_2 removal with geologic storage. The area allocated to the six crops declines by 2.1 million ha and is land on which switchgrass would potentially be grown. The agricultural model includes the cost of growing switchgrass, and only in counties where it is profitable (i.e., leads to a positive profit) is switchgrass planted and harvested. In this scenario, a total of 24.0 million tonnes of biomass from switchgrass is harvested due to the rapid electrification. We show the geospatial distribution of lands that transition from corn production to switchgrass production due to electrification at a biomass price of \$100/tonne or less in **Figure 6-14**. Note that 143.9 million tonnes of agricultural residues (i.e., corn

Table 6-6. *Biomass supply at various biomass prices for switchgrass growth on lands spared due to vehicle electrification.*

	BASELINE SUPPLY (Million dry tonnes)			ALL 2050 LDV SALES ELECTRIC SUPPLY (Million dry tonnes)			
Biomass Price (*$/tonne*)	Corn Stover	Wheat Straw	Total	Corn Stover	Wheat Straw	Switchgrass	Total
37	1.2	6.5	7.7	1.0	6.4	0.6	8.1
55	1.2	13.6	14.8	1.1	13.5	11.5	26.1
73	134.0	16.9	150.9	127.1	16.8	24.0	167.9
92	136.4	17.2	153.6	129.7	17.1	23.6	170.4
110	137.3	17.4	154.7	131.0	17.3	23.4	171.7
128	138.1	17.5	155.7	132.2	17.4	23.0	172.6
147	138.9	17.6	156.6	133.3	17.5	22.2	173.1
165	139.7	17.7	157.5	134.4	17.6	21.7	173.7
183	140.5	17.8	158.3	135.4	17.7	20.9	174.0

Table 6-7. *Area allocated in million hectares to corn, wheat, and switchgrass. The columns "corn stover" and "wheat straw"indicate the area harvested for biomass. The commodities modeled are barley, corn, rice, sorghum, soybeans, and wheat. LDV = Light-duty vehicle.*

BASELINE SUPPLY (Million Hectares)					ALL 2050 LDV SALES ELECTRIC SUPPLY (Million Hectares)				
	Corn		Wheat		Corn		Wheat		Switchgrass
Biomass Price ($/tonne)	Corn Stover	Total	Wheat Straw	Total	Corn Stover	Total	Wheat Straw	Total	
0		29.1	0.0	14.1	0.0	26.9	0.0	13.9	0.0
37	0.4	29.1	4.1	14.2	0.4	26.9	4.1	14.0	0.1
55	0.4	29.1	8.4	14.2	0.4	26.9	8.3	14.1	0.9
73	25.5	29.2	11.3	14.3	23.9	27.0	11.2	14.1	2.1
92	28.2	29.4	12.4	14.3	26.3	27.2	12.4	14.2	2.1
110	28.8	29.5	13.9	14.4	26.9	27.4	13.8	14.3	2.1
128	29.0	29.7	14.3	14.5	27.1	27.6	14.2	14.4	2.0
147	29.2	29.8	14.4	14.6	27.4	27.8	14.3	14.4	1.9
165	29.3	29.9	14.5	14.6	27.5	28.0	14.4	14.5	1.9
183	29.5	30.0	14.6	14.7	27.7	28.2	14.4	14.6	1.8

stover and wheat straw) are harvested because agricultural residue production and harvesting is cheaper than switchgrass production.

The EV assessment illustrates two possible paths forward for US agriculture. The first is a status quo with baseline electrification rates and no prices on biomass and carbon. In this baseline path, profitability for farmers decreases due to production growth's outpacing demand growth. The second scenario presents a path in which the US road transportation sector observes rapid growth of EVs by 2050 in addition to biomass and carbon prices. This analysis demonstrates the potential of biomass-feedstock production and soil-based CO_2 removal with minimal impacts on commodity prices assuming that land transitions out of row-crop production and into switchgrass due to changing market demand. Soil-based CO_2 potential from planting perennial carbon crops, such as switchgrass, are detailed in **Chapter 3 – Soils.** Distiller's dried grains with solubles (DDGS) are an important byproduct of ethanol production used for animal production. If ethanol decreases so will DDGS. But since ethanol decline does not change maize production proportionately, enough feed will still be available. At least five other aspects affecting agriculture warrant attention.

First, it is unclear what the effects of climate change will be on agricultural yields in the future. Increasing heat stress on plants can decrease yields, affecting supply to the point where the demand decline of ethanol is accompanied by a reduction in supply. This would potentially lead to an opposite effect of that described in the EV assessment because of upward pressure on crop prices.

Second, the provision of ecosystem services and voluntary carbon markets will likely shape future agricultural production. Entities offering payments to farmers for soil-based CO_2 removal could be competing with governmental programs such as the USDA's CRP. However, the USDA announced recently that the CO_2 removal potential of land enrolled in the program will be more heavily weighted in the decision process.

Third, the EV assesment assumes perfect foresight in terms of prices received for crops, biomass, and carbon; Dumortier 2014 [36] have shown that under return uncertainty from

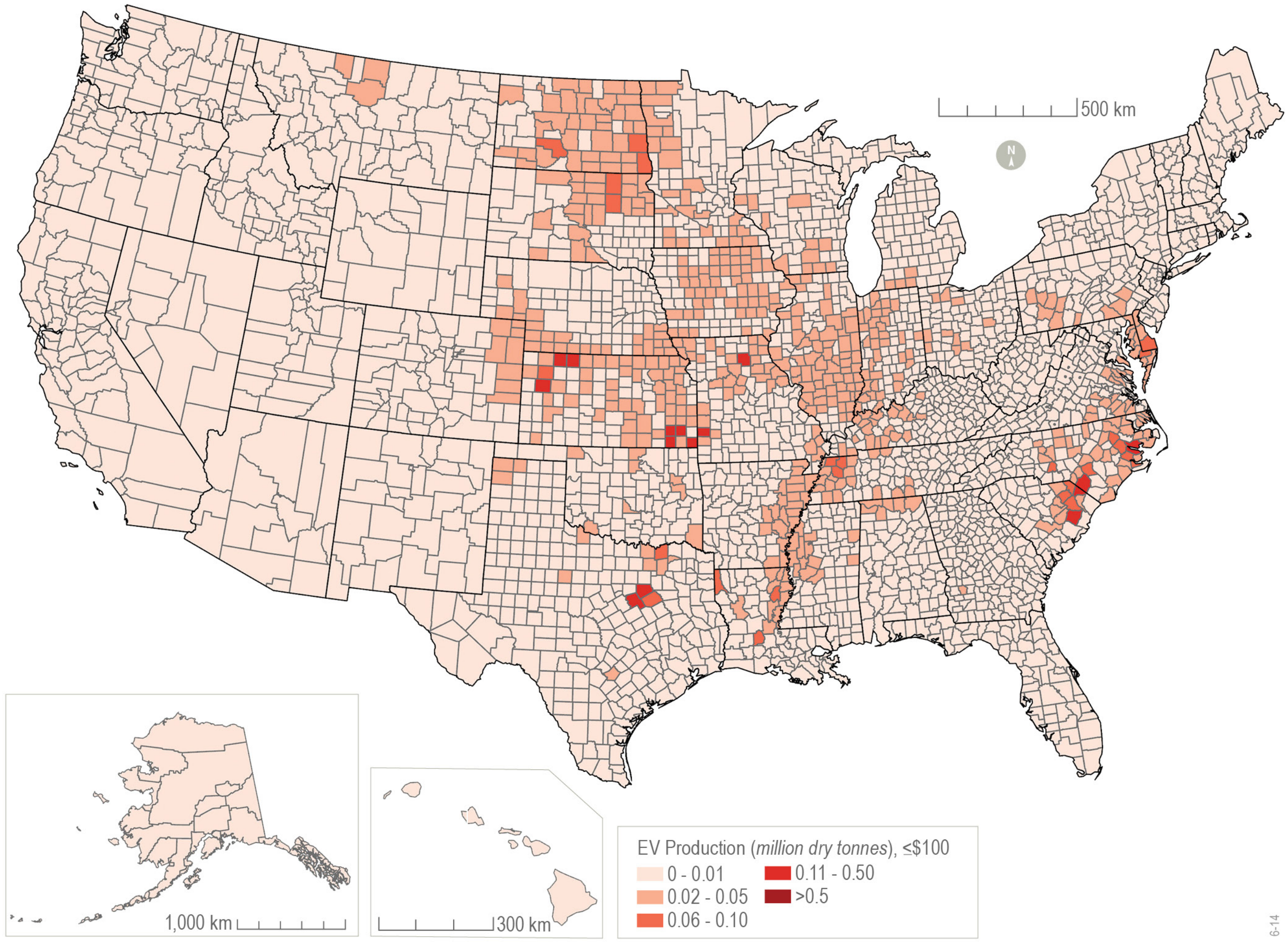


Figure 6-14. *Map of lands that convert to switchgrass due to decline in corn ethanol demand due to vehicle electrification at $100/dry tonne.*

agricultural and/or bioenergy crop production, investment is delayed. That is, farmers will wait to gather more information about future price development before planting switchgrass due to the establishment cost and multi-year commitment period of switchgrass. In the economic literature, this delay is referred to as the real-option value. That is, farmers have an option to wait and delay investment into a new technology (i.e., switchgrass) to gather more information about price development.

Fourth, the establishment of a new commodity on a large scale has other risks as well. For example, farmers may be unfamiliar with the timing and quantity of inputs and input management in general to achieve the highest yield. In the case presented here, switchgrass would likely not have an export market, and its value would be constrained to bioenergy and carbon storage.

Last, but certainly not least, is the uncertainty regarding the future use of corn ethanol beyond its current production technology and use. Given the interest in sustainable aviation fuels (SAF) or the possible combination of corn-ethanol production with carbon capture and storage (yielding a low carbon fuel), corn ethanol demand may not be reduced significantly in the upcoming decades.

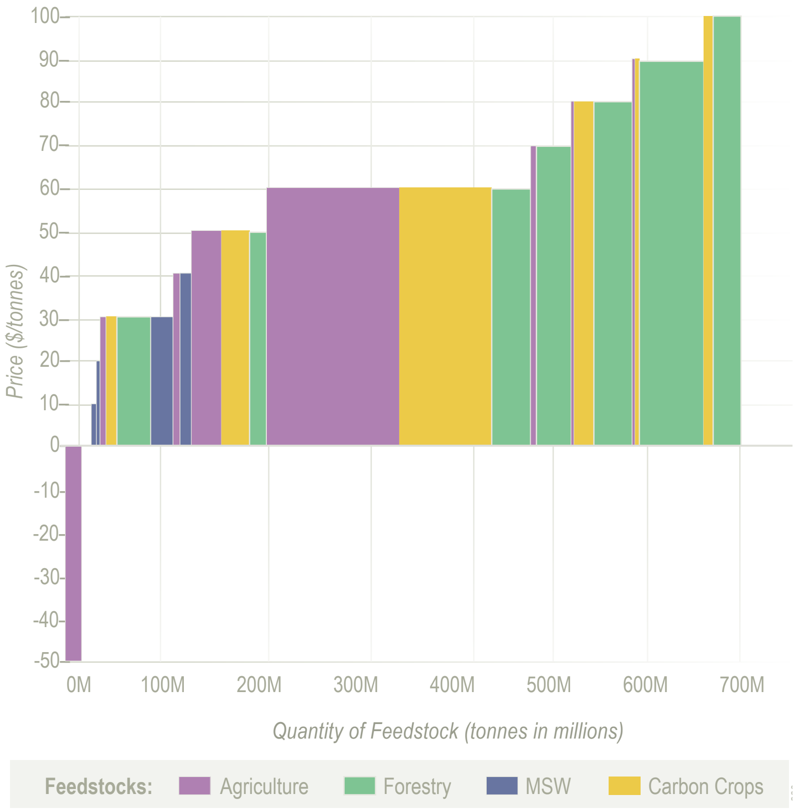


Figure 6-15. *Supply curve for zero-cropland-change biomass. The total biomass available in the zero-cropland-change approach is 648 million tonnes.*

Figure 6-15 shows the supply curve for the "zero-cropland-change" 2050 biomass assessment. The blue, purple, and green bars represent biomass from the baseline assessment, and the yellow bars correspond to additional carbon crops grown on non-cropland. The carbon crops shown correspond to a total of 154 million additional tonnes of switchgrass annually at a price less than $100/tonne.

Maximum-Economic-Potential Assessment: *Carbon Crop Potential from Market Response on Agricultural Lands*

In the maximum-economic-potential assessment, we allowed biomass crops (e.g., switchgrass and willow) and crop residues (e.g., corn stover and wheat straw) to come into production on any cropland or pastureland where it is profitable to do so (see **Appendix 6** for additional methods). Total agricultural lands considered included 123 million ha of cropland and 149 million ha of pastureland, of which 30 million ha covert to biomass crops at a price of $73/dry tonne (**Table 6-8**). We applied environmental constraints for soil conservation and soil organic carbon to crop-residue harvesting as described in the Billion Ton Update (2011) [12]. We investigated the potential for land to convert to switchgrass biomass production given the estimated yields on agricultural lands and the regional costs of production at increasing market prices.

Our results reveal how much biomass-crop production might occur on all US lands. The use of all lands will directly compete for land use with traditional commodity uses. We account for this interaction and report the price impacts. The maximum-economic-potential assessment allows for the conversion of annual cropland to perennial biomass crops, which will have a positive effect on soil-based CO_2 removal. The maximum-economic-potential-assessment pays an incentive to cropland to convert to perennial grasses at a price equating to the CO_2 value of offered biomass prices. Rates of soil-carbon accumulation vary with climate and soil characteristics. We tracked the net soil-based CO_2 removal and total soil-based climate benefit of land conversion, including N_2O mitigation, as reported in **Box 3-2** "Maximum Economic Potential" in **Chapter 3 – Soils.**

The maximum-economic-potential assessment aligns with the DOE 2016 Billion Ton Report [8], which estimates that ~400–700 million tonnes per year of biomass crops can be produced in the conterminous United States if market demand is realized. Though land availability is a constraint to biomass-crop production, our analysis and the 2016 Billion Ton Report [8] suggest that, with agricultural intensification, this production is possible on about 9% of US cropland and pastureland, while meeting projected future demands for food, feed, fiber, and exports. Though some commodity-crop price increases may be expected if biomass crops are produced at scale (see 2016 Billion Ton Report; Table C-9 and C-10), benefits of biomass-crop production include increased farm incomes, reduced government expenditures for farm-support programs, reduced soil erosion, and improved water quality [11].

Maximum-Economic-Potential Assessment Results

Our results show that 515 million dry tonnes of biomass could be harvested annually from 30 million ha of crop and pasture lands and 29 million ha of cropland harvested for residues at a reference price of $73/dry tonne (**Figure 6-16; Table 6-8 and 6-9.**) At a price of $110/dry tonne, 688 million dry tonnes could be produced. Production of biomass from US agricultural lands reaches a maximum of 831 million dry tonnes of carbon crops at the highest price simulated ($183/dry tonne).

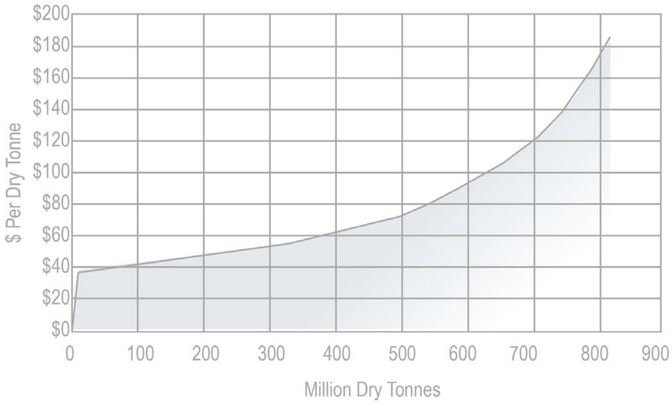


Figure 6-16. *Maximum-economic-potential biomass production. Supply curve of agricultural residues and carbon crops from all lands under the maximum-economic-potential assessment.*

At the reference price of $73/dry tonne, 20.4 million ha of pastureland and 9.2 million ha of cropland transition to switchgrass and woody biomass crops. As biomass prices increase, land converting to biomass crops continues to expand, reaching nearly 32.9 million ha of pastureland and 30 million ha of cropland at the highest simulated price of $183/dry tonne. **Figure 6-17** shows the spatial distribution of carbon crops (poplar, switchgrass, and willow production combined) that result from economic modeling. The lands that contribute carbon crops in this assessment were concentrated in Texas, Oklahoma, and Kansas and were also distributed in the Southeast, upper Midwest, and Appalachia.

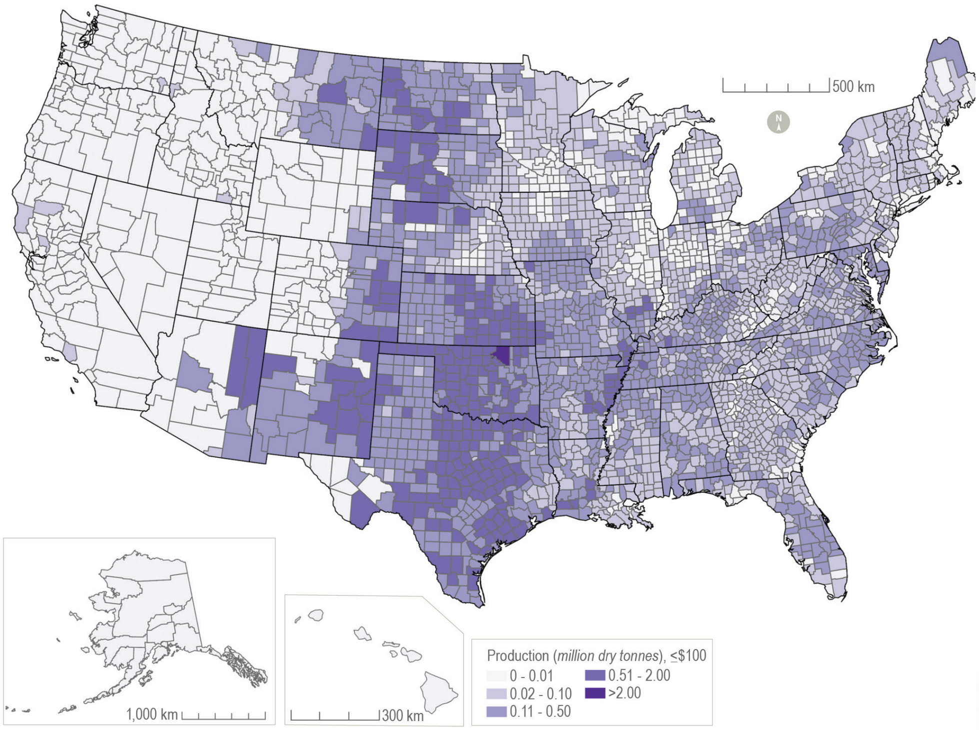


Figure 6-17. *Map of maximum-economic-potential biomass production from switchgrass, willow, and poplar combined at $100/dry tonne. The county-level production of the three types of biomass are shown separately in Appendix 6. Note the higher production scale on this maximum-economic-potential map than for the other carbon -crop assessments.*

Table 6-8. *Maximum-economic-potential assessment land conversion at increasing prices.*

Biomass Price	Pasture to Switchgrass	Pasture to Willow/Poplar	Cropland to Switchgrass	Cropland to Willow/Poplar	Total Land to Biomass Crops	Total Cropland Harvested for Residues
($/dry tonne)	*(Million ha)*					
$ –	0.0	0.0	0.0	0.0	0.0	0.0
$37	0.0	0.0	0.8	0.0	0.8	0.0
$55	9.1	0.5	5.1	0.1	14.8	22.3
$73	18.5	1.9	7.4	1.8	29.7	29.1
$92	20.8	4.8	9.5	4.0	39.1	31.5
$110	20.8	9.0	11.2	6.3	47.3	32.4
$128	18.7	12.2	11.9	8.9	51.8	33.8
$149	17.9	13.9	12.5	11.4	55.8	34.3
$165	17.6	15.0	13.2	13.7	59.6	34.2
$183	16.9	16.0	13.8	15.9	62.5	33.8

Table 6-9. *Maximum-economic-potential assessment production of biomass by land type at increasing biomass prices.*

Biomass Price	Biomass from Pastureland	Biomass from Cropland	Biomass from Residue Harvesting	Total Biomass
($/dry tonne)	*(Million dry tonnes)*			
$ –	0.0	0.0	0.0	0.0
$37	0.0	9.6	0.0	9.6
$55	142.9	48.0	144.9	335.7
$73	242.0	88.1	185.4	515.5
$92	266.2	139.1	204.7	610.0
$110	282.8	191.0	214.2	688.0
$128	286.5	227.4	226.4	740.2
$147	286.2	259.5	230.3	776.1
$165	285.2	288.0	230.6	803.8
$183	284.6	316.8	230.0	831.4

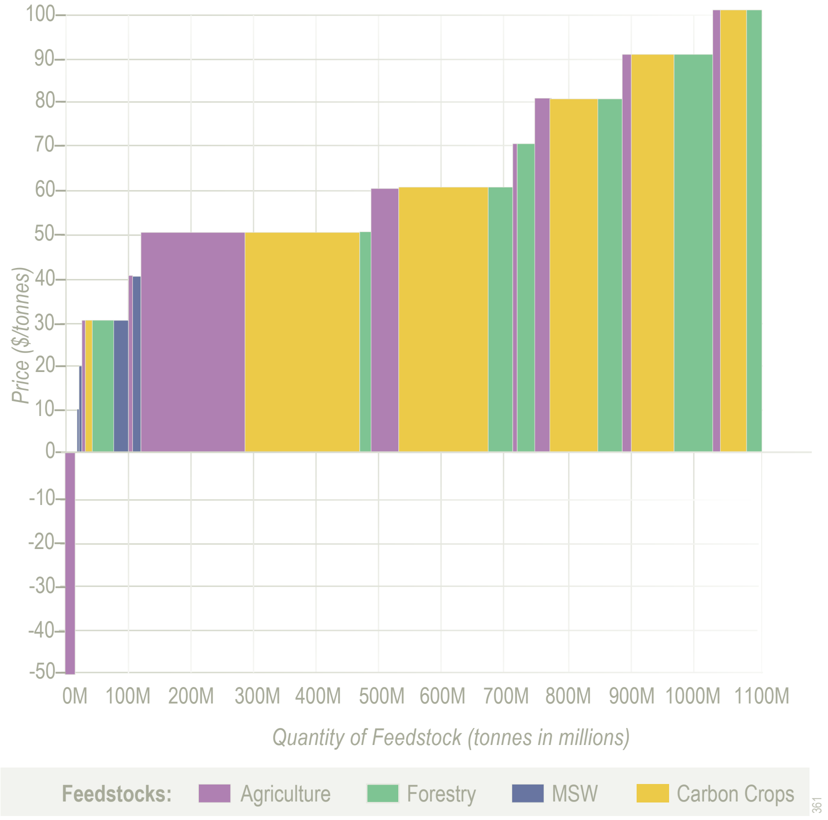


Figure 6-18. Price Impacts. *Supply curve for maximum-economic-potential biomass. Carbon crops are produced at prices between $50–$100/dry tonne; the total biomass potential is over 1 billion tonnes/year.*

Figure 6-18 shows the biomass supply curve for the entire maximum-economic-potential assessment, including forestry and MSW. Carbon crops in this assessment become available at biomass prices between $50 and $100/dry tonne.

Allowing biomass to compete for land with other agricultural uses impacts commodity prices in the maximum-economic-potential assessment (**Table 6-10**). As biomass prices increase and more land transitions to biomass crops, commodity-price impacts also increase. At a reference price of $73/dry tonne, prices increase by 6.2%, 11.5%, and 8.3% for corn, wheat, and soybeans, respectively. Corn-price increases are moderated at higher prices due to corn acreage staying steady from receiving residue-harvesting revenue. Soybean prices are most impacted by biomass competition with prices increasing by 68% above baseline in the highest priced simulation

Although commodity-crop price increases can negatively impact consumers, they can also mitigate historic chronic overproduction and below-cost commodity prices, both of which have negative consequences for farmers and international food security [32]. Readers can consider the range of biomass production approaches within the context of potential future tolerance for commodity crop price impacts.

Table 6-10. *Impact of maximum-economic-potential on commodity prices, in percent change from baseline prices in 2050.*

Biomass Price	% Change in Commodity Prices		
($/dry tonne)	Corn	Wheat	Soybean
$ –	0.0%	0.0%	0.0%
$37	0.5%	1.2%	0.8%
$55	3.5%	5.9%	4.5%
$73	6.2%	11.5%	8.3%
$92	6.5%	17.4%	16.7%
$110	11.2%	23.3%	23.2%
$128	7.2%	29.8%	39.1%
$147	5.7%	39.1%	51.7%
$165	7.0%	40.9%	64.2%
$183	8.0%	47.0%	67.7%

BOX 6-4

Opportunity for Cover Cropping to Produce BiCRS Feedstocks

Soil-based CO_2 removal incentives could expand practices on croplands that may provide an additional source of biomass. Cover cropping, the planting of ryegrass or other species during a rotational period that would otherwise be left fallow, produces additional plant biomass that does not compete with food production and is not sold as a commodity crop. Cover crop biomass may provide an additional source of BiCRS biomass feedstock although the harvest of a portion of aboveground biomass would likely reduce the soil carbon benefit. We simulated the biogeochemical and economical potential for cover crop expansion in the United States (see **Chapter 3**) and found that cover cropping could expand to 3.6 to 22.1 million hectares of cropland for CO_2 removal incentives of $40 and $100 per tonne CO_2, respectively. We tracked the aboveground biomass of cover crop (ryegrass) in each county assuming 50% carbon content in ryegrass shoots. To maintain some soil carbon benefits, we assume aboveground biomass harvest is limited to 50%. Without accounting for a shift in economics due to payment for ryegrass biomass, the available biomass from ryegrass cover crop could contribute an additional 3.1 million dry tonnes per year, depending on CO_2 price (**Table 6-11**), this would represent a lower limit for economically available biomass that could be harvested from cover cropping, without a biomass incentive.

Summary of 2050 Biomass Potential Results and Regional Distribution

Our mid-century biomass-assessment results are summarized in **Table 6-12**. We find potential availability of nearly 500 million tonnes of biomass without any change to land management in our baseline assessment for 2050. We identified the potential for over 140 million tonnes of additional biomass potential from growing switchgrass on non-cropland in the zero-cropland-change category. In alignment with the Billion Ton Report assessments, we find the potential for over 1 billion tons of biomass that could be available for BiCRS in our maximum-economic-potential category, where we did not apply constraints to limit carbon crops from current cropland. In the following **section (6.3)**, of this chapter, we distribute this biomass to available conversion technologies to develop an understanding of how the biomass availability impacts CO_2 removal and cost system wide.

Because of the diverse geography, geology, climate, biomass, economies, and populations across the United States, we have divided the country into 22 regions to capture the pertinent carbon removal considerations that fit between

Table 6-11. *Annual production of ryegrass biomass due to cover cropping, assuming 50% of the crop could be harvested the rest remains as residue to the soil. Economic viability included only soil-based incentives without payments for ryegrass biomass.*

Practice	Soil-Based Incentive	Equivalent Biomass Price	Economically Viable Land Area	Ryegrass Biomass Feedstock
	$USD/Tonne C02	*USD/dry tonne*	*Million Ha*	*Million dry tonnes per year*
Cover crop	40	73	2.8	2.3
Cover crop	100	166	20.8	15.4

Table 6-12. *Summary of results for 3 major biomass assessment approaches for 2050.*

Mid Century Potential Biomass Availability (Million Dry Tonnes) at $100/Tonne			
Biomass Type	**2050 Baseline (1)**	**Zero Cropland Change (2)**	**Maximum Economic Potential (3)**
Wet Waste (Manure + Food)	37.4	37.4	37.4
Agriculture	172.3	172.3	214.2
Forestry	125.8	125.8	125.8
Western Forest Restoration	107.7	107.7	107.7
Municipal Solid Waste	51.4	51.4	51.4
Restored Prairie on CRP lands	–	13.0	–
Switchgrass on marginal lands	–	120.8	–
Switchgrass on lands spared due to electrification	–	20.1	–
Maximum potential switchgrass	–	–	338.6
Maximum potential willow	–	–	100.0
Maximum potential poplar	–	–	35.2
TOTAL	**494.6**	**648.5**	**1,010.3**

the county and country levels. A detailed description of our approach to assigning these regions and a synopsis of general CO_2 removal considerations in each region across the removal categories can be found in **Chapter 10. Figure 6-19** shows the total biomass production within each region according to our (a) zero-cropland-change and (b) maximum-economic-potential assessments. The maps also show geologic-storage locations as shaded areas for context. We find that the regions where carbon crops are modeled to come into production in each of these two assessment approaches are similar, with South Central, Appalachia, Southeast, Upper and Lower Midwest, Lower Mississippi, and Texas regions providing the majority of carbon crops. We did not normalize the regional biomass supplies by area; therefore, smaller regions have lower production, as shown, but not necessarily lower production density.

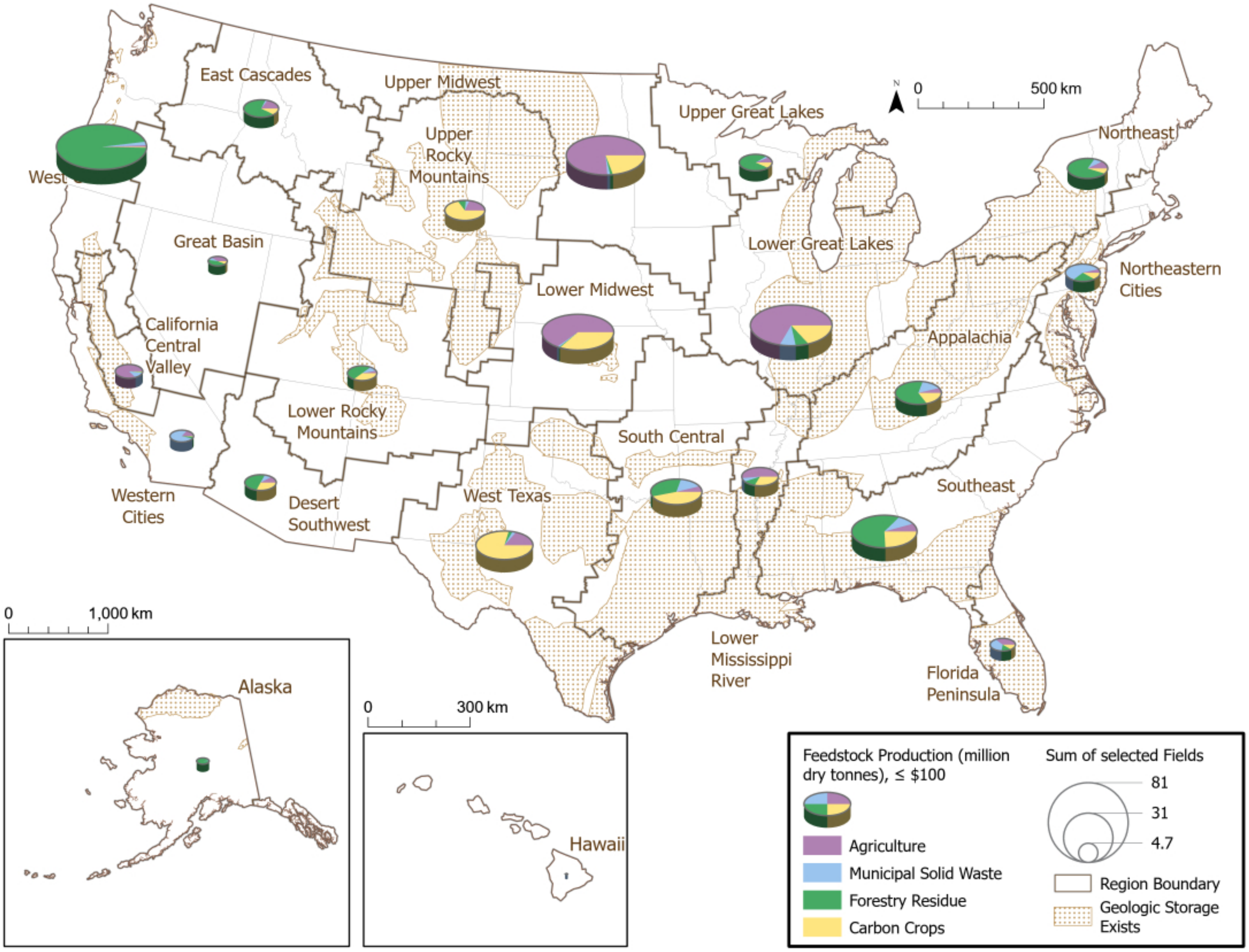


Figure 6-19a. *U.S. carbon-removal regions with biomass potential according to zero-cropland-change assessment.*

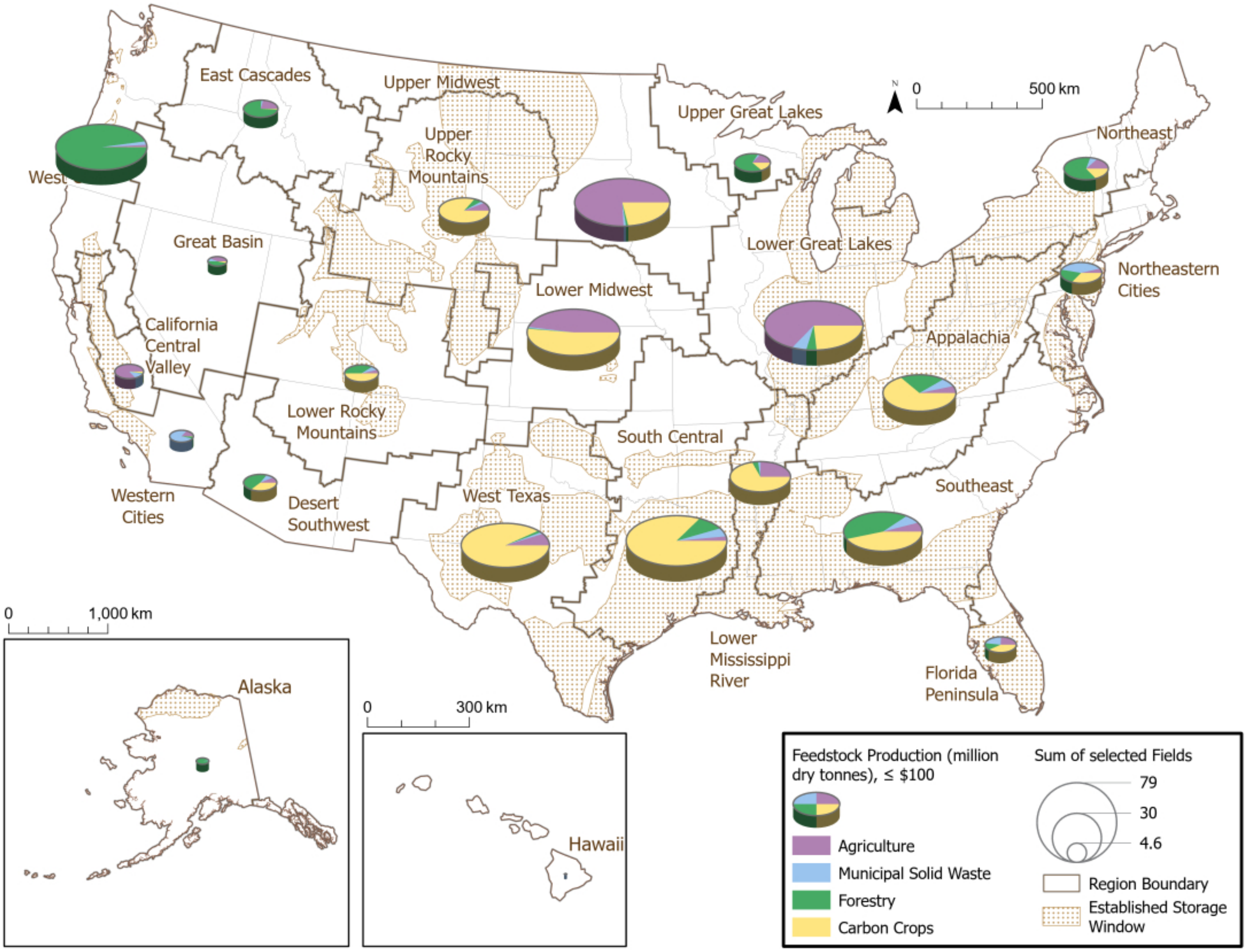


Figure 6-19b. *US carbon-removal regions with biomass potential according to maximum-economic-potential assessment.*

6.3 BiCRS Conversion Technologies

BiCRS requires the union of land, biomass, biorefinery, co-product offtake, and CO_2 storage to achieve CO_2 removal from the atmosphere. **Section 6.1** described 2025 and 2050 biomass supply from wastes and residues, and **Section 6.2** described approaches to increasing biomass supply for BiCRS through production of dedicated carbon crops. This **section (6.3)** describes the remaining critical steps to produce energy products, biomaterials, and carbon-storage products to enable BiCRS. The goal of this section is to understand the scale, cost, and impact of BiCRS for CO_2 removal in the United States by linking biomass supply to transportation and conversion infrastructure. We developed a computational-optimization tool to assist in this understanding and applied constraints or varied the biomass feedstocks introduced to the model to answer specific questions. For example, we sought to understand how the approach to cultivation of carbon crops impacts carbon-removal capacity and cost, how BiCRS pathways can be used to meet US demand for hydrogen and SAF, and how the build-out of a CO_2 trunk line can impact accessibility and cost of BiCRS in specific regions.

Figure 6-20 shows the general biomass-conversion technologies, bioproducts, and sinks that we analyze in **Section 6.3**. In this section, we describe the specific biomass-conversion technologies we assumed in this report, as well as our assumptions about biomass suitability for these technologies. In addition, we describe potential biorefinery sizes and sites and connect this information to system-wide and regional BiCRS carbon-removal costs, products, and impacts.

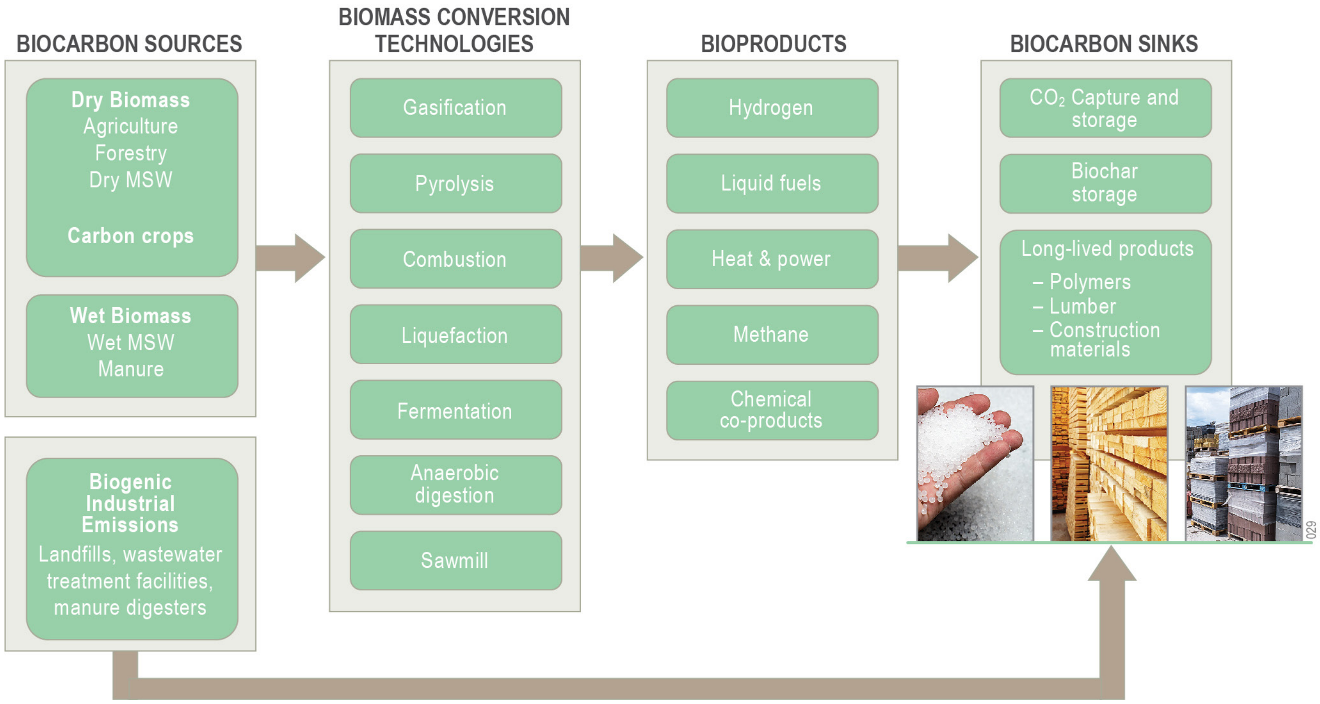


Figure 6-20. *Overview of BiCRS pathways analyzed in this report.* ***Chapter sections 6.1 and 6.2*** *described our assessment of biocarbon sources, and* ***Section 6.3*** *directs the appropriate biocarbon sources to conversion technologies to evaluate CO_2-removal capacity and cost. MSW = municipal solid waste.*

BiCRS Biorefineries: Selection and Description of Biomass Conversion Technologies

BiCRS facilitates the conversion of biologically fixed CO_2 into a wide range of different end products with varying degrees of durable CO_2 removal. Since the primary goal of BiCRS is durable removal of CO_2 from the atmosphere, in this section, we define CO_2 as the primary BiCRS bioproduct and other additional value-added bioproducts as the co-products. BiCRS co-products can be classified as bioenergy, biochemicals, and biomaterials and can contribute to carbon removal by various mechanisms. For this study, we selected seven BiCRS technologies, which can produce seventeen distinct co-products categorized as bioenergy, biochemicals, and biomaterials (shown in **Figure 6-21)**. The technologies are classified as thermochemical, biological , and mechanical and include gasification, combustion, fermentation, pyrolysis, sawmill, anaerobic digestion (AD), and hydrothermal liquefaction (HTL). All BiCRS technologies selected for analysis are of TRL 7+ and have been demonstrated at relevant scale and under realistic conditions to enable quantitative comparisons. We also only included BiCRS practices that are supported by extensive literature on 100-year carbon removal durability. We did not include any assumptions about cost reduction due to learning.

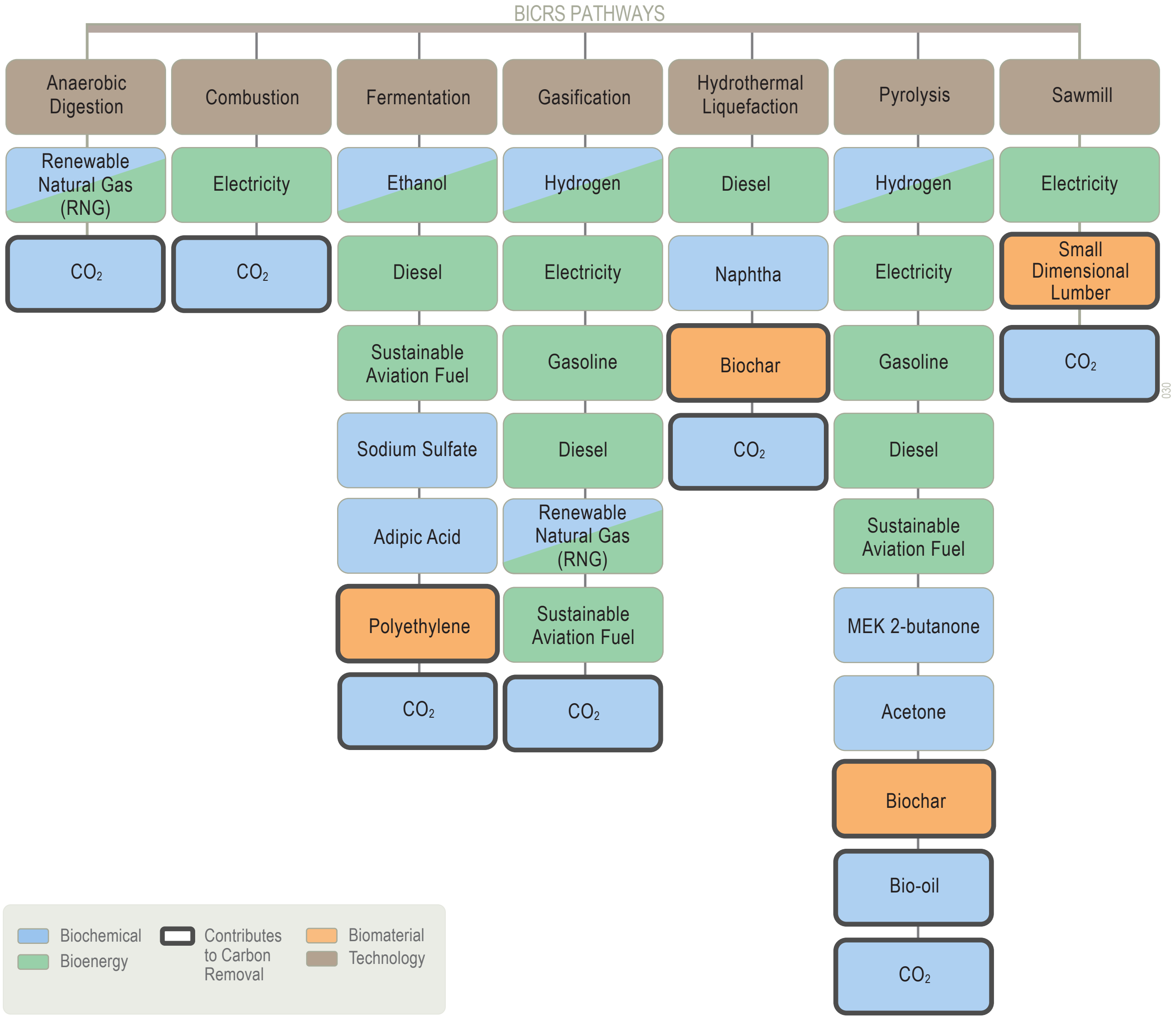


Figure 6-21. *BiCRS pathways assessed, including the conversion technologies and bioproducts. Bioproducts that store carbon and contribute to 100-year carbon removal are outlined.*

BiCRS Technology Classifications

We categorize the BiCRS biomass conversion technologies as thermochemical, biological, or mechanical: thermochemical technologies rely on heat and/or inorganic catalysts, biological technologies use micro-organisms and/or enzymes, and mechanical technologies use physical forces to reconfigure biomass into bioproducts. Thermochemical technologies are advantageous due to their ability to rapidly process a variety of feedstocks into various products but require complex operations under harsh conditions. Biological technologies are advantageous due to their mild process conditions and high value products but are limited to a relatively small set of feedstocks and require lengthy process times. Mechanical technologies are advantageous due to their simplicity and low-risk but are limited to a relatively small set of feedstocks and low-value products.

Thermochemical BiCRS Technologies

Gasification

Gasification is a mature thermochemical process that can convert any carbon-based material into various fuel products; it was first used in the 1800s with coal and later natural gas [37]. While smaller proof-of-concept projects have been shown, full-scale biomass gasification projects are yet to be demonstrated. The largest biomass gasification biorefinery in the world is in Finland and only processes about 526 metric tons per day of forestry biomass [38]. Despite being mature and efficient for coal, biomass gasification's complexity leads to higher costs [39], resulting in much smaller-scale biorefineries compared to coal/natural gas gasification.

Gasification involves breaking down biomass at high temperatures (700–1200 °C) and pressures (3–30 bar) into syngas, which is primarily composed of carbon monoxide, hydrogen, CO_2, and a small amount of CH_4. Syngas can then be converted into various products via different downstream processes, as shown in **Figure 6-22.** As an endothermic process, gasification requires heat. Heat required for gasification processes can either be provided directly from partial oxidation inside the gasifier (via an oxidizing agent such as oxygen, steam, or air) or indirectly from combusting char, syngas, or biomass in a separate reactor and then transferring heat via heat carriers. Char from gasification is typically combusted for process heat and is not considered an option for carbon storage and removal mainly due to its properties, which are strongly influenced by the type of thermochemical technology. Char produced via gasification has a high ash content and heavy metals, which is unsuitable for soil amendment and, therefore, cannot facilitate carbon removal. Thus, this analysis does not consider treating char as a co-product or carbon-removal agent. Gasification is preferably used to process low-moisture feedstock (<20% moisture content) over high-moisture feedstock to minimize the energy needed for biomass drying and to maximize thermal efficiency. Our analysis assumes an oxygen-blown gasification reaction (see **Figure 6-22**), based on models from Larson et al. (2009) [40], with a basis of 2000 metric tons per day of biomass input. For full process description and modeling assumptions for each product, see **Appendix 6.**

Gasification stands out among technologies with its high CO_2-removal potential. For all fuel products except hydrogen, 26%–36% of carbon in biomass is converted into fuels, while the remaining 64%–74% can potentially be captured and stored (after recycling and combustion for process heat and electricity). Hydrogen offers the highest carbon-removal potential (ranging from 1.50–1.85 tonnes of CO_2/tonnes of biomass), as 100% of carbon in biomass can be theoretically captured and stored, given that the produced fuel (hydrogen) is carbon-free. Gasification is a capital-intensive process; the gasifier alone can contribute to 25% of the capital cost. Larger biorefinery sizes can take advantage of economies of scale, which could have a 32%–44% reduction effect on capital costs.

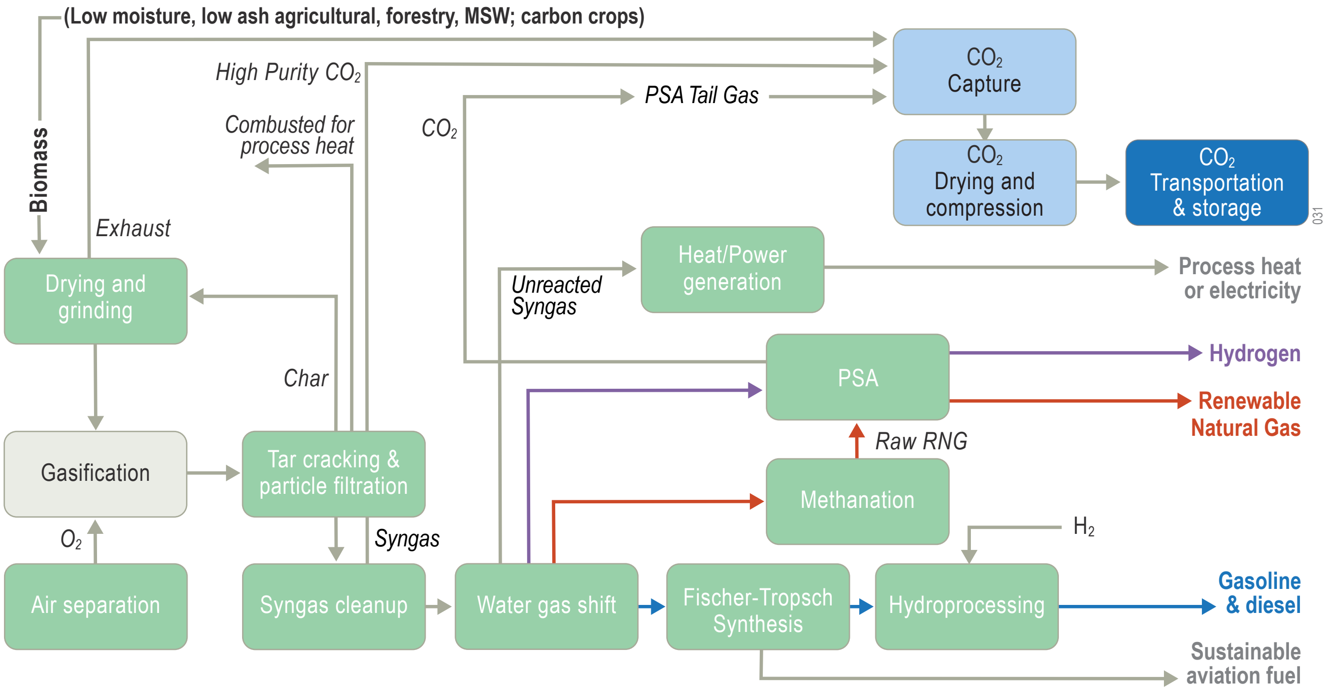


Figure 6-22. *Simplified block flow diagram of gasification to various products with carbon capture and storage. Three gasification pathways are included in this diagram: gasification to liquid fuels, gasification to H_2, gasification to renewable natural gas (RNG).*

Pyrolysis

Similar to gasification, pyrolysis is also a thermochemical process that converts biomass into various energy products. Pyrolysis was reconsidered as a technology to reduce fossil-oil dependence during the oil crisis and was commercialized during the 1970–1980s [41]. Since then, there have been several commercialized pyrolysis biorefineries globally ranging from 84–500 tonnes of biomass throughput per day, where most are using woody biomass as feedstock and producing bio-oil to be upgraded to transportation fuels [42-44]. Most pyrolysis companies focus on smaller or modular systems to better scale with farm sizes.

Pyrolysis is carried out at moderate operating temperatures (300–600 °C) and atmospheric pressures in the absence of oxygen. It offers a lower capital cost than gasification due to its moderate operating conditions. Pyrolysis breaks down biomass and produces products in three phases—gas, liquids, and solids. There are mainly two types of pyrolysis—slow and fast. They differ in operating temperature, heating rates, and residence time and therefore result in different distribution of the three phase products. Fast pyrolysis operates at higher temperatures and rapidly quenches pyrolysis vapors, maximizing bio-oil yields. The resulting bio-oil can be converted into various end products, such as H_2 or transportation fuels, or it can be blended with petroleum-derived asphalt to create bio-asphalt [45]. In our analysis, we focused on fast pyrolysis for all pathways due to the potential to upgrade bio-oil into multiple valuable end products. The modeled fast pyrolysis process is based on previous work at the National Renewable Energy Laboratory (NREL) [46], assuming 2000 metric tons per day of biomass throughput. For full process description and modeling assumptions for each product, see **Appendix 6.**

Fast pyrolysis, like gasification, favors low-moisture feedstock (<20% moisture content) to minimize heat demand and thus maximize thermal efficiency [47]. Bio-oil, as the main product of fast pyrolysis (typically 60–70 wt% of biomass), can be further upgraded into various products (see **Figure 6-23**). Bio-oil can be upgraded into liquid fuels (e.g., gasoline and diesel) via hydrotreating to produce either hydrogen via steam reforming or bioasphalt, assuming direct blending of bio-oil into fossil asphalt at a 10% rate [48]. Fast pyrolysis also produces by-products like non-condensable gases and biochar. The gases are typically combusted for process heat and power with CO_2 capture. Biochar is a porous carbon-

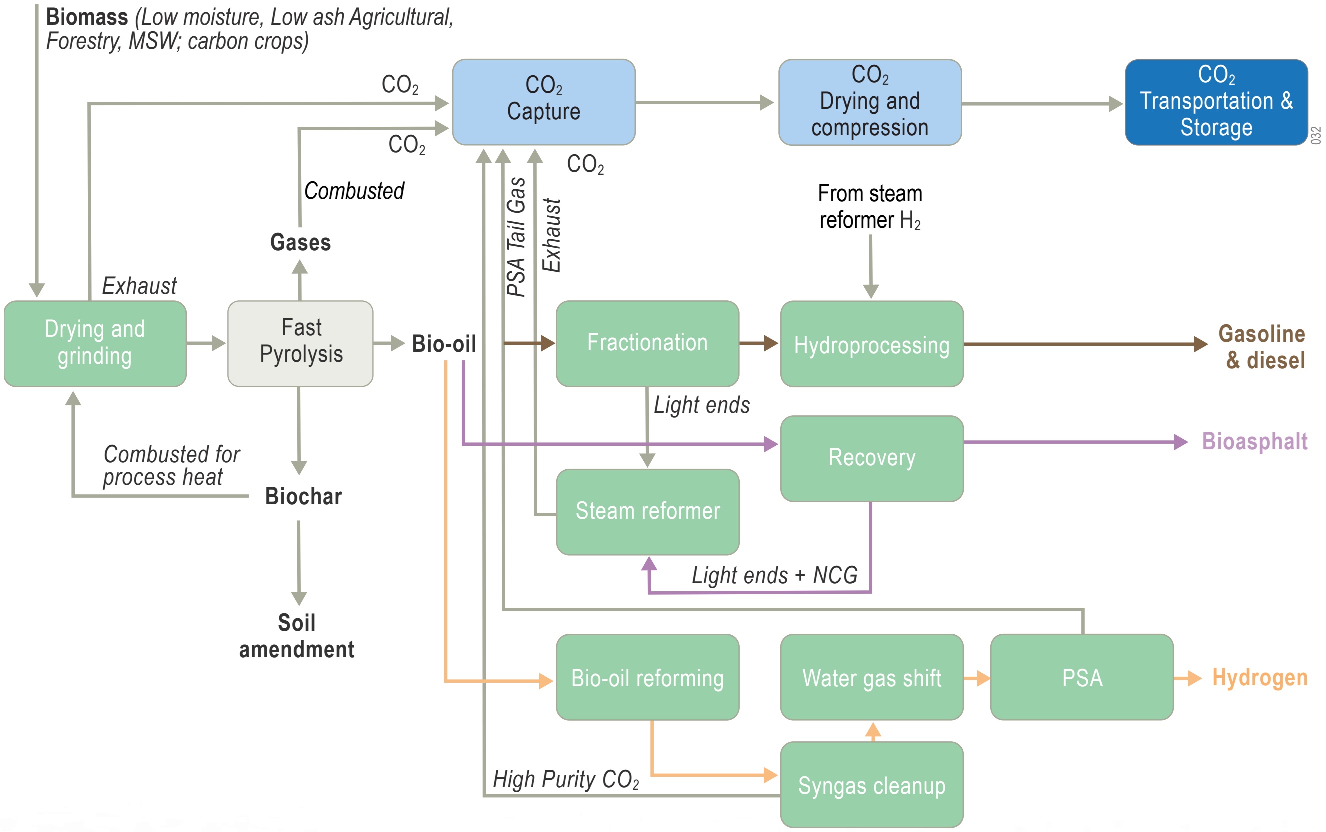


Figure 6-23. Simplified block flow diagram of pyrolysis to various products with carbon capture and storage. Three pyrolysis pathways are included in this diagram: pyrolysis to liquid fuels, pyrolysis to H_2, and pyrolysis to bio-oil to make bioasphalt.

rich product **(typically 12-25% of total biomass' carbon depending on feedstock type)**. In our analysis, biochar serves two purposes: providing process heat and energy through combustion or facilitating carbon removal when sequestered in soil. We assume that 80% of biochar carbon can be stored for over 100 years, while 77% of bio-oil carbon can persist as asphalt for over 100 years [49, 50]. The overall carbon-removal potential of pyrolysis depends on the product. When liquid fuels are produced, 33% of the carbon in biomass is converted to fuels and the remaining 67% can potentially be captured and stored. Similar to gasification, when hydrogen is produced, all carbon in the biomass can theoretically be captured as the fuel produced does not contain any carbon. When products like biochar and bioasphalt are produced, we assume 57%–74% of carbon in the biomass can be captured and durably stored in these products. This results in varying carbon-removal potential from 0.58 to 1.14 tonnes of CO_2/tonnes of biomass, depending on the final product.

Combustion

Combustion of biomass for generating high-quality heat is an established technology that can process a variety of different biomass feedstocks. The chemistry involved in biomass combustion is simple and low risk. However, the main products generated from biomass combustion—steam and electricity—are relatively low value and must compete with emerging low-carbon energy technologies, such as photovoltaics, wind turbines, and heat pumps. Nonetheless, combustion of biomass to produce bioenergy with carbon capture and storage has an important role to play in decarbonization due to its high carbon-removal potential [51, 52]. Conventionally, it has been demonstrated on a commercial scale to be economically viable under certain circumstances [53]. Herein, we model a conventional biomass combustion to electricity with carbon capture and storage process comprising several unit operations: biomass feed handling and conditioning, combustor, boiler, turbogenerator, and CO_2 capture, drying, and compression, as shown in **Figure 6-24** . For full process description and modeling assumptions, see **Appendix 6.** The gate-to-gate carbon removal efficiency of the combustion BiCRS pathways is estimated as 1.628 tonnes CO_2/tonne biomass , which is 90% of the theoretical removal efficiency, for both near- and long-term assessments. We modeled only greenfield combustion biorefineries given the relatively small number of existing biomass-to-electricity combustion facilities in the United States.

Hydrothermal liquefaction (HTL)

HTL is a thermochemical process that converts biomass into liquid fuels at moderate temperatures (250–375 °C) and operating pressures of 4–22 MPa [54]. It differs from gasification and pyrolysis as it can efficiently convert higher moisture biomass, like manure and food waste , into biocrude without the need for biomass drying. The process we analyzed in this report recycles the aqueous liquid product streams to AD and steam reforming, generating the hydrogen needed for biocrude upgrading via hydrotreating. Around 53% of the carbon in biomass is converted into fuels, with an additional 31% of the carbon in off-gas streams being captured and stored. However, due to low concentrations and small volumes, a small portion of carbon (less than 16%) remains vented, posing challenges and costs for capture and storage. In a zero-emission grid future in 2050, HTL has the potential to remove 0.49–0.62 tonnes CO_2/tonne biomass. The HTL process modeled in this analysis, as shown in **Figure 6-25** , is based on recent work at the Pacific Northwest National Laboratory (PNNL) [55]. The process is based on a 110 dry tons of sludge per day HTL biorefinery and a biocrude-upgrading facility that processes 38 million gallons of biocrude per year, fed from multiple

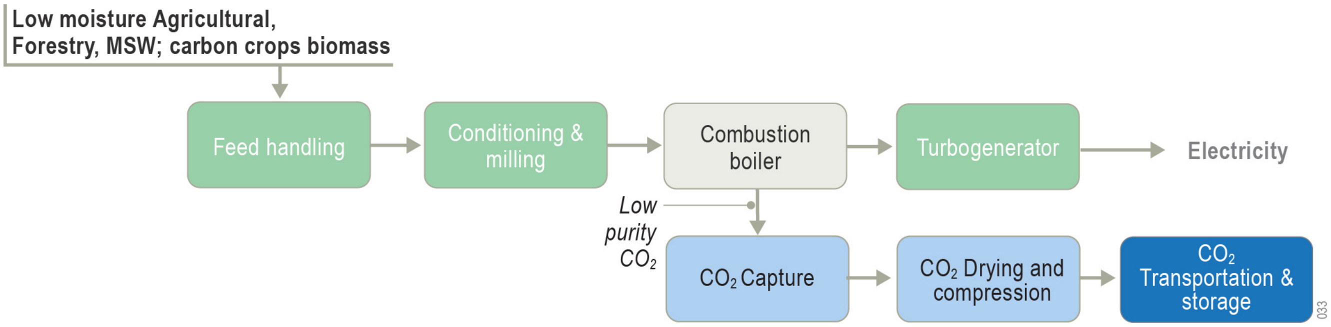


Figure 6-24. *Simplified block flow diagram of biomass combustion to produce electricity with carbon capture and storage.*

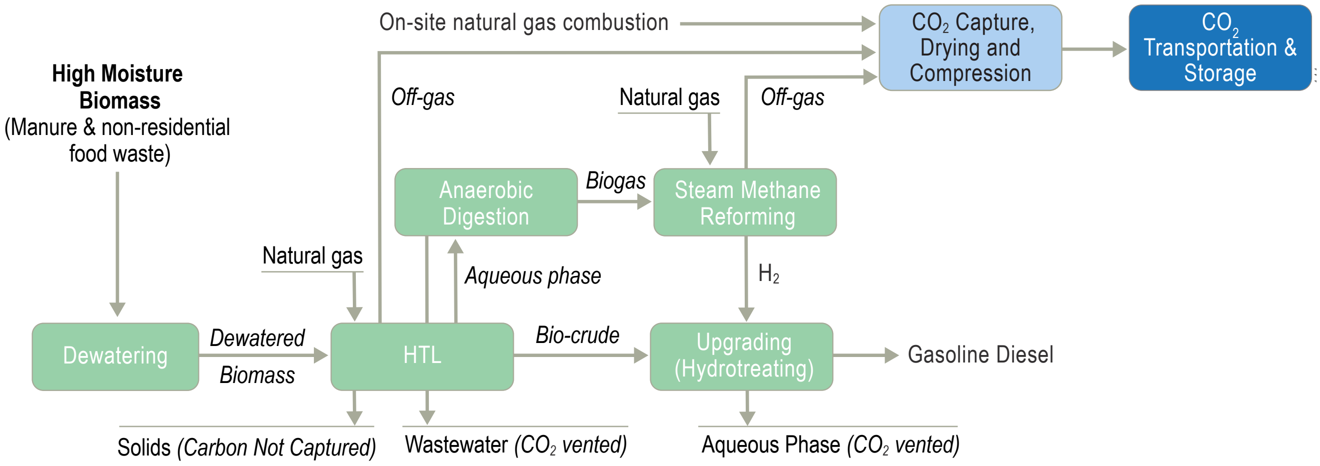


Figure 6-25. *Simplified block flow diagram of hydrothermal liquefaction (HTL) to liquid fuels with carbon capture and storage.*

HTL biorefineries. For full process description and modeling assumptions, see **Appendix 6**. In this analysis, we scale HTL facilities based on the wet-waste source capacity, with a minimum biomass throughput of 100 dry tons per day required to ensure economic competitiveness [55]. Despite its promise for sustainable fuel production from wet biomass, HTL biorefineries are not yet commercialized due to high equipment costs, elevated energy expenses, and the challenges of transporting wet feedstock over large distances [56].

Biological BiCRS Technologies

Fermentation

Fermentation of biomass into valued biochemicals, biofuels, and biomaterials is a robust industry in the United States. The fermentation of corn starch into ethanol fuel generates ~45 million tonnes of high-purity biogenic CO_2 per year, thereby offering the potential for significant carbon-intensity reduction of ethanol fuel when CO_2 capture and sequestration is incorporated [57]. Carbon-negative fermentation technologies typically require biomass feedstocks that are less resource intensive than corn starch, such as agricultural residues and other lignocellulosic biomass materials [26]. We modeled the fermentation of clean lignocellulosic residues and carbon crops into five main products: renewable diesel, ethanol, jet fuel, polyethylene, and CO_2 (**Figure 6-26**). Additional co-products include adipic acid and sodium sulfate. Fermentation of lignocellulosic biomass has been proven to be technically viable at industrial scales, although economic viability has been challenging to sustain. Several major industrial projects for the fermentation of lignocellulose into

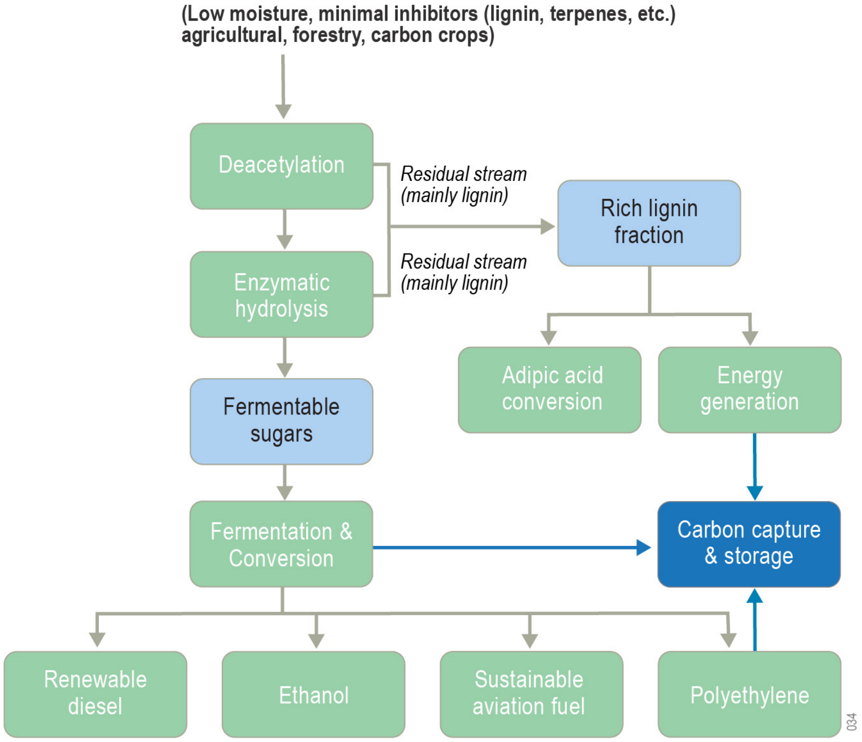


Figure 6-26. *Simplified block flow diagram of fermentation to various products with carbon capture and storage. The diagram illustrates four main fermentation bioproducts: renewable diesel, ethanol, sustainable aviation fuels, and polyethylene. Lignin is utilized either in on-site energy generation through combustion or upgraded to adipic acid, alongside the four fermentation bioproducts.*

ethanol failed in the United States between 2010 and 2015, which created a sense of pessimism around the industry [58]. However, now there is renewed interest in lignocellulosic fermentation due to the ability to make products of higher value than fuels, such as polyethylene and adipic acid, and to the additional revenue possible from capturing CO_2 [59]. Ethanol fermentation, along with other types of anaerobic fermentation, produce clean gaseous byproduct streams of CO_2 purity exceeding 90 vol%, thereby making them ideal candidates for low-cost CO_2 capture. However, the capital and operating costs associated with fermentation biorefineries are high, which present challenges to greenfield carbon-negative fermentation biorefineries.

The two fermentation platform technologies used in this study both involve the deacetylation and enzyme hydrolysis pretreatment but differ in their treatment of lignin. The platform without adipic-acid production utilizes all lignin for heat and power production with CO_2 capture and sequestration. The platform with adipic-acid production utilizes a fraction of the lignin for heat and power production with CO_2 capture and sequestration. We modeled four bioproducts via the two fermentation platforms, giving a total of eight fermentation pathways as shown in **Figure 6-26**. For each of the four bioproducts, namely renewable diesel, ethanol, jet fuel, and polyethene, we developed models both with and without adipic-acid synthesis. The carbon-removal potential for fermentation to the four bioproducts ranges from 0.81 to 1.33 tonnes CO_2/tonne biomass. We describe our analysis methods for each of the four bioproducts and their associated carbon conversion efficiencies in **Appendix 6**.

Anaerobic Digestion (AD)

AD for producing RNG is a rapidly growing industry in the United States due to the ability to produce a drop-in replacement for natural gas while avoiding methane emissions from the degradation of high-moisture biomass feedstocks, including manure and MSW. RNG production for CO_2 removal is challenging due to the relatively small amount of carbon removed per unit biomass feedstock. AD converts biomass into three products: methane, CO_2, and digestate, of which we assumed only captured CO_2 (with geologic storage) can contribute to removal. All carbon in the digestate and RNG is assumed to be released back into the atmosphere as CO_2 in less than 100 years and thus does not contribute to removal. In this study, we modeled the conversion of manure and food waste to RNG via the following operations: feed handling, AD, biogas upgrading into RNG, RNG compression, and CO_2 drying and compression, as shown in **Figure 6-27.**

The biogas yields from AD vary considerably with feedstock type, with dairy manure and food waste providing the lowest and highest biogas yields, respectively [60-62]. We established a minimum biogas flow of 10,000 tonnes-biogas per year as a requirement and thus assessed only relatively large AD facilities. We assessed techno-economic parameters for AD, biogas upgrading, and methane injection using published literature for guidance [63-65]. Biogas is composed of 60 vol% methane and 40 vol% CO_2, and we assumed electricity for biogas production and upgrading to have an energy value of 0.34 kWh/Nm3-CH_4 [63, 66]. We assumed that the resulting RNG is sold for pipeline injection. The CH_4 generated during biogas upgrading is of high enough purity to be ready for sale after drying and compression. The gate-to-gate carbon removal efficiency of the AD pathway varies with feedstock, from 0.039 tonnes of CO_2 per tonne biomass for AD of manure to 0.395 tonnes of CO_2 per tonne of biomass for AD of food waste using 2050 grid assumptions (see **Appendix 6**,**Table A6-6** and **A6-7** for detailed summary tables). The lower removal efficiency for the pathway with dairy/beef manure is due to the low net amounts of CO_2 generated per tonne of biomass (see **Appendix 6** for methods used to quantify costs of CO_2 capture, drying, and compression).

We also assessed the techno-economics of removing carbon via existing biogas emissions from landfills and wastewater-treatment plants (WWTPs). We established a minimum biogas flow of 10,000 tonnes-biogas per year as a requirement and thus only considered relatively large landfills and WWTPs in this study. We included biogas upgrading, RNG compression,

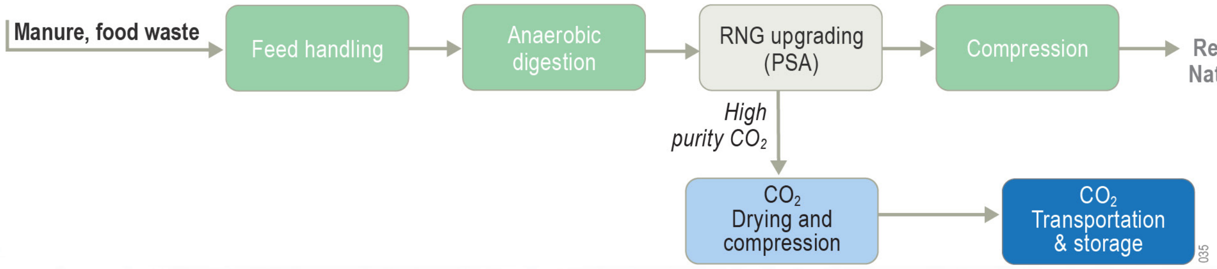


Figure 6-27. *Simplified block flow diagram of anaerobic digestion (AD) to produce renewable natural gas (RNG) with carbon storage.*

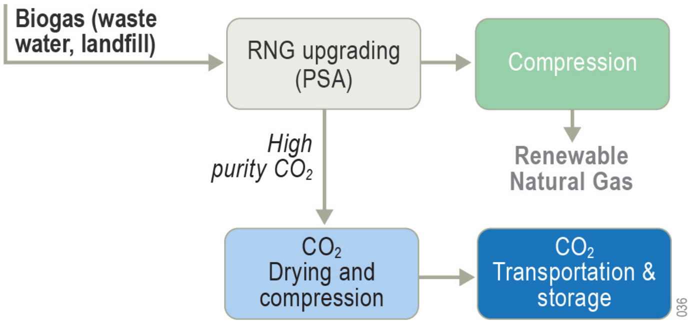


Figure 6-28. *Simplified block flow diagram of biogas capture and storage on existing landfill and wastewater-treatment plants (WWTPs).*

and CO_2 drying and compression in the biogas pathway, as shown in **Figure 6-28**. We assumed landfill biogas to be 60 vol% methane and 40 vol% CO_2, whereas we assumed WWTP biogas to be 65 vol% methane and 35 vol% CO_2. The carbon removal for landfills includes the CO_2 captured from biogas upgrading and the residual carbon in the biomass that does not biologically degrade into biogas. The carbon removal for WWTPs includes only the CO_2 captured from biogas upgrading since the residual carbon in the digestate is assumed to oxidize into CO_2 in less than 100 years. The gate-to-gate carbon-removal efficiency of the existing biogas-source pathway varies with feedstock, from 0.3 tonnes of CO_2 per tonne of biogas for the WWTP pathway to 1.2 tonnes of CO_2 per tonne of biomass for the landfill biogas pathway using 2050 grid assumptions. The lower removal efficiency for the WWTP pathway is due to the small amounts of CO_2 captured per tonne biomass and the degradation of all non-digested carbon into CO_2 at end-of-life (<100 years); we provide more discussion on this topic in the results section. (see **Appendix 6** for methods used to quantify costs of CO_2 capture, drying, and compression).

Mechanical BiCRS Technologies

Sawmill

Sawmills involve mechanical operations to shape and configure biomass resources, mostly forestry biomass, into various structural bioproducts. In this study, we focus on the production of low-value, small-dimensional lumber from sustainably sourced forestry biomass (class 2 small-diameter trees). We model a sawmill with the following operations: feed handling, debarking, sawing, combustion for heat and power, and CO_2 capture, drying, and compression, and shown in **Figure 6-29**.

We assume 47% of initial biomass feedstock is converted to small-dimensional lumber and the remaining material is used to produce electricity [67]. The energy demand for the process is 482 kWh/dry ton of feedstock [67]. The process model for sawmilling includes end-of-life handling of the small-dimensional lumber, where it is assumed 16% and 17% of the lumber is incinerated and recycled, respectively [68]. We assumed that recycling consumes 72% less energy than virgin biomass processing [69]. The remaining 67% of the lumber is assumed to store 50% of its carbon for 100 years [70] (this is consistent with the whole-tree carbon-removal efficiency provided by the Forest Vegetation Simulator in the Forestry Section). We estimated capital costs for the sawmill process from literature [71]. We modeled the biomass combustion facility with guidance from NREL's published reports [72]; see section on biomass combustion for more details. In this model, all heat and power demands are met by the combustion facility, and excess power is sold to the grid as a co-product. The gate-to-gate carbon-removal efficiency of the sawmill BiCRS pathways is 1.325 tonne of CO_2 per tonne of biomass, or 71% of the theoretical removal efficiency.

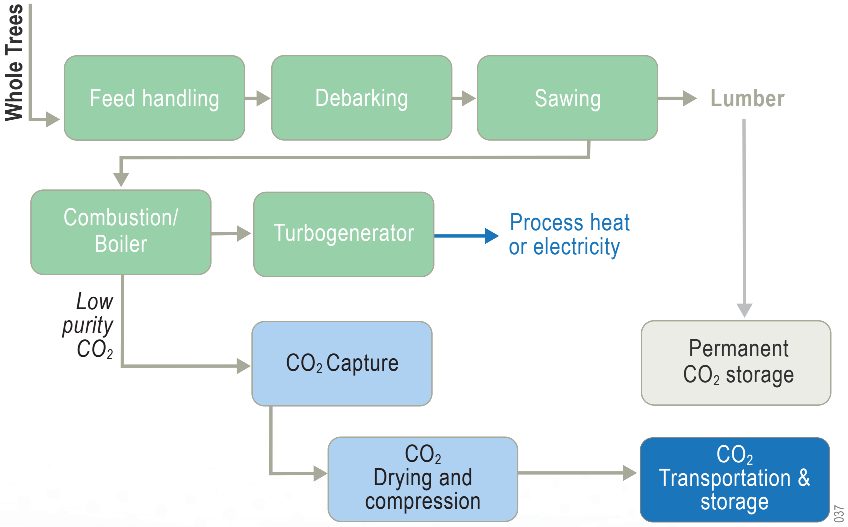


Figure 6-29. *Simplified block flow diagram of sawmill to lumber with carbon capture and storage.*

BOX 6-5

Emerging BICRS Pathways

While the BiCRS pathways included in this chapter detail high-value and high TRL pathways, such as production of liquid fuels and biochemicals, another suite of BiCRS pathways had insufficient maturity for a rigorous TEA or simply focus on durable utilization and/or storage of a carbon product. A central thesis for these approaches is that natural biogenic carbon re-emission can be avoided by addressing the underlying causes of decay, including microbes, invertebrates, photochemical degradation, and fire.

The following emerging BiCRS technologies have the potential for meaningful carbon removal, in some cases as low-cost options in the near term, while more valuable utilization approaches evolve and achieve scale: steel manufacturing, mass timber, pyrolysis with bio-oil injection, biochar-reinforced concrete, wood burial, composting with CO_2 capture, macroalgae sinking, bioenergy-driven DAC with storage (DACS), and biochar and bioasphalt. We provide a short overview of each of these pathways in the following section.

Steel Manufacturing

The iron and steel industry contributes 7% of CO_2 emissions from energy and industrial processes globally [73]. High TRL, low-carbon energy technologies, such as photovoltaics and wind turbines, are not effective at fully decarbonizing steel manufacturing, particularly virgin steel. Virgin-steel production requires fossil carbon–derived coke material for reduction of iron oxide in the blast furnace to produce metallic iron and copious amounts of CO_2. Recent studies have illuminated the potential for carbon-negative steel production using pyrolysis-derived biocoke in the blast furnace [74, 75]. The majority of carbon removed via biocoke is from the capture of gaseous biogenic CO_2 emitted from the blast furnace, but a meaningful amount of biogenic carbon is also stored in the steel product; carbon constitutes 0.2–2.0 wt% of steel.

Mass Timber

In the United States, the timber industry draws down more than 100 million- tonnes of CO_2 from the atmosphere each year in the form of wood products [76]. Most timber is used in residential construction, where a new home has the potential to remove ~18 tonnes of CO_2 in the form of wood products [76]. Mass timber is an emerging type of wood product that can be used in place of steel in large buildings, including multi-story office buildings. Cross-laminated timber, glulam, parallel-strand lumber, and mass plywood panels are a few examples of engineered wood products with substantial potential for carbon removal [57, 77]. Current examples of mass timber buildings include a 10-story corporate office building [78], and the world's tallest timber building standing at 18 stories [79]. A standard multi-story office building using mass timber in place of steel and concrete has the potential to store ~2000 tonnes of CO_2 [80]. The timescale of CO_2 storage via mass timber varies, but >100 years is achievable if the building is maintained well during use and handled appropriately at end-of-life. As with other biomass-based approaches, special attention should be paid to sustainable feedstock sourcing and effects on nutrient cycling.

Pyrolysis with Bio-oil Injection

Bio-oil produced from pyrolysis of biomass has typically been used directly or indirectly for energy production. A promising use of bio-oil for carbon removal is via geologic injection [81]. Biochar has traditionally been viewed as the primary means to remove carbon via pyrolysis, but its potential is limited by land area and reversal of carbon removal upon biochar degradation [57]. Bio-oil injection is similar to CO_2 injection in that the carbon is stored in geologic sites, although the durability of storing bio-oil is currently more uncertain than CO_2 [81]. Bio-oil injection does not create value other than carbon removal. Traditionally, the value of chemicals and fuels that can be made from bio-oil have been greater than the value of removing carbon due to their ability to displace fossil-carbon products. However, the value of carbon removal is dynamic and heterogeneous. A major advantage of bio-oil injection is the ability to generate bio-oil onsite, local to the biomass resource, with subsequent transportation of the bio-oil to a centralized injection well. The transportation of bio-oil has the potential to be more cost effective than biomass given its higher carbon density. In addition, transporting bio-oil requires less costly infrastructure than transporting CO_2.

Biochar-Reinforced Concrete

Removing atmospheric carbon by incorporating biochar into cement as aggregate or as a curing agent is gaining considerable attention due to its potential for high impact [82]; global production of cement and concrete constitutes 6% of total industrial and energy-related CO_2 emissions [73]. Adding biochar into concrete mix has been shown to increase compressive strength while not diminishing other properties [82, 83]. Similar to incorporating biogenic carbon in steel, the specific mass of biochar incorporated into concrete is relatively small (~1% of concrete), but the potential for impact is large given the massive quantities of concrete that are produced globally each year.

Wood Burial

Wood burial involves the sustainable harvest and storage of wood in dry or anoxic underground environments [84]. The recalcitrance of lignocellulose coupled with low moisture and oxygen content are assumed to prevent microbial degradation of the woody materials. The estimated durability of the carbon storage is >100 years, and is based on the existing academic literature on landfill design for many forms of waste. There is uncertainty as to how wood storage approaches will vary across biomass compositions, sites, and climates [84]. In addition, wood burial conflicts with several principles of circularity, including keeping (bio)materials in use and providing economic benefits. Wood burial does not provide any value other than carbon removal unless, for example, carbon financing enables additional forest restoration treatments (e.g., western U.S. forests at high risk of severe wildfire). In addition, careful accounting of carbon and nutrient turnover as well as sustainable feedstock sourcing guidelines are essential safeguards to the scaling of this nascent idea. Straightforward carbon accounting and potential for large scale and low cost removal make wood burial a promising method for carbon removal at sites with low access to geologic storage or biorefineries, or in near-term scenarios where no current cost-effective utilizations are available.

Composting with CO_2 Capture

Composting is an established industrial bioprocessing technology that converts food waste and other types of urban waste into a nutrient- and carbon-rich soil amendment [85]. Significant quantities of biogenic CO_2 are emitted during the composting process via microbial respiration [85-87]. Capturing CO_2 during this bioprocess has the potential to make composting carbon-negative, even if the carbon in the compost product itself does not contribute to removal. Relative to AD, composting has several advantages including lower capital costs, more stable bioprocessing, lower energy demand and potential for heat recovery, and elimination of pathogens and weed seeds [85, 86, 88, 89]. In addition, the US EPA views composting as a higher value use of biomass waste than bioenergy production [90]. There have been no reported studies of composting with CO_2 capture, and therefore insufficient data are available to properly assess composting as a BiCRS pathway in this study.

Macroalgae Sinking

The growth and subsequent sinking of macroalgae, or seaweed, is an emerging method of carbon removal due its simplicity and potential large-scale impact [91, 92]. Unlike terrestrial biomass, macroalgae grown in the ocean is not limited by land area and does not require intensive fertilizer application due to the natural abundance of nutrients in coastal waters. Carbon removal is possible if the macroalgae are grown near the surface of ocean where sunlight is available and then intentionally sunk to the bottom of the ocean where low temperatures, minimal mixing, and anoxic conditions prevent decomposition [92]. Substantial side effects are possible when macroalgae are grown at large scale in open ocean systems, including reducing phytoplankton net primary productivity due to competition for nutrients and sunlight. In addition, the potential for nutrient export from surface waters to the deep ocean could lead to reorganization of food webs [92].

Bioenergy-Driven Direct Air Capture (DAC)

DAC has incredible potential to remove significant quantities of CO_2 from the atmosphere, but a major limitation is the availability of clean, low-cost energy. DAC ia an energy-intensive pathway for carbon removal, which is why areas with abundant low-carbon energy are being identified as near-term regions for deployment. The use of biomass-derived energy to drive DAC has the potential for synergistic co-benefits if the biogenic CO_2 is captured along with the air-derived CO_2 [93]. Liquid-solvent DAC technologies that require high-quality thermal energy are particularly amenable to using direct-fired biomass kilns or furnaces [93]. Biomass is the only low-carbon energy source that can provide high-temperature heat (>500 °C) at low cost while also enhancing the net carbon removed [93].

Biochar and Bioasphalt

Bioasphalt and biochar are two emerging biorefinery products with carbon-removal potential; these products were only included in our analysis in a limited capacity due to uncertainties around asphalt blend rates and durability of carbon storage in the product. The markets with the largest carbon-removal potential are construction for bioasphalt and agriculture for biochar. Commercial use of bioasphalt remains limited, but academic studies and demonstration projects continue to grow [94]. Industrial reports suggest that bioasphalt is an effective GHG reduction strategy for the asphalt industry, but studies of its long-term carbon-removal potential are still needed [95]. Biochar has received more coverage from the scientific literature, and biochar markets are growing [96]. Biochar studies suggest that, when used in appropriate contexts, biochar can be an effective carbon-removal material [97]. Effective biochar use relies on a good understanding of biochar preparation, soil micro-organism behavior, and land management practices [98]. Appropriate life cycle accounting of the biogenic emissions (both CO_2 and CH_4) generated through the conversion process as well as experimental studies rigorously quantifying decay rates once applied to surficial soils are needed.

BiCRS Feedstock Eligibility Criteria

Connecting Biomass to the Appropriate Conversion Technology

Each BiCRS technology has a set of criteria for biomass feedstock eligibility, as shown in **Table 6-13**. The key drivers for assigning the most appropriate technology for feedstock conversion are moisture, ash content, and, to a lesser extent, presence of inhibitors for fermentation. Biomass feedstocks with moisture contents >60% are considered "high moisture" and are suitable for AD or HTL, as shown in **Table 6-13.** For the full list of biomass and its eligible BICRS technology see **Appendix 6**. In our study, biomass types with moisture content >60% are wet wastes, including manure and food waste, which typically cannot be economically transported long distances due to the high water mass in the biomass [97]. Wet wastes are therefore treated as point-source feedstocks and require the construction of greenfield AD or HTL biorefineries co-located with the source of waste. Ash content is another property to consider for gasification and pyrolysis technologies due to the associated technical complications, like agglomeration and bridging [99]. We selected an ash content of 10% as the threshold value for gasification and pyrolysis technologies, which excludes several high-ash feedstocks, including rice hulls, sugarcane trash, sorghum stubble, and certain types of MSW. However, pretreatment or modification of these biorefinery processes could potentially enable the use of these feedstocks in the future. Combustion has the largest number of eligible feedstocks (and annual dry tonnes of biomass) with the only requirement being a biomass moisture content <60%. The sawmill technology in our study only accepts forestry biomass of small diameter (<11 inches), which primarily includes thinned trees of large enough size for low-cost, small-dimensional lumber [100-102]. Fermentation accepts low-moisture feedstocks with minimal inhibitors (lignin, terpenes, etc.) that have been proven technically feasible, including agricultural residues and hardwood forestry biomass [103-105]. Our analysis assessed feedstock availability for two years: 2025 and 2050. Herein, all stated metrics and assumptions are for both 2025 and 2050 unless stated otherwise. The 2025 biomass availability includes all feedstocks except restored prairie, switchgrass, poplar, and willow, which are the four additional feedstocks available in the 2050 assessment.

Table 6-13. *The biomass composition criteria and mass of eligible biomass feedstocks for each BiCRS technology. Biomass from the Maximum Economic Potential assessment.*

BiCRS Technology	Biomass Composition Criteria	Annual Feedstock Availability
		(Million tonnes)
Anaerobic Digestion & Hydrothermal Liquefaction	> 60% moisture	37.4
Gasification and Pyrolysis	< 60 % moisture < 10% ash	847.4
Combustion	< 60 % moisture	863.2
Fermentation	< 60 % moisture Minimal inhibitors	624.2
Sawmill	Whole small diameter tree only	86.4

Our Analysis Approach: *Boundary Conditions, Life-Cycle Assessment, and Technoeconomic Assessment (TEA) Assumptions*

For each BiCRS technology, we developed process models and associated products to provide mass and energy flow data for each unit operation (see **Appendix 6** for detailed process flow diagrams of each BiCRS pathway). We accounted for the cost of capturing gaseous CO_2 and storing it underground as a potential carbon-removal solution. Additionally, we explored four other bioproducts that have the capacity to store carbon for an extended period and thus contribute to carbon removal. These products include polyethylene, bioasphalt, biochar, and small-dimensional lumber. The estimated carbon durability for all five carbon storage sinks is summarized in **Table 6-14**. Other co-products and waste residues containing carbon, such as adipic acid and solid digestate, are assumed to fully decompose and release back into the atmosphere within 100 years.

Table 6-14. *Summary of the associated sinks and 100-year durability of five products that can contribute to carbon removal.*

Product	Carbon Sink	100 Year Carbon Durability
Carbon Dioxide	Geological Storage	100%
Polyethylene	Product and Landfill	60%
Bio-oil (Bioas-phalt)	Asphalt	77%
Biochar	Soil	80%
Small Dimensional Lumber*	Structures and Landfill	50%

*Durability of small dimensional lumber is 23% relative to the whole tree, in agreement with durability assumptions in the forestry chapter.

Figure 6-30 shows the various flows of carbon to and from the atmosphere over the life-cycle of a bioproduct. We use CO_2 to represent CO_2e emissions for simplification. We calculated net CO_2 removal by subtracting the total emissions (from biomass, CO_2 supply chains, and biomass-conversion processes) from the initial atmospheric CO_2 capture during biomass growth through photosynthesis, in addition to the CO_2 that can be captured onsite. A BiCRS pathway is classified as carbon-negative when the sum of emissions is less than the combined amount of CO_2 captured from the atmosphere and the CO_2 captured at the biorefinery. **Figure 6-30** presents all the detailed direct and indirect emissions that have been considered in this analysis. The LCA system boundary includes cradle-to-grave emissions except for the emissions from transport of bioproduct from conversion facility to end-of-life. The emissions associated with bioproduct end-of-life are calculated using the 100-year durability shown in **Table 6-14.**

We calculated the cost of carbon removal as the incremental costs to remove CO_2 for all potential negative-emission BiCRS pathways in \$/tonne CO_2, as shown in Equation 1 (see **Appendix 6** for other equations). We focus on CO_2-removal cost without considering avoided emission impacts. We assumed the cost and carbon intensity of electricity and hydrogen purchased externally to the conversion facility to be constant across regions for both near- and long-term, as shown in **Table 6-15**. For other economic parameters and emissions factors, see **Appendix 6**.

Equation 1

$$\textit{Carbon Removal Cost} = \frac{\textit{Levelized Cost of BiCRS} - \textit{Revenue from Bioproduct}}{\textit{Net Carbon Removal}} \quad [=] \quad \frac{\$}{\textit{tonne } CO_2}$$

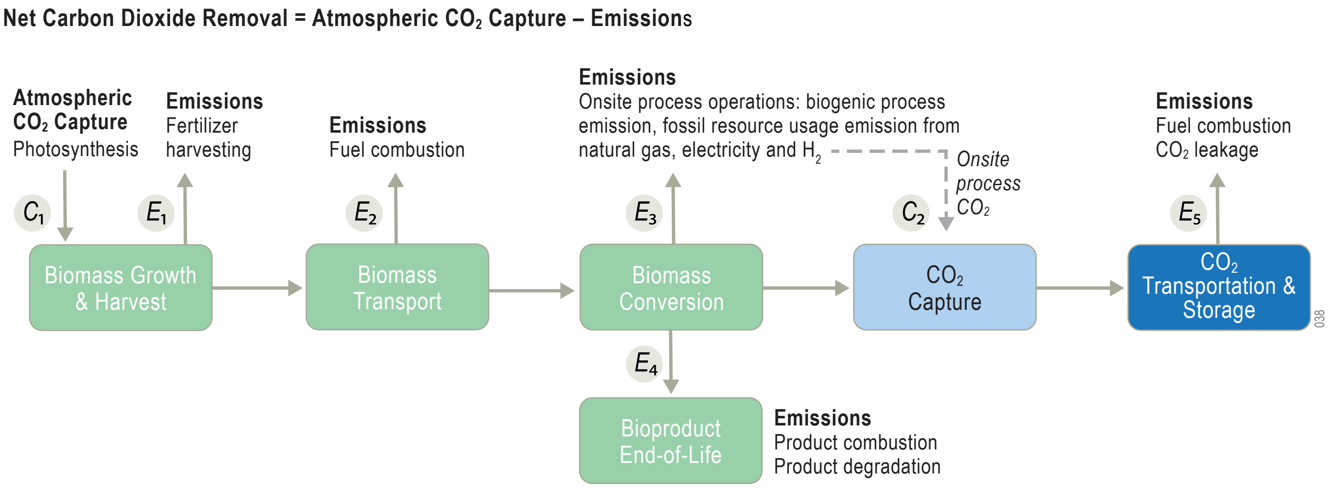


Figure 6-30. *Overview of carbon accounting calculations for BiCRS pathways. Net CO_2 removal = C1+C2-(E1+E2+E3+E4+E5).*

Table 6-15. *Costs and emission factors for electricity, natural gas, and hydrogen used onsite at biorefineries for 2025 and 2050. (Data source: EIA electricity data, EIA natural gas data [91, 92], NREL H_2 price [93], GREET [94].*

	2025 (Near-Term)		2050 (Long-Term)	
	Cost	Emission	Cost	Emission
Industrial Electricity	\$0.08/kWh	0.3878 kg CO_2/kWh	\$0.08/kWh	0.0 kg CO_2/kWh
Natural Gas (NG)	\$0.15/m_3	2.76 kg CO_2/kg NG	\$0.15/m3	2.76 kg CO_2/kg NG
Hydrogen (H_2)	\$2.0/kg	16.12 kg CO_2/ kg H_2	\$2.0/kg	0.0 kg CO_2/ kg H_2

Results: *Carbon-Removal Capacity and Cost for Selected Biorefineries*

Figure 6-31 compares the net CO_2-removal potential and CO_2-removal cost at the biorefinery-plant level, focusing solely on the biorefinery's operations without considering biomass or CO_2 logistics. The scale of the biorefinery shown in **Figure 6-31** is 1000 dry tonnes of biomass per day. The evaluated BiCRS pathways are divided into three categories based on feedstock: low-moisture biomass conversion pathways (dark blue), wet-waste biomass conversion pathways (light blue), and existing biogas capture pathways (dark grey). These pathways are categorized into four quadrants based on their biomass-removal potential and cost.

In general, pathways with higher carbon-removal potential per tonne biomass tend to have lower removal costs. For instance, gasification/pyrolysis-to-H_2 and combustion-to-electricity pathways have exceptionally high CO_2-removal potential because most of the biogenic carbon is separated from their bioproducts, making it possible to capture and store it underground. In contrast, pathways like fermentation to liquid fuels (ethanol, diesel, SAF) produce hydrocarbon products where some of the biogenic carbon remains in the co-product. The emissions resulting from the end use of these products are challenging to capture consistently and do not contribute to removal. Additionally, these pathways require high capital investments, leading to higher removal costs compared to the upper left quadrant (**Figure 6-31**).

Wet-waste biomass conversion pathways mainly fall into the bottom right quadrant due to their lower biomass carbon-removal potential and lower revenue from the products they generate. We describe biomass carbon-removal potential from wet waste in the Biocarbon Infrastructure, Logistics, and Transportation (BILT) results section on wet waste (see below). In addition, when calculating the cost of removal for AD, we use a conservative selling price for RNG based on fossil–natural gas prices, without accounting for policy incentives or avoided emissions. It is important to note that revenue from product sales significantly affects the CO_2-removal cost, as shown in the sensitivity analysis depicted in **Figure 6-33**. Additionally, despite the high relative cost per tonne of CO_2 removed for wet waste (manure, food waste) conversion pathways, treatment of wet waste is necessary to avoid methane emissions.

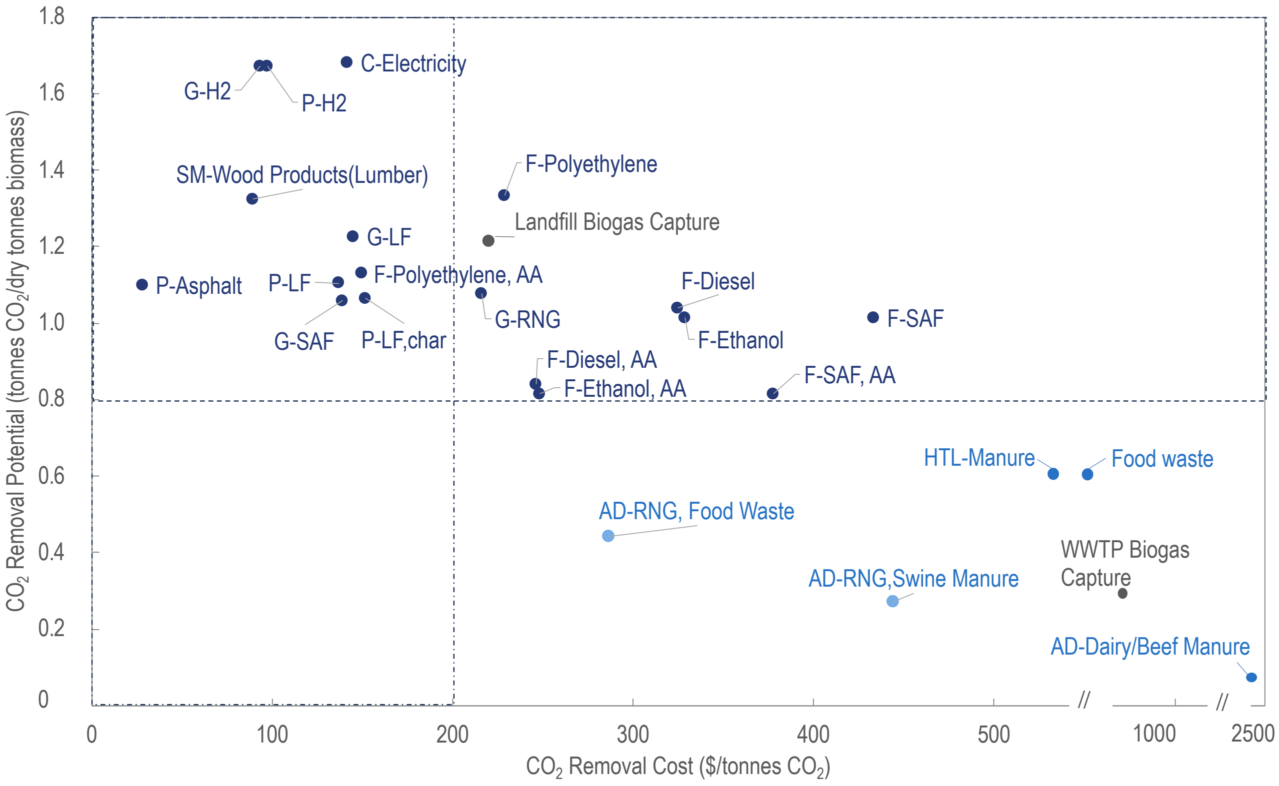


Figure 6-31. *CO_2-removal cost versus CO_2-removal potential on a "per dry tonnes of biomass" basis. The figure showcases the analysis based on a baseline biorefinery scale of 1000 dry tonnes of biomass per day. The focus is solely on carbon removal at the biorefinery gate, excluding emissions from biomass harvest, transportation, CO_2 transportation, and injection. All feedstock is assumed to have a biomass cost of $60/dry tonne. Conversion technologies are represented by abbreviations: G (gasification), C (combustion), P (pyrolysis), F (fermentation), AD (anaerobic digestion), HTL (hydrothermal liquefaction) and SM (sawmill). Products include liquid fuels (LF), sustainable aviation fuel (SAF), renewable natural gas (RNG), and adipic acid (AA). We use the abbreviation WWTP to represent wastewater treatment plant.*

Figure 6-32 illustrates the impact of a zero-emissions grid by comparing the CO_2-removal potential on a "dry tonne of biomass" basis for all BiCRS pathways at the biorefinery-plant level between 2025 and 2050. In 2050, assuming a zero-emissions grid and H_2, most pathways exhibit increased carbon-removal potential compared to 2025, where current grid and H_2 emissions are considered. With the assumption of a net-zero-emissions grid and H_2 in 2050, the overall net carbon removal potential rises for most pathways. Pathways like fermentation to SAF or polyethylene—which consume more electricity and H_2 as part of the process than other pathways—experience a more significant increase in carbon-removal potential at the biorefinery level with a 2050 zero-emissions grid. Pathways like gasification to H_2, combustion, and sawmill, which generate clean electricity on-site, show minimal changes in net carbon-removal potential between 2025 and 2050.

We performed sensitivity analyses for three input parameters that we found have the greatest impact on the cost of CO_2 removal: product selling price (**Figure 6-33**), feedstock cost (**Figure 6-34**) and capital-recovery factor (**Appendix 6, Figure A6-11**). In each sensitivity analysis, we varied one parameter from the baseline by +/-50%, while keeping all other input parameters constant. We present the relative change to baseline CO_2-removal cost to show the sensitivity of each pathway's CO_2-removal cost to the variable parameter.

The impact of product selling price, feedstock cost, and capital-recovery factor on CO_2-removal cost varies depending on the conversion pathways as follows: pathways that yield high-value, long-lasting co-products (e.g., polyethylene, asphalt, and wood products) or pathways that generate valuable byproducts (e.g., adipic acid) are more sensitive

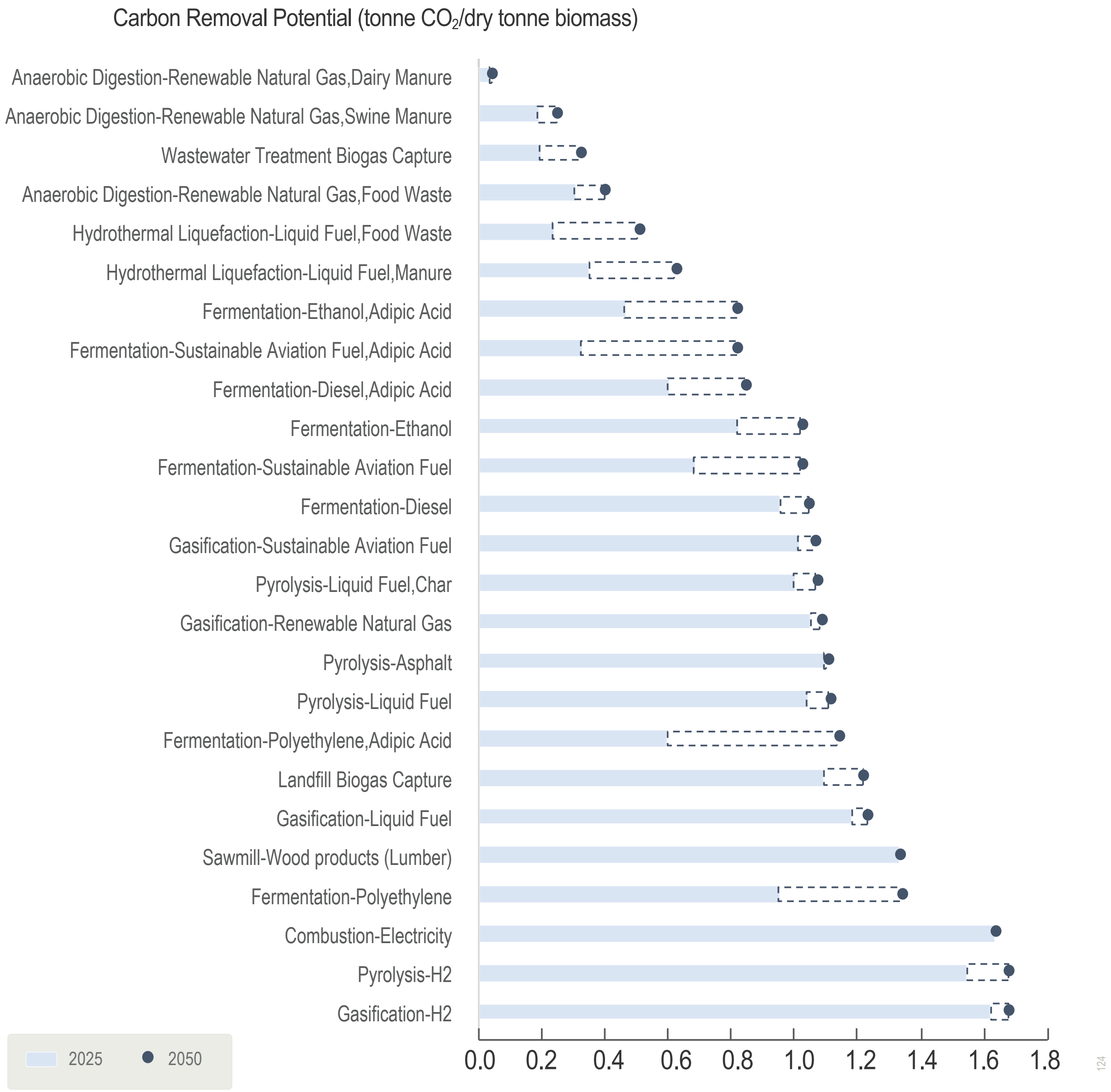


Figure 6-32. *Projected 2025 and 2050 grid and hydrogen emissions impact on biomass CO_2-removal potential on a "per dry tonne of biomass" basis. The analysis assumes a net-zero-emissions grid and net-zero-emissions hydrogen production for 2050, while utilizing current emissions factors for the grid and hydrogen production in 2025. The figure highlights findings based on a baseline biorefinery scale of 1000 dry tonnes of biomass per day. It specifically focuses on carbon removal at the biorefinery gate, excluding emissions associated with biomass harvest and transportation, CO_2 transportation, and injection.*

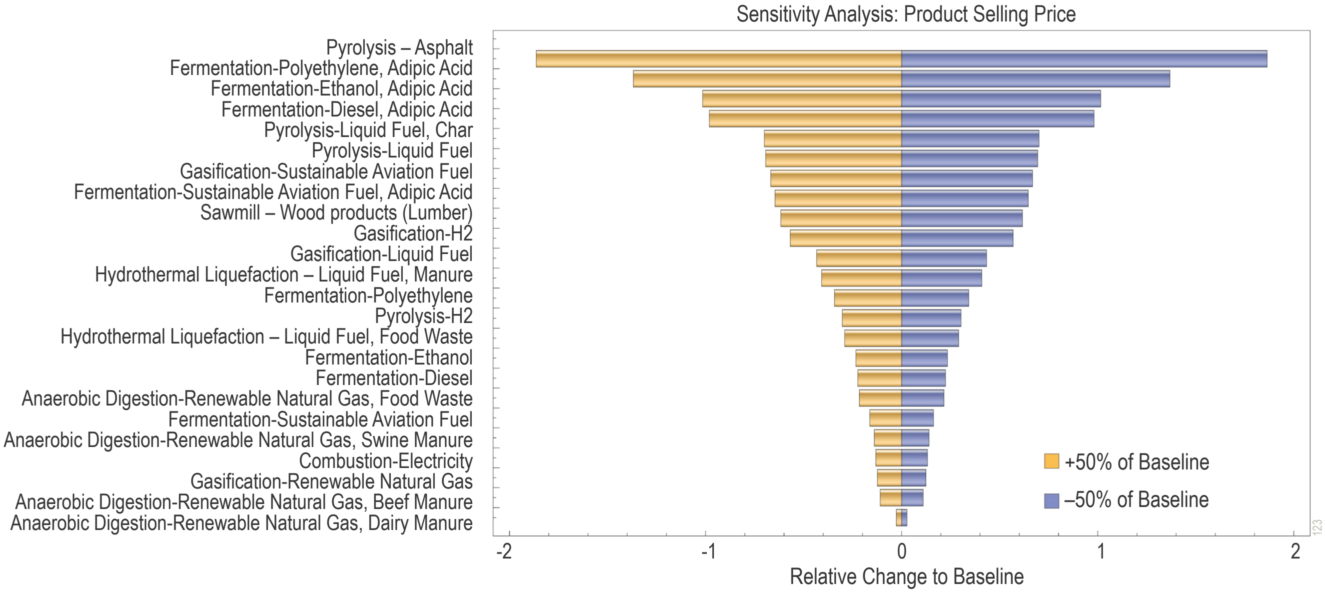


Figure 6-33. *Variation of CO_2-removal cost relative to the selling price of bioproducts. Bioproducts refer to all bioenergy, biochemicals, and biomaterials products that can be produced alongside CO_2 and contribute additional economic values to BiCRS. The selling price of the product was varied by both increasing (+50%) and decreasing (-50%) it relative to the baseline product selling price, as outlined in* **Table 6-17.**

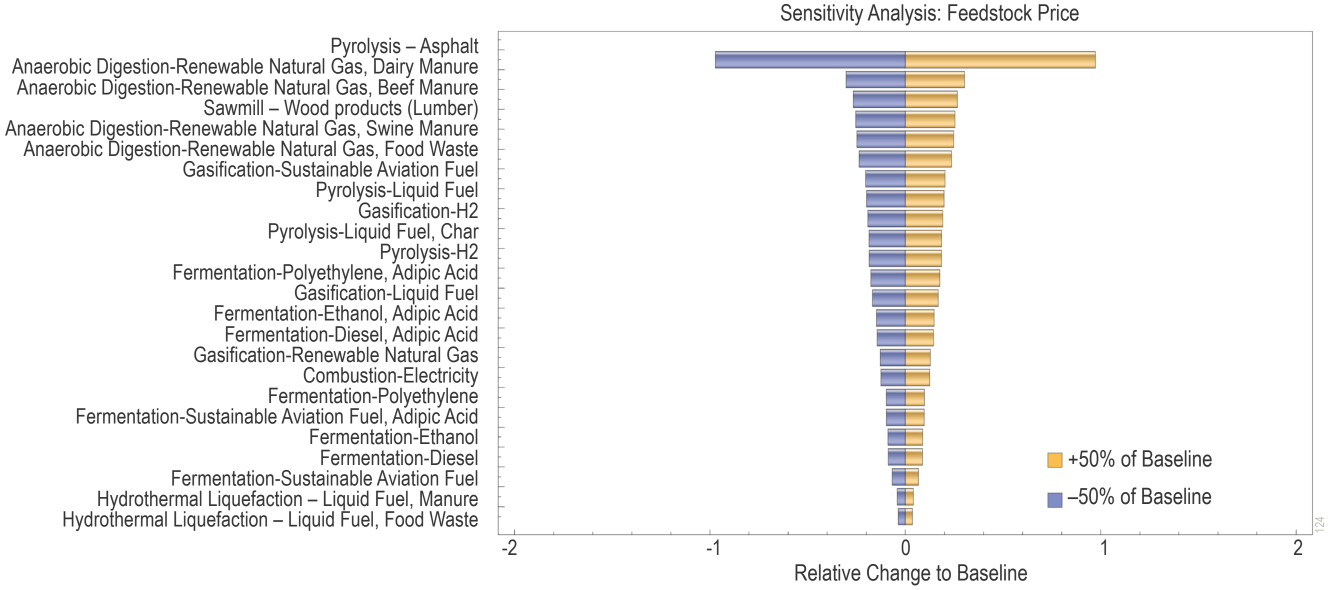


Figure 6-34. *Variation of CO_2-removal cost relative to the feedstock collection price. The feedstock collection price was varied by both increasing (+50%) and decreasing (-50%) it relative to the baseline feedstock collection price of $60/dry tonne biomass.*

to changes in selling price due to the presence of multiple revenue streams. Capital-recovery factor (see **Appendix 6, Figure 6-11)** plays a more important role in the CO_2-removal costs for the pathways that require a higher capital investment (e.g., gasification and fermentation). Feedstock cost has a lower impact on the CO_2-removal cost overall, except for bioasphalt and AD, where feedstock cost is a significant fraction of the total cost due to the relatively lower capital investment for pyrolysis and AD.

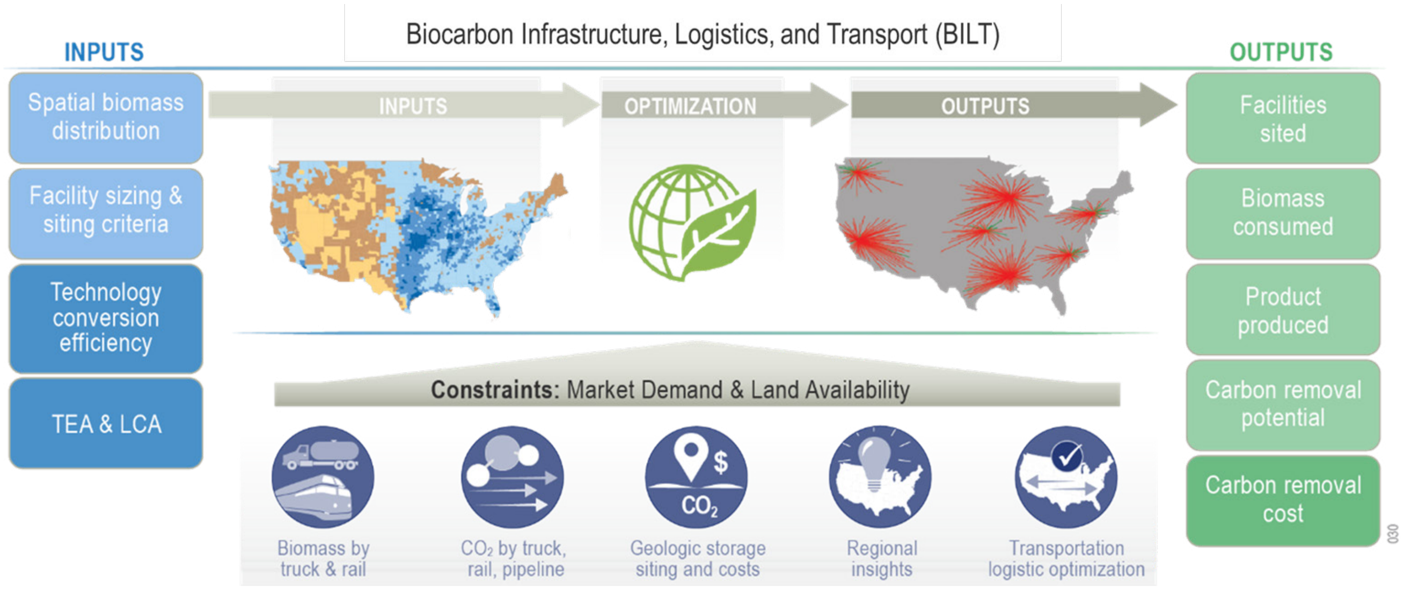


Figure 6-35. *Illustration depicting functionality of the Biocarbon Infrastructure, Logistics, and Transportation (BILT) optimization model as used in this chapter, showing major inputs, outputs, and constraints. TEA = technoeconomic assessment; LCA = life-cycle assessment.*

Siting and Sizing Facilities for Biomass Accessibility and Carbon Storage: *Description of the Biocarbon Infrastructure, Logistics, and Transportation (BILT) Optimization Model*

Rationale for Development and Application of the Biocarbon Infrastructure, Logistics, and Transportation (BILT) Model

Oak Ridge National Laboratory (ORNL) developed the Biofuel Infrastructure, Logistics, and Transportation model to optimize biomass logistics for biofuel production. In our work, we extended the tool—referred to hereafter as the Biocarbon Infrastructure, Logistics, and Transportation (BILT) model—to model BiCRS logistics with the objective of maximizing the carbon removed (rather than carbon abated) and including consideration of multimodal transportation for both biomass (truck, rail) and CO$_2$ (truck, rail, and pipeline). Our BILT model (depicted in **Figure 6-35**) also includes process modeling, economic analysis, and assessments of environmental impact across 27 different pathways of biocarbon utilization, encompassing various thermochemical, biochemical, and mechanical biomass-conversion technologies. This comprehensive approach enables understanding of how different biomass sources and utilization methods can contribute synergistically to regional- and system-scale CO$_2$ removal.

Results from the BILT optimization represent a small subset out of a multitude of options; many technologically mature BiCRS pathways can remove significant quantities of CO$_2$ while realizing other regional and national goals, such as reducing pollution or avoiding waste-disposal costs. We used BILT in this analysis to understand the major cost and removal impacts, as well as tradeoffs, to assist in decision-making at the national and regional scale.

Biocarbon Infrastructure, Logistics, and Transportation (BILT) Description

Our BILT optimization model minimizes the cost of carbon removal across spatial biomass availability, conversion-facility capacities and locations, biomass and CO$_2$ transportation modes and distances, and carbon-storage mechanisms. The model solves the optimization problem via a mixed-integer program that uses the Gurobi mathematical optimization solver(see **Appendix 6** for details). The optimization model first quantifies the theoretical maximum carbon removal where almost all accessible sustainable biomass is devoted to removing the most carbon, regardless of the costs, and then determines the lowest-cost solution in which a specified target carbon removal is achieved; the optimal solution in this context refers to a selection of particular BiCRS technologies and transportation modes that achieve the lowest cost of carbon removal. The potential locations for siting biomass-conversion facilities by BILT are pre-determined using the exclusion criteria shown in **Table 6-16**. We allowed the capacity for fermentation, combustion, gasification, pyrolysis, and sawmill facilities to range between 1000 and 5000

Table 6-16. *The exclusion and requirement criteria for siting all low moisture conversion facilities in the BILT model. Facilities for high moisture waste were sited at the waste location.*

Exclusions	Requirements
Population density of more than 500 people within 1 square mile	Water supply of 12.5k gallons/minute within 20 miles++
Wetlands or open water	Within 200 miles of rail transfer station for biomass and CO$_2$
Protected lands	Within 50 miles of pipeline transfer station for CO$_2$***
Slope greater than 12%	
Landslide hazard	
100-year floodplain	

++ Fermentation is the most water-intensive BiCRS technology and consumes less than 12.5k gallon/minute

*** Only for the long-term future 2050

dry tonnes per day (based on biorefinery scales in current industries like ethanol fermentation) in increments of 1000 tonnes per day. BILT optimizes the facility size by balancing the benefits of economies of scale and costs of biomass logistics at larger scales. AD and HTL facilities are built at the source of wet waste and have capacities equal to the available wet waste at that location.

BILT has established the modes and distances for transporting biomass and CO$_2$, as depicted in **Figure 6-36**, for both near-term (2025) and long-term (2050). We calculate both CO$_2$ and biomass transport by truck and rail for 2025; for 2050, we added an additional trunk CO$_2$ pipeline. **Chapter 5 –CO$_2$ and Biomass Transport** presents comprehensive cost breakdowns for all three transportation methods. To ensure economic efficiency and feasibility in supply-chain logistics, we used a maximum trucking distance of 200 miles (322 km) for both biomass and CO$_2$ [110] and constrained biorefinery location to within 50 miles (80 km) from the pipeline.

Table 6-17. *Assumed market demands and selling prices for bioproducts considered in BiCRS pathways for 2025 and 2050. Data are from the following data sources, and do not include current incentives for bio-derived or low-carbon-emission products. (Data sources: EIA Annual Energy Outlook [111]; Road Map to a US Hydrogen Economy [112]; Freedonia Group Lumber Industry Report [113]; Global Industry Analyst Inc. Acetone Market Data [114]; Grandview Research Adipic Acid Market Size, Share and Trend Analysis Report [115]; Statista Research Department Polyethylene Market Data [116]; and World Highways Asphalt Market data [117].)*

Product	Units	2025	2050	Selling Price ($2022)
Electricity	Billion kWh	10,850	11,950	$0.08/kWh
RNG	Billion MJ	34,251	38,220	$4.17/kJ
Gasoline	Billion gallons	134	134	$2.30/gal
Diesel	Billion gallons	60.7	56.7	$2.44/gal
Jet fuel	Billion gallons	26.4	34.7	$2.28/gal
Ethanol	Billion gallons	14.9	16.9	$1.62/gal
Hydrogen	Million tons	12.3	50.0	$2.00/kg
Bioasphalt binder	Million tons	3.15	7.28	$152.24/tonne
Bio-polyethylene	Million tons	29.1	57.8	$1208.93/tonne
Adipic acid	Million tons	3.15	9.92	$1.72/kg
Acetone	Million tons	2.00	2.51	$1170/tonne
Lumber	m^3	45,827,900	51,912,700	$171/m^3
Biochar	Million tons	Information unavailable		$95.43/tonne

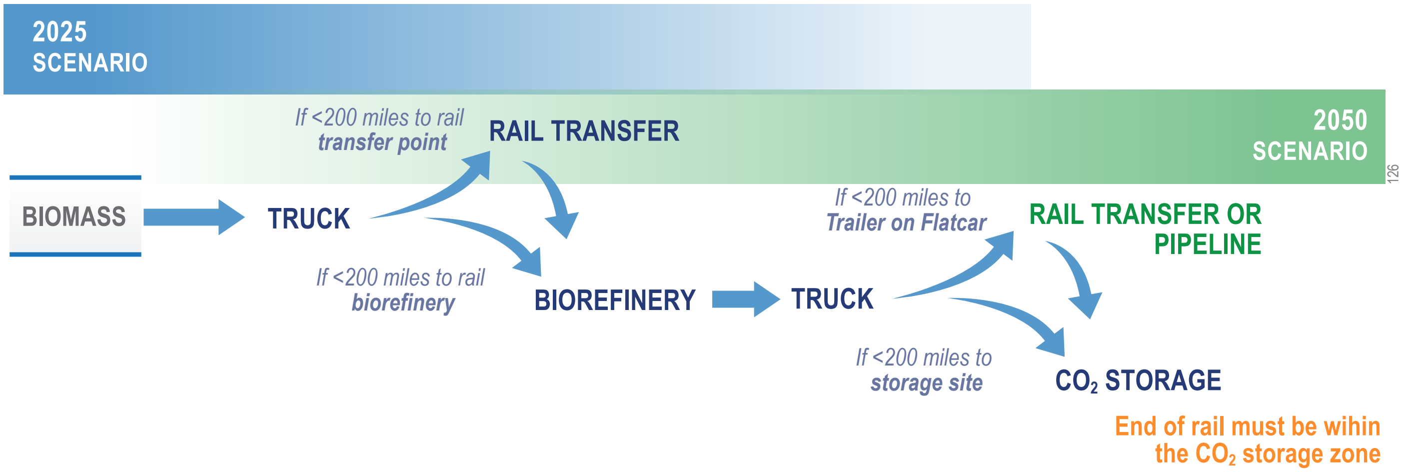


Figure 6-36. *Biomass and CO_2 transport assumptions used by the Biocarbon Infrastructure, Logisitics, and Transportation (BILT) model. A more detailed description of CO_2-removal pathway transportation logistics and costs can be found in Chapter 5–CO_2 and Biomass Transport.*

Bioproduct Market Constraints used in Biocarbon Infrastructure and Logistics Model

BiCRS can produce a wide range of energy products, including RNG, gasoline, diesel, jet fuel, ethanol, hydrogen, and electricity, alongside valuable commodities like bio-oil, biopolyethylene, adipic acid, acetone, and lumber (see **Table 6-17**). We assume these bioproducts are sold in the market and generate revenue to reduce the carbon-removal costs of BiCRS. Therefore, the economic viability of BiCRS pathways heavily depends on energy and commodity markets. These markets play a pivotal role in determining the demand, price, and growth potential of biorefinery products, limiting the volume of products that can be sold at specific price levels. For additional assumptions on bioproducts' market constraints, see **Appendix 6.**

To comprehensively account for market demand in our analysis and prevent oversaturation, we have integrated market constraints into BILT. To address the volatility and uncertainty in market demands, we have gathered historical market-size data and projections from credible sources to represent near- and long-term market trends, as presented in **Table 6-17**. We gathered all data for bioenergy products from the 2022 US EIA Annual Energy Outlook, while data on biochemicals and biomaterials are based on multiple available market-research reports [111-117]. We have not attempted to predict the potential impacts of consumer-market preferences, public incentives, and technological innovations, all of which can significantly influence the supply and demand dynamics of biorefinery products.

Results from the Biocarbon Infrastructure, Logistics, and Transportation (BILT) Model

BILT optimization provided insights to the following questions, which we will address in subsequent sections.

- How much net CO_2 can we remove considering the full supply chain of biomass and distribution of CO_2? And at what cost?
- How much additional carbon removal can carbon crops provide?
- Which BiCRS pathways can help achieve maximal CO_2 removal at the lowest cost?
- What role does each CO_2-removal region play in BiCRS deployment?
- What are the most economical biorefinery scales and siting locations?
- How does carbon-removal cost change according to different system-wide removal targets?
- How does product selling-price change the competitiveness of different pathways?
- What are the potential impacts of BiCRS pathways on SAF supply and carbon removal?

We evaluated carbon-removal potentials ranging from 25% to 99% of maximal removal (relative to biomass availability) to understand the scope of different carbon-removal quantities and their impact on the optimal removal strategy. We showcase the 90% removal results as technically feasible and ambitious. Our results show that the optimal strategy also balances between technologies that maximize carbon removal and those that reduce carbon-removal costs. In later sections, we investigate the various removal options to comprehend the role of different technologies under different carbon removal targets.

Net CO_2 Removal Capacity and Cost for the three Biomass Assessments Described in Sections 6.1 and 6.2

We summarize net CO_2-removal potential for all long-term 2050 biomass assessments and near-term 2025 biomass assessment in **Table 6-18**, considering the full system of supply chain of biomass, biomass conversion, and distribution of CO_2 at 90% of maximum removal potential (based on available biomass). Overall, in 2050, we find a removal potential of 614–1140 million tonnes CO_2/year through low-moisture biomass, including forestry, agriculture residue, MSW, and carbon crops, at an average cost of less than $91/tonne CO_2. The major biomass difference between baseline and the zero-cropland-change case is the additional usage of 137 million dry tonnes per year of carbon crops, adding 206 million tonnes of additional net CO_2 removal at a slightly higher cost. Wet-waste biomass can contribute another 22 million tonnes of CO_2 removal per year but at a cost of $1242/tonne; see section on BILT results using wet waste for details. Moreover, we found that in 2050, 100 million tonnes of biogas CO_2 can add another 57 million tonnes of CO_2 removed per year, at a price of $51/tonne. The near-term potential BiCRS carbon-removal capacity for 2025 is significantly lower (by a difference of 244–770 million tonnes per year) at a higher cost. The primary contributing factors to the higher projected costs in 2025 are the reduced availability of biomass resources and higher grid emissions in 2025 compared with 2050.

Pathways for Maximizing CO_2 Removal at Minimal Cost

As shown in **Figure 6-37**, under the zero-cropland-change biomass assessment, we find potential for 820 million tonnes CO_2/year using 527 million dry tonnes of low-moisture biomass/year including forestry, agriculture residue, MSW, and carbon crops, at an average cost of $91/tonne CO_2. The BiCRS pathways selected include gasification to H_2, combustion to electricity, and pyrolysis to bio-oil to bio-asphalt.

Table 6-18. Summary of BILT model results for carbon dioxide removal tonnes and cost for 2050 Baseline, Zero Cropland Change, and Maximum Economic Potential biomass assessments and 2025 Baseline biomass assessment to achieve 90% of carbon removal capacity (related to total biomass availability).

	Feedstock	Low Moisture	Wet Waste	Biogas	Total
Feedstock Used (million dry tonne/year)	2025 Baseline	239	36	84	359
	2050 Baseline	390	37	100	527
	2050 Zero-Cropland-Change	527	37	100	664
	2050 Maximum-Economic-Potential	738	37	100	875
Net CO_2 Removal Potential (million tonne/year)	2025 Baseline	370	11	39	420
	2050 Baseline	614	22	57	693
	2050 Zero-Cropland-Change	820	22	57	899
	2050 Maximum-Economic-Potential	1140	22	57	1219
CO_2 removal cost ($/tonne CO_2)	2025 Baseline	99	2357	70	---
	2050 Baseline	84	1242	51	---
	2050 Zero Cropland Change	91	1242	51	---
	2050 Maximum Economic Potential	90	1242	51	---

We found that gasification to H_2 is preferred in several regions. Gasification to H_2 can process a variety of feedstock types, has a high carbon-removal efficiency, and can generate significant revenue from selling H_2 at $2/kg. Combustion to electricity is also selected in a few regions, such as the Northeast, due to the combustion pathway's high carbon-removal potential and compatibility with high ash-content biomass like MSW. Pyrolysis to produce bio-oil that can be blended with fossil asphalt to produce bio-asphalt is also selected due to its low capital investment and relatively high CO_2-removal potential. Pyrolysis is primarily located in regions where more mature technologies are not able to scale due to lack of biomass or geologic storage. Even though pyrolysis to bio-oil to bio-asphalt is a low removal-cost BiCRS pathway, literature suggests that currently bio-oil can be blended with fossil-derived asphalt up to a composition of 10%. This low blend rate therefore limits its overall contribution to carbon removal in our analysis.

Figure 6-37 also shows major biomass transportation modes, with the thick arrows representing biomass transportation by rail and thin lines showing local truck transportation. The most prominent long-distance transportation of biomass by rail occurs from Northern California to facilities located in proximity to geologic storage in Wyoming and from Iowa to the Gulf Coast. These cases highlight areas where the

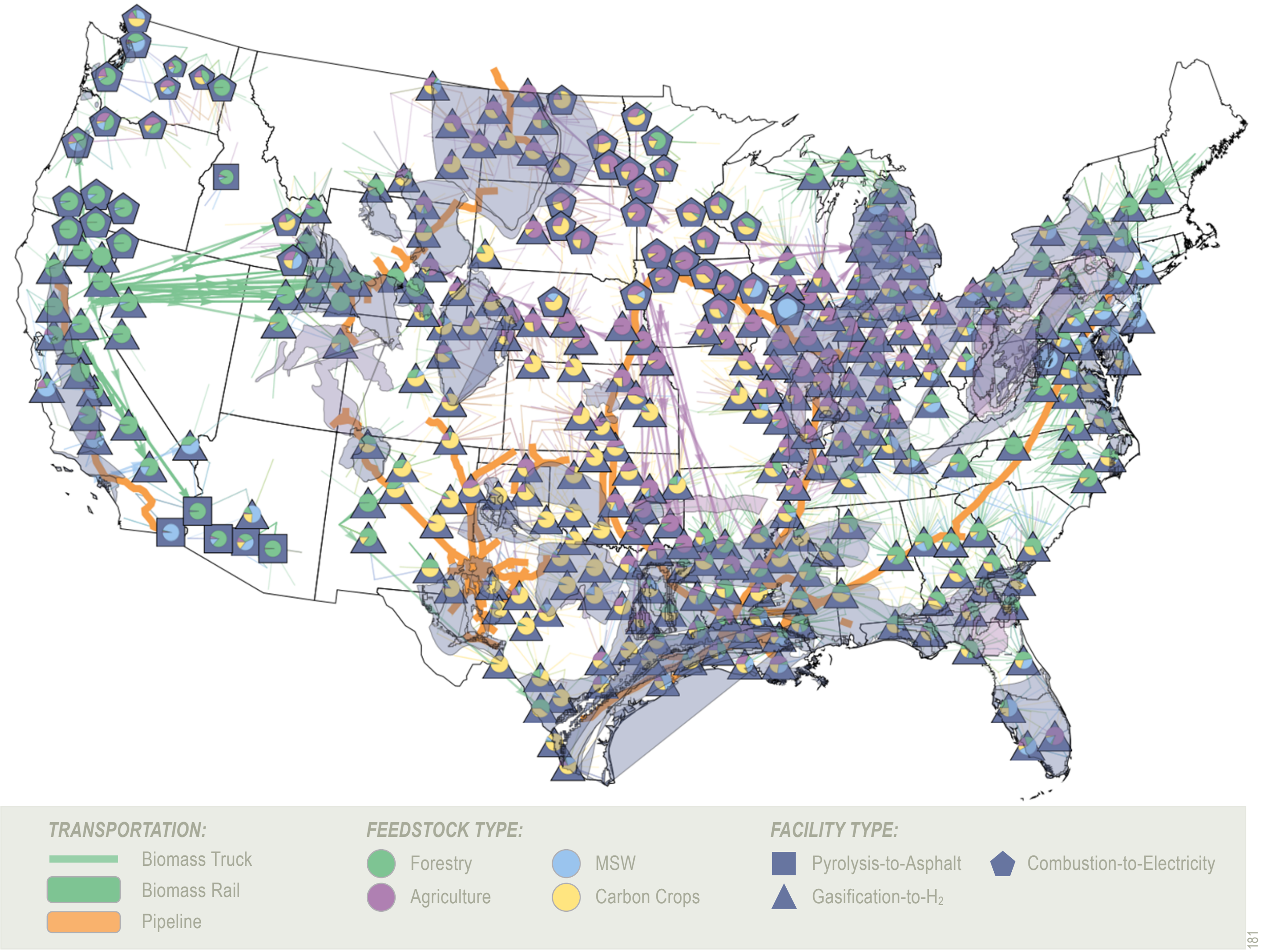


Figure 6-37. *Biocarbon Infrasturcture, Logistics, and Transportation (BILT) model result: 90% carbon-removal capacity for zero-cropland-change biomass. A snapshot of a US BiCRS system that could achieve 90% carbon-removal capacity (related to total biomass availability) at minimal cost ($/tonne CO_2). The symbols represent facility type, and symbol color represents biomass type. The symbol size represents the CO_2 facility removal capacity ranging from 1.3-3 million tonnes/ year. Orange lines represent CO_2 pipelines (current and future); thick lines represent biomass transportation by rail and narrow lines by truck. The total CO_2-removal potential depicted here represents 820 million tonnes/year at a minimal removal cost of $91/tonne CO_2, with 34 million tonnes of hydrogen production. MSW = municipal solid waste.*

biomass-density saturates the available biorefineries in the local area that may be in closer proximity to geologic storage. These results would likely change if we increased the biorefinery size or reduced the allowable distance between facilities in our model constraints. However, we chose these constraints based upon our assessment of feasibility and precedent for biorefinery size and siting.

Carbon Negative Hydrogen Production: Implications of a Dominant BiCRS Pathway

Hydrogen is a major product in this analysis, but the industry will need to address several challenges and limitations for the scale of implementation described here. BiCRS hydrogen has some advantages relative to electrolysis hydrogen, as it does not rely heavily on grid electricity and produces two products of value, decarbonized hydrogen and carbon-removal services. The US DOE has put forward a Clean Hydrogen Roadmap [112] that projects a hydrogen demand of 50 million tonnes/year by 2050. The primary uses are projected to be decarbonized chemical production; heavy-duty transportation; iron, steel, and cement; and grid electricity. As shown in **Table 6-19**, BiCRS carbon-removal pathways can produce hydrogen at the scale of this projected need. However, BiCRS carbon-negative hydrogen must also complement other high-priority biomass uses, such as in the production of SAF. We note that hydrogen is also needed to refine SAF, though we did not analyze this product synergy. The most important limitation in realizing carbon-negative hydrogen at the scale described in our analysis is the lack of transportation infrastructure. There are many opportunities for co-locating hydrogen with existing industrial facilities for chemical and energy production. Biorefineries could produce hydrogen on demand, but they will likely need storage. Hydrogen storage requires special and costly containers to store hydrogen at high pressures or cryogenic temperatures with boil-off capture to reduce losses. Special containers will also be needed for truck or rail transport, which could be expensive without compression to increase the amount transported on a volume basis. For long-distance transport, dedicated pipelines may be the most cost-effective option, but they will take time to permit and build.

Lowest-Cost BiCRS Deployment Opportunities

In comparison to 90% CO_2-removal potential (as shown **Figure 6-37**), we show BILT results for a lower-cost deployment of BiCRS technologies, corresponding to a CO_2 removal potential of 455 million tonnes CO_2/year (50% of the theoretical maximum removal potential) as shown in **Figure 6-38**. We found that near-term opportunities exist primarily in regions with a convergence of high-density biomass feedstocks and low-cost geologic storage for CO_2. Specifically, areas such as the Gulf Coast, the Great Lakes region, and California exhibit promising potential for low-cost BiCRS deployment. The first 450 million tonnes of CO_2 can be removed at a net CO_2 removal cost of $68/tonne CO_2, compared to the 90% removal goal of $91/tonne CO_2 as discussed above. Low-cost and high-removal-potential pathways like gasification to H_2, combustion to electricity, pyrolysis to bio-oil to bio-asphalt, and sawmill to wood-product pathways are featured in the optimized results as promising low-cost deployment BiCRS technologies in different regions.

Table 6-19. *Summary of hydrogen production from BiCRS for baseline, zero cropland change and maximum economic potential biomass at a 90% removal capacity, assuming a $2/kg hydrogen selling price. At a hydrogen selling price of $1/kg, the amount of hydrogen produced in the optimization falls to 11 million tonnes per year.*

Biomass Assessment (2050)	Biomass Used	CO_2 Removal Potential	CO_2 Removal Cost	H_2 Production	2050 Projected Hydrogen Demand
	(Million tonnes/year)	*(Million tonnes/year)*	*($/tonne CO^2)*	*(Million tonnes/ year)*	*(Million tonnes/year)*
Baseline	390	614	84	27	50
Zero-Cropland-Change	527	820	91	34	50
Maximum-Economic-Potential	738	1140	90	50	50

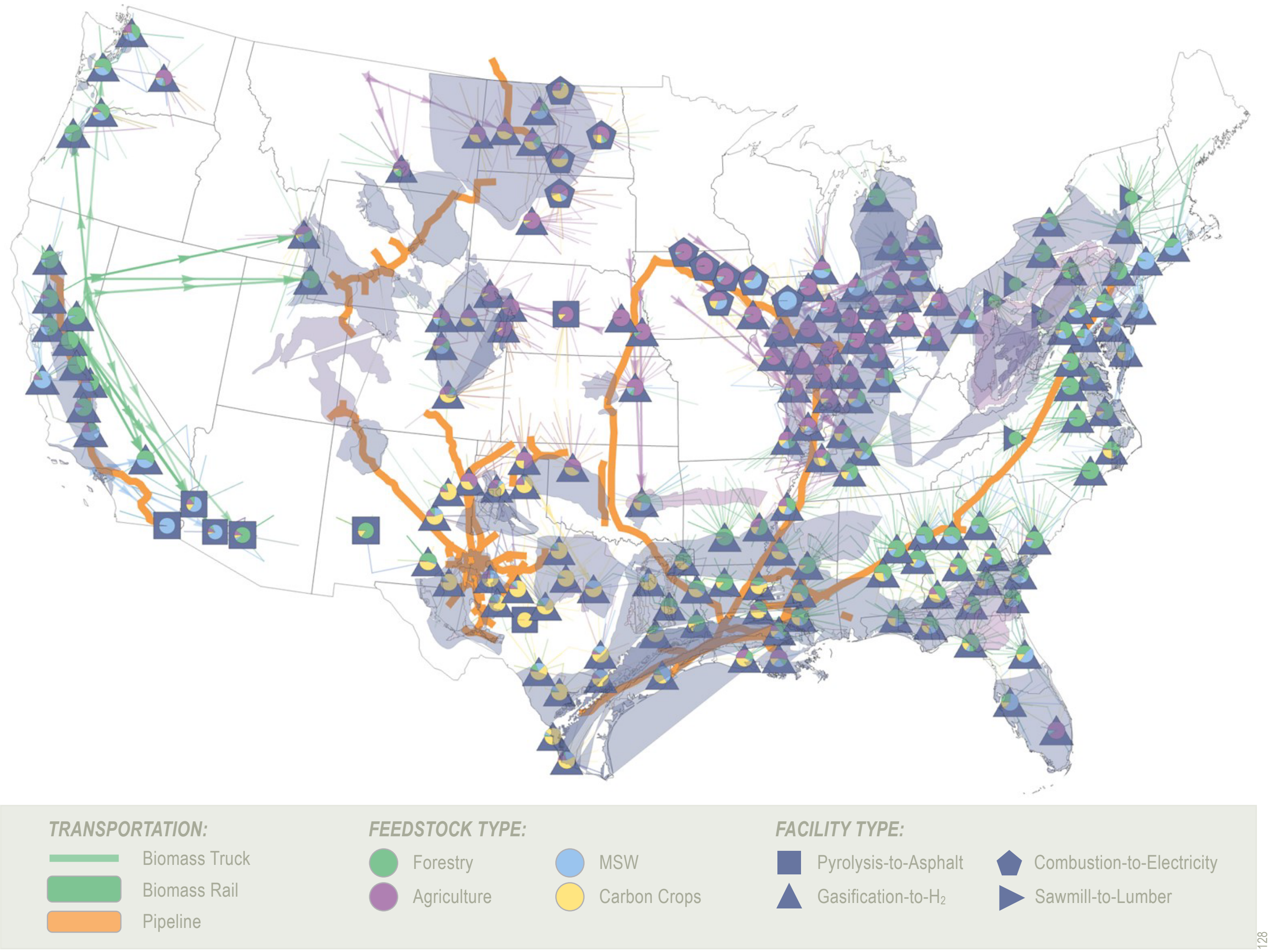


Figure 6-38. *Biocarbon Infrastructure, Logistics, and Transportation (BILT) model result: 50% carbon-removal capacity for zero-cropland-change biomass. A snapshot of a US BiCRS system that could achieve 50% carbon-removal capacity (related to total biomass availability) at minimal cost (\$/tonne CO_2). The symbols represent facility type, and symbol color represents biomass type. The symbol size represents the CO_2 facility removal capacity ranging from 1.9-3 million tonnes/year Orange lines represent CO_2 pipelines (current and future), thick lines represent biomass transportation by rail and narrow lines by truck. The total CO_2-removal potential depicted here represents 455 million tonnes CO_2/year at an average removal cost of \$68/tonne CO_2, with 20 million tonnes of hydrogen production. MSW = municipal solid waste.*

Impact of Pipeline Infrastructure on CO_2 Transportation Cost

To assess the impact of CO_2 pipelines, we conducted a comparative analysis contrasting cases with and without CO_2 pipelines (as drawn in e.g., **Figure 6-38**, represented as thick orange lines) in a 2050 zero-cropland-change biomass assessment, utilizing our BILT model. In both cases, gasification for hydrogen production remained the dominant technology, driven by high carbon-removal capacity and favorable economics. In the presence of CO_2 pipelines, the optimized solution includes construction of more large-scale gasification to H_2 biorefineries, while without CO_2 pipeline access, the solution includes more pathways that do not require CO_2 transportation, such as sawmill to lumber products.

Figure 6-39 presents a comparison of CO_2 transportation costs for gasification-to-H_2 biorefineries across diverse regions, accounting for the presence or absence of the hypothetical CO_2 pipeline infrastructure. Regions significantly benefiting from the hypothetical CO_2 pipeline infrastructure are near the pipeline and have high biomass density and longer distances to geologic storage sites; these regions are

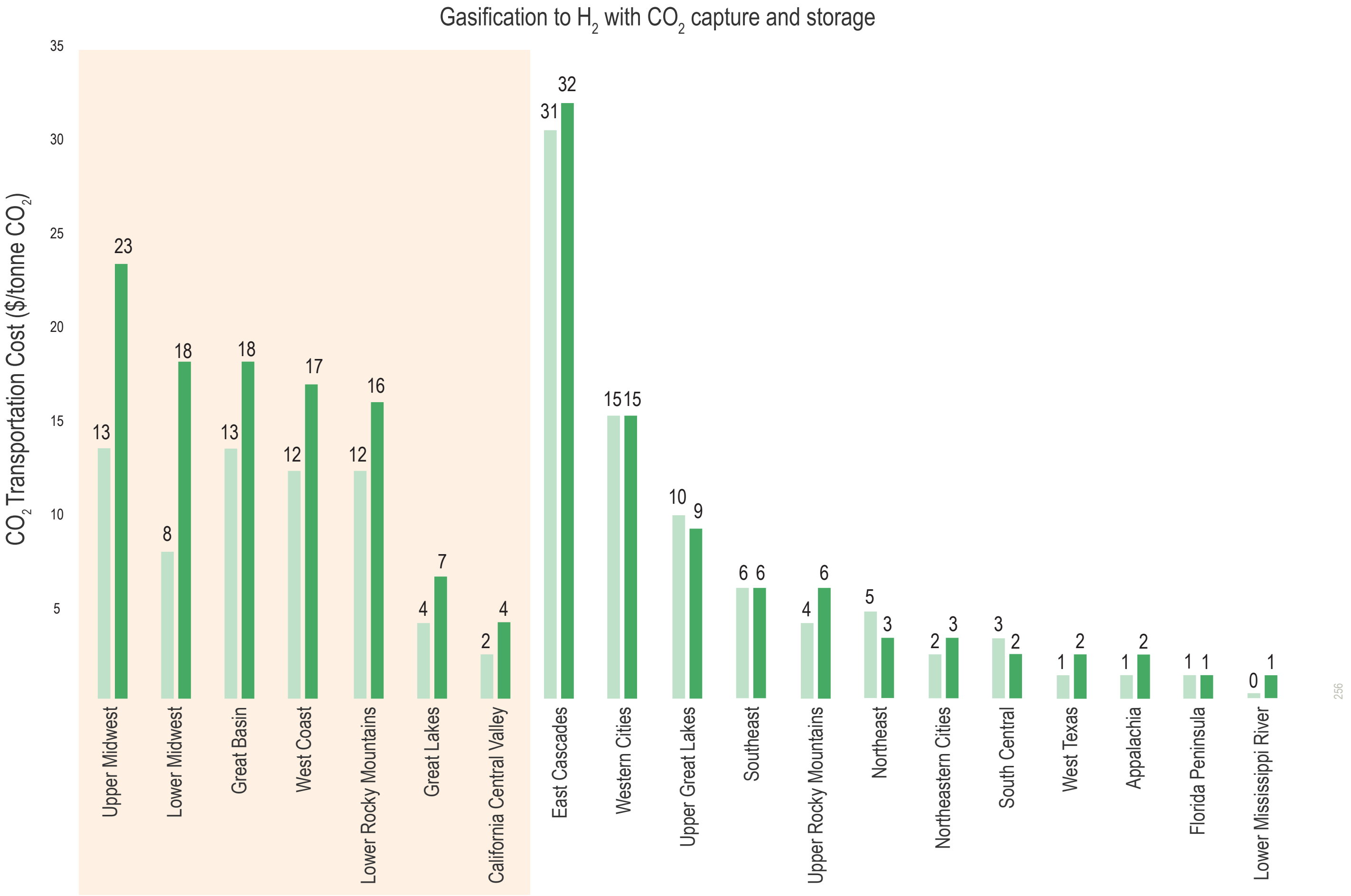


Figure 6-39. *CO_2-transportation cost for gasification-to-H_2 biorefineries in different regions compared with and without CO_2 pipeline infrastructure.*

highlighted within an orange box in **Figure 6-39**. Notably, the Upper and Lower Midwest regions stand out as beneficiaries of this specific pipeline implementation; large gasification to H_2 biorefineries in those regions can save $10/tonne CO_2 on transportation cost with pipeline infrastructure, which could lead to substantial annual savings of $27 million for each gasification-to-H_2 biorefinery with a capacity of >5000 tonnes/day. Similarly, regions like the Great Basin and West Coast benefit from neighboring states' pipeline infrastructure, offering potential CO_2 transportation cost savings of approximately $5/tonne CO_2.

Impact of the Carbon-Removal Target on Total Costs and Cost Breakdown

We evaluated carbon-removal potentials ranging from 25% to 99% of maximal removal to understand the scope of different carbon-removal quantities and their impact on the optimal removal strategy. As the carbon-removal target increases, the minimum cost of removing each tonne of CO_2 increases. **Figure 6-40** shows the net removal cost ranging from $51/tonne up to $108/tonne when the removal goal increases from 25% (228 million tonnes CO_2/year) to 99% (901 million tonnes CO_2/year). Capital cost and operating cost of biorefineries are the most influential factors, accounting for approximately 60%–68% of the total cost. Feedstock cost and biomass transportation cost also have significant impact, representing approximately 20%–25% of the total cost. In contrast, the costs of CO_2 transportation and injection play relatively minor roles in the overall cost when compared to the other variables. It is important to note that our study employed a general transportation cost per tonne of CO_2 per mile for different modes of transportation (a detailed calculation is summarized in **Chapter 5 –CO_2 and Biomass Transport**). However, we recognize that specific CO_2 logistic designs may vary for different case studies, and transportation costs could differ significantly accordingly. Moreover, BiCRS pathways have the advantage of producing marketable products, which can generate revenue to offset the substantial capital and operating investment associated

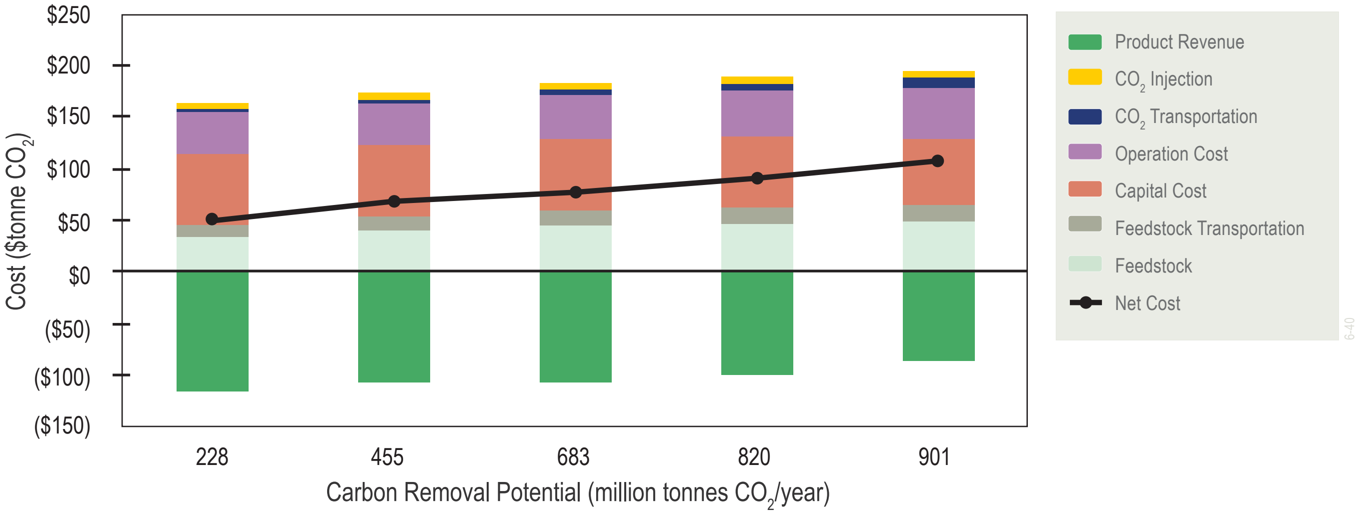


Figure 6-40. *The breakdown of CO_2-removal cost according to different CO_2-removal targets . The maximum CO_2-removal potential, utilizing 2050 zero-cropland-change biomass, is estimated to be 901 million tonnes CO_2/year. To assess incremental milestones, the following percentages of the maximum removal potential are considered: 25% (228 million tonnes/year), 50% (455 million tonnes/year), 75% (683 million tonnes/year), and 90% (820 million tonnes/year). The figure showcases the corresponding CO_2-removal costs associated with each of these removal targets, providing insights into the cost implications of achieving different levels of CO_2 removal.*

with biorefineries. This revenue plays a crucial role in reducing the overall cost of CO_2 removal. Therefore, the selling price of the products becomes a critical factor that directly impacts the CO_2-removal cost.

The Lowest-Cost Biorefinery Scales, Locations, and Logistics

In addition to identifying the lowest-cost pathways to achieve a CO_2 removal target, our analysis also revealed several important findings regarding biorefineries' size, siting, and logistics. We found that the BILT model selected larger-scale biorefineries of 5000 dry tonnes/day when the biomass was available in that location to benefit from economies of scale. Our results demonstrated that moving biomass over longer distances via railways proves to be more cost-effective than transporting large volumes of CO_2. This conclusion is quantitatively demonstrated in **Chapter 5 –CO_2 and Biomass Transport.** When all biorefineries in a high biomass-density region had been saturated, the model moved biomass by rail from high biomass-density areas, like the West Coast and Midwest, to regions with low biomass availability but suitable geologic storage, such as Texas and the Rocky Mountain region. The optimized solution injects 380 million tonnes CO_2 directly into storage, while 320 million tons are transported via short-distance trucking (<200 miles) to geologic storage areas. Another 80 million tonnes of CO_2 is transported by pipeline, with the potential to transport even larger volumes if more short-distance trunk lines are established to connect biorefineries to the main pipeline network.

Impact of Product Selling Price on the Competitiveness of Gasification to H_2

We have shown that product selling prices have significant impact on CO_2 removal costs for different BiCRS pathways (see **Figure 6-33)**. Here, we explore the influence of H_2 selling price on the overall CO_2-removal strategy by reducing the H_2 selling price to $1/kg (versus $2/kg) and conducting a BILT optimization using zero-cropland-change biomass. **Figure 6-41** showcases the lowest cost strategy for achieving a 90% of maximum removal goal with zero cropland change biomass. Our analysis revealed a diversified set of four BiCRS pathways that effectively achieved the removal goal of 820 million tonnes of CO_2 per year at a minimum cost. These four pathways are combustion to electricity, gasification to H_2, sawmill to wood products, and pyrolysis to bio-oil to bio-asphalt. It is important to note that the decrease in H_2 selling price resulted in a higher overall CO_2-removal cost of $139/tonne. The model selected higher-cost BiCRS pathways to reach the target of removing 820 million tonnes of CO_2 per year with zero-cropland-change biomass.

When we assume a lower H_2 selling price, gasification to H_2 is no longer the dominating BiCRS pathway due to the reduced revenue generation. Combustion to electricity emerges as a dominating pathway due to its high carbon-removal efficiency, ability to handle various feedstocks, and the potential to generate revenue through electricity sales at a price of 8 cents/kWh. Additionally, the construction of sawmill-to-wood-product biorefineries increases notably,

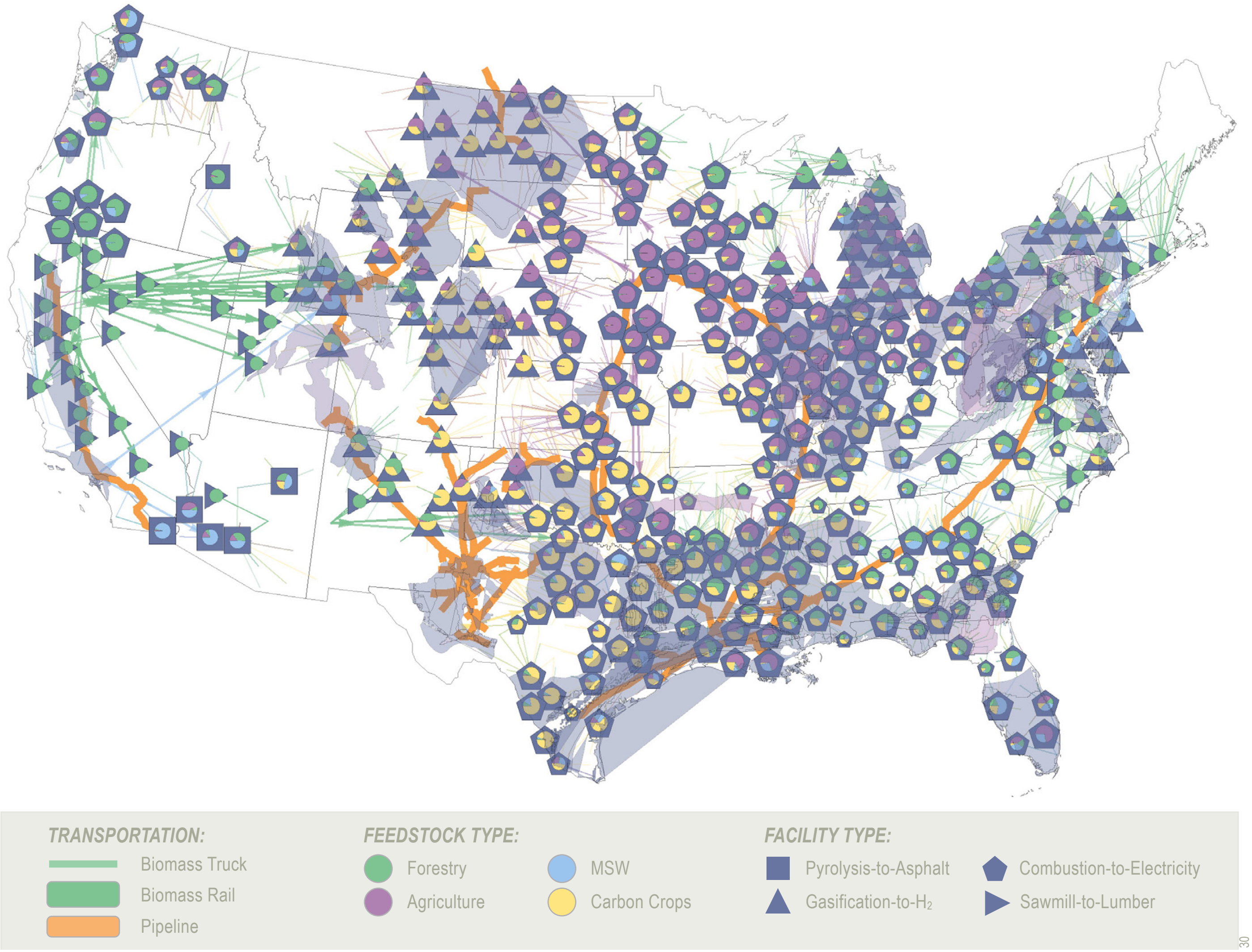


Figure 6-41. *Biocarbon Infrastructure, Logistics, and Transportation (BILT) model result: 90% carbon-removal capacity for zero-cropland-change biomass and reduced H_2 selling price. A snapshot of a US BiCRS system that could achieve 90% carbon-removal capacity (related to total biomass availability) at minimal cost ($/tonne CO_2) with a H_2 selling price of $1/kg. The symbols represent facility type, and symbol color represents biomass type. The symbol size represents the CO_2 facility removal capacity ranging from 0.50 to 2.83 million tonnes/year. Orange lines represent CO_2 pipelines (current and future); thick lines represent biomass transportation by rail and narrow lines by truck. The total CO_2-removal potential depicted here represents 820 million tonnes/year; however, due to the low revenue generated from selling hydrogen at a lower price, the hydrogen production in this case is projected to be 11 million tonnes/year, and the average removal cost is projected to be $139/tonne CO_2. MSW = municipal solid waste.*

particularly in regions abundant in small-diameter tree biomass but lacking geologic storage capacity. The sawmill pathway has a promising removal potential that stores carbon in two different forms: in long-lived wood products and underground. This loosens the requirement to transport large amounts of CO_2 and therefore make this pathway more competitive in areas that lack geologic storage. With the H_2 selling-price change to $1/kg, the pyrolysis to bio-oil to bio-asphalt pathway remains unchanged from the zero-cropland-change biomass assessment at a H_2 price of $2/kg. While it offers low costs, this pathway's overall contribution to CO_2 removal is limited due to our assumptions on the blending potential of bio-oil in asphalt.

Using BiCRS to Supply Sustainable Aviation Fuel (SAF) and Carbon-Removal Services

To understand how BiCRS can supply the SAF market while maximizing carbon removal, we set the BILT objective to maximize SAF production while minimizing carbon-removal costs. We considered two major aviation-fuel-production

Table 6-20. *Summary of sustainable aviation fuel (SAF) and SAF equivalent production, carbon dioxide removal tonnes, cost and avoided emissions for baseline, zero cropland change, and maximum economic potential biomass assessments to achieve 90% of carbon removal capacity (related to total biomass availability).*

2050 Feedstock Assessment	Feedstock Used	SAF Production	SAF Equivalent Production*	Net CO^2 Removal Potential	CO^2 Removal Cost	Avoided Emissions
	Million dry tonne/year	*Billion gallons/ year*	*Billion gallons/ year*	*Million tonne/ year*	*\$/tonne CO_2*	*Million tonne/ year*
Baseline	368	8	20	364	151	565
Zero Cropland Change	506	11	28	490	146	762
Maximum Economic Potential	720	16	39	694	149	1082

*SAF equivalent production includes aviation fuels, gasoline, and diesel production, all in units of SAF gallons.

pathways—gasification to SAF and fermentation to SAF—with both pathways integrating carbon capture and storage to maximize carbon removal. We showcase the 90% removal result as an ambitious but technically feasible target.

Table 6-20 provides a summary of SAF production, corresponding CO_2-removal potential, feedstock usage, and avoided emissions for the three biomass assessments projected for 2050. We observed discrepancies in the total biomass consumed between the SAF-only case and the previous case where other processes were also considered. The major difference arises from high ash-content biomass that was excluded from gasification or fermentation to SAF production due to low process efficiency. However, this type of biomass was used in the combustion-to-electricity pathway in the previous case.

Typically, aviation fuel is produced alongside other liquid fuels like gasoline or diesel. By utilizing highly efficient catalysts and controlling the reaction pathway, it is possible to shift the selectivity and produce a greater quantity of the desired target product. Therefore, we report SAF production separately and also include SAF-equivalent production, which takes into account gasoline- and diesel-range products. With the current accessible and suitable low-moisture biomass ranging from 368 to 720 million dry tonnes per year, the results suggest we can produce 8–16 billion gallons of SAF annually and generate 20–39 billion gallons of SAF equivalent. Additionally, we can achieve a net CO_2 removal ranging from 364 to 694 million tonnes per year at a cost of less than \$151/tonne. Note that the fuel selling price significantly influences the removal cost, as discussed in the sensitivity analysis section. While this study primarily focuses on net carbon removal, we acknowledge the benefits of avoided emissions when replacing fossil fuel products. Based on the current emission factors of fossil aviation fuel, we estimate that the avoided emissions from deploying the SAF pathway could reach 565–1082 million tonnes of CO_2e per year.

Figure 6-42, the BILT SAF-only case, demonstrates the lowest-cost strategy to achieve 90% of the maximum-removal target using zero-cropland-change biomass. Gasification is widely preferred over fermentation for SAF production. This preference stems from several factors: gasification offers a higher removal potential and significantly lower operating costs compared to fermentation. Fermentation to aviation fuels requires substantial capital investment and incurs highly variable operating costs, which cover expenses for chemicals, enzymes, and catalyst materials used in biomass pretreatment, enzymatic hydrolysis, and ethanol upgrading to SAF. We acknowledge that there are advantages to utilizing fermentation for SAF production, especially in regions where fermentation infrastructure is already well-established, but we did not address this aspect in this particular BILT example. We observed that the same regions with established fermentation infrastructure, such as the Great Lakes, Southwest, and Midwest, also show the greatest potential for SAF production, primarily due to their abundance of suitable biomass resources.

We additionally conducted an analysis to prioritize biomass utilization and CO_2 removal while aiming to satisfy 50% of DOE's 2050 SAF goal of 35 billion gallons as depicted in the **Executive Summary Figure ES-4**. After this SAF goal was fulfilled, we directed the remainder of the biomass toward other low cost BiCRS pathways. The data in **Figure ES-4** reflect use of 301 million dry tonnes per year of biomass to generate 17.5 billion gallons of SAF annually. The remaining biomass is allocated to produce 17 million tonnes of hydrogen, 50 million MWh of electricity, and 7 million tonnes of bio-oil for bioasphalt applications. This strategy facilitates an annual CO_2-removal capacity of 654 million tonnes, achieved at a cost of \$124/tonne CO_2.

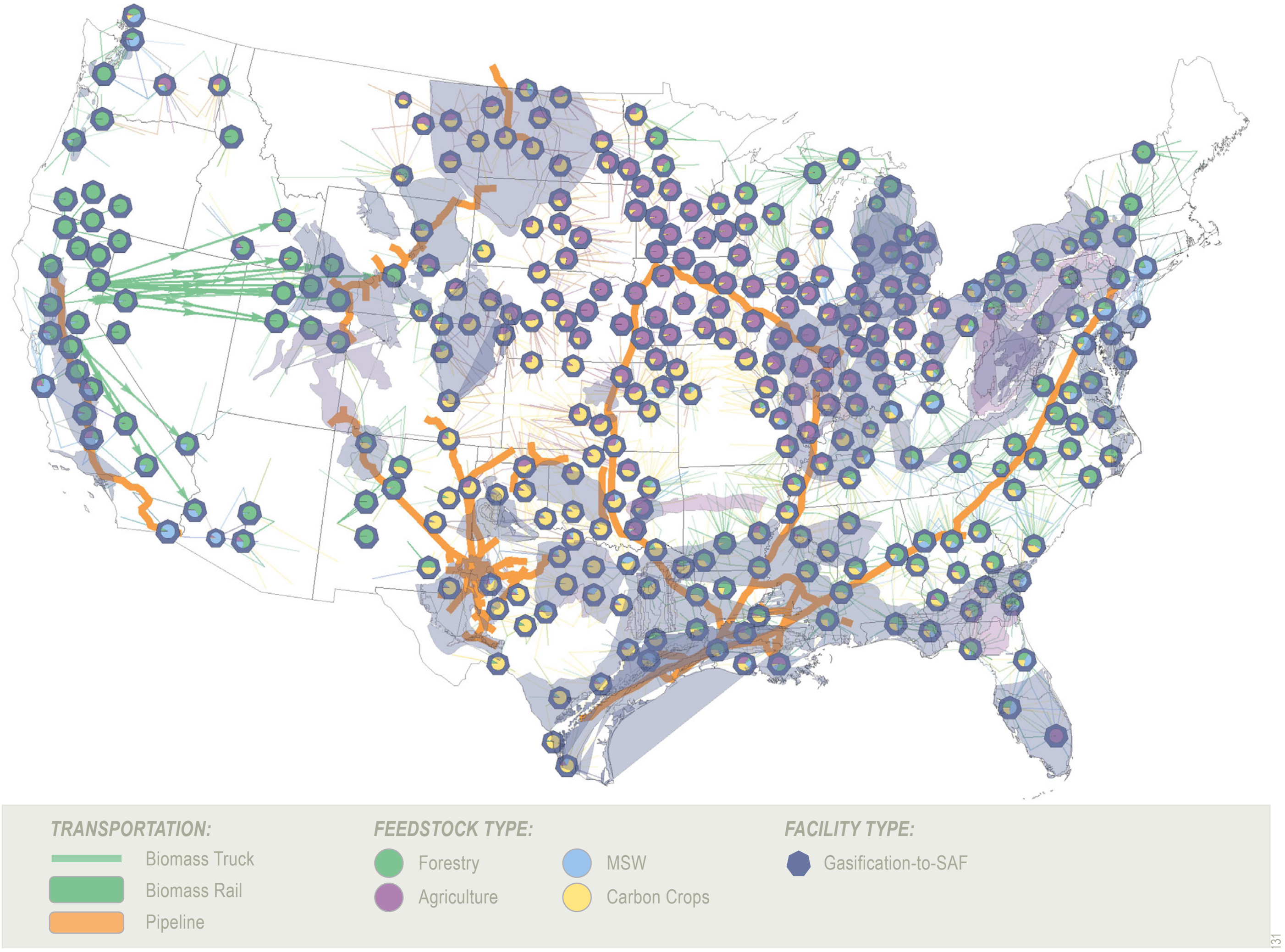


Figure 6-42. *Biocarbon Infrastructure, Logistics, and Transportation (BILT) model result: zero-cropland-change biomass used exclusively for sustainable aviation fuel (SAF). A snapshot of a US BiCRS system that exclusively utilizes 2050 zero-cropland-change biomass for the SAF sector. The symbols represent facility type, and symbol color represents biomass type. The symbol size represents the CO_2 facility removal capacity ranging from 0.58-1.78 millions/year. Orange lines represent CO_2 pipelines (current and future); thick lines represent biomass transportation by rail and narrow lines by truck. The total SAF production potential is 11 billion gallons/year, with SAF-equivalent production of 28 billion gallons/year. CO_2-removal potential depicted here represents 490 million tonnes per year at an average removal cost of \$146/tonnes CO_2. MSW = municipal solid waste.*

BILT wet-waste results

We modeled processing of wet-biomass waste via BiCRS technologies separately from dry-biomass feedstocks. The primary wet wastes included are swine manure, dairy and beef cattle manure, food waste (diverted from landfills), landfill biogas (resulting from biogenic organic waste in landfills), and WWTP biogas (resulting from biogenic organic waste in wastewater). We ran BILT optimizations for manure and food waste using greenfield AD and HTL as the two BiCRS technology options. We ran separate BILT optimizations for landfill and WWTP biogas where existing biogas collection is utilized and new biogas-upgrading units are installed (see **Appendix 6**). Under these assumptions, approximately 80 million tonnes of CO_2 are removed through these wet-waste pathways, the majority of which is from existing sources of biogas generated at landfills and WWTPs.

The costs of removing CO_2 from existing landfills and WWTPs are significantly lower (\$40–\$51/tonne CO_2) than those of greenfield AD and HTL facilities treating manure and food waste (\$770–\$1242). The primary reasons for this cost discrepancy are the low carbon-removal potential and high capital costs of greenfield AD and HTL facilities. We discuss the factors leading to low carbon-removal potential for some wet wastes in **Appendix 6**. It is important to note that all wet-waste conversion pathways are crucial for avoiding methane emissions and other pollution. We discuss these factors in the sections on emissions reduction and EEEJ later in the chapter.

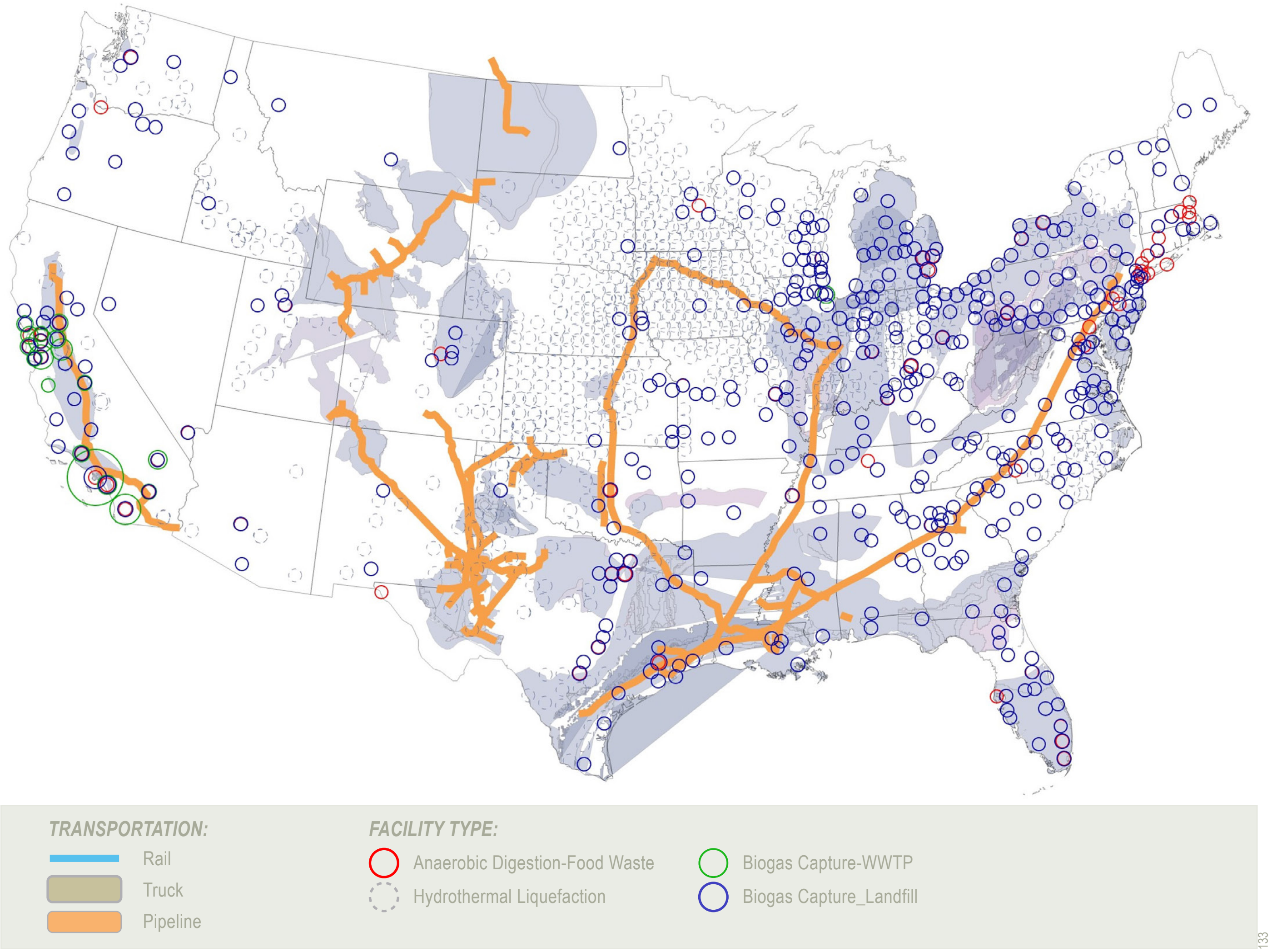


Figure 6-43. *Biocarbon Infrastructure, Logistics, and Transportation (BILT) model result: wet waste 90%. A snapshot of a US BiCRS system that could utilize wet waste to achieve 90% carbon-removal capacity (related to total biomass availability) at a minimal cost ($/tonne CO_2). The symbol colors represent facility type. Symbol sizes represents the CO_2 facility removal capacity ranging from 1.2 tonnes/year to 7 million tonnes/year. Orange lines represent CO_2 pipelines (current and future). Wet-waste biomass is processed locally, and the BiCRS facilities are designed to match the available capacity of the wet-waste resources. The total CO_2-removal potential depicted here represents 22 million tonnes/year at an average removal cost of $1242/tonne CO_2.*

The spatial distributions of BiCRS facilities for utilizing wet waste are shown in **Figure 6-43** for the 90% removal target. For the 50% removal target (see **Appendix 6, Figure A6-8**), the majority of carbon removal is via AD of swine waste, HTL of various wastes, biogas processing at existing landfills, and biogas processing from WWTPs in southern California. AD of food waste is present in the Northeastern United States for the 90% removal target but to a lesser extent than the other pathways. For the 90% removal target, the majority of carbon removal is via HTL of various wastes, biogas processing at existing landfills, and biogas processing from WWTPs in southern California. The notable shift from AD of swine waste in the 50% target to HTL in the 90% target can be explained by feedstock costs and economies of scale. The costs of food-waste feedstocks are higher than the costs of manure, which leads to more manure use at the lower carbon-removal target. The costs of several manure-feedstock resources are assumed negative as described in **Section 6.1**; the low carbon-removal potential of manure is overcome by such low feedstock costs. However, the quantity of low-cost manure is relatively low, leading HTL to be employed to achieve the 90% removal target. Economies of scale are also a factor at the 90% removal target since HTL is more capital-intensive than AD and thus benefits from larger scales of production.

Table 6-21. *Comparison of CO_2 removal and avoidance plus removal, along with the associated costs for CO_2 removal versus the costs for per tonne of CO_2 removal plus avoidance. The table summarizes multiple representative cases that have been presented above, including zero cropland change biomass assessments at different H_2 selling prices (\$2/kg versus \$1/kg), Zero Cropland Change biomass assessments for sustainable aviation fuels production, biogas capture, and wet waste biomass for renewable natural gas production.*

Biomass Assessment (2050)	Quantity (Million Tonne CO_2)		Cost (\$/Tonne CO_2)	
	Removal	Avoidance + Removal	Removal	Avoidance + Removal
Zero Cropland Change Low Moisture Biomass (\$2/kg H_2)	820	820	91	91
Zero Cropland Change Low Moisture Biomass (\$1/kg H_2)	820	820	139	139
Zero Cropland Change Low Moisture Biomass (Sustainable Aviation Fuel Production Only)	490	762	146	94
Biogas	57	1241	51	2
Wet waste	22	139	1242	200

How Do Prominent BiCRS Pathways Impact Our Ability to Reduce CO_2 Emissions?

In our study, we primarily focus on the net removal of atmospheric carbon and the associated removal costs. However, we are aware of the substantial potential for avoided emissions resulting from the production of bio-products that can replace fossil-based alternatives. Estimating avoided emissions involves considering regionally specific counterfactual scenarios, and their complexity is the main reason why they are regarded as secondary in this study. Nonetheless, we have quantified the avoided fossil-carbon emissions in a simplified manner and showcase their benefits alongside carbon removal (as depicted in **Table 6-21**). Two key factors contribute to CO_2 avoidance in our analysis. (1) Displaced fossil-CO_2 emissions: this factor accounts for the reduction in CO_2 emissions achieved by utilizing biofuels as a substitute for fossil-based fuels. (2) Biogenic CH4 avoidance: this factor takes into consideration the avoidance of biogenic methane emissions, achieved by preventing decomposition of wet wastes, such as manure and food waste. We utilized these two factors in quantifying CO_2 avoidance for each pathway, as represented in **Equation 2**

Equation 2

CO_2 avoided + removed = FD + BMA + BCA – FN

FD = Displaced fossil-carbon emissions by using biofuel

BMA = Avoidance of biogenic methane emissions

BCA = Biogenic CO_2 captured and stored in geologic sites or long-lived products

FN = Sum of fossil carbon emissions along BiCRS supply chain

The accounting ensures carbon is not counted twice when calculating avoidance plus removal. We only consider biofuels displacing fossil fuels, and thus there is no overlap with carbon removal since the carbon in biofuels does not contribute to removal. The counterfactuals assume continued fossil-fuel use for jet fuel, gasoline, diesel, naphtha, and hydrogen production, as well as methane emissions upon degradation of wet wastes (manure and food waste); the electrical grid is assumed to be net-zero in 2050, so no emissions are avoided in producing electricity from biomass. Quantities of CO_2 increase and costs decrease when avoidance is added to removal, as shown in **Table 6-21**. Notably, the differences are most dramatic for pathways that involve the release of methane; the large quantity of avoided emissions in the biogas pathway are primarily from avoided methane emissions in landfills. The total carbon-removal potential and the removal-plus-avoidance potential for scenarios with \$1 and \$2 per kg H_2 selling prices are the same, due to assumptions of a low-carbon electrical grid in 2050. Overall, the costs of removal and avoidance combined (per tonne of CO_2) are significantly lower than for removal alone.

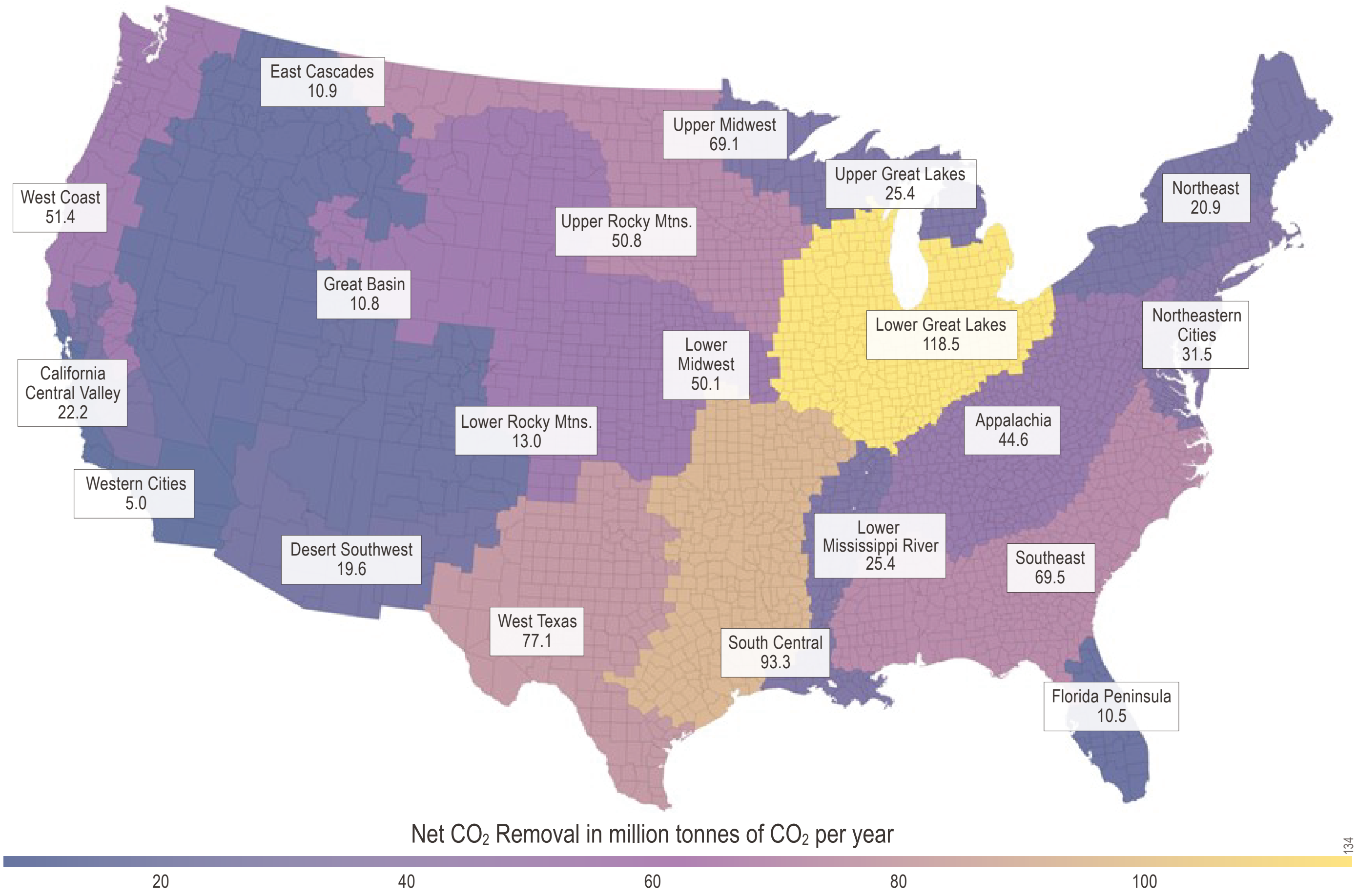


Figure 6-44. *Carbon Removal by Region. CO_2-removal potential across different regions in the United States utilizing 2050 zero-cropland-change biomass that could achieve 90% carbon-removal capacity (related to total biomass availability) at minimal cost ($/tonne CO_2). CO_2 removal potential is calculated as net removal potential by taking into account all emissions from biomass growth, harvest, transportation, and conversion and CO_2 capture, transportation, and injection.*

Regional Highlights and Opportunities

Figures 6-44, 6-45, 6-46 present regional maps that provide a comprehensive overview of regional removal potential, removal cost, and CO_2 transportation. For the breakdown of cost and product revenue, see **Appendix 6, Figures A6-9 and A6-10**. These maps are based on the results of BILT optimization, specifically focusing on the zero-cropland-change biomass assessment (low-moisture biomass only) and 90% removal potential. Our analysis revealed that every region has the opportunity to implement some aspect of BiCRS and contribute to carbon-removal efforts. Below we highlight six regions and the distinct roles they can play in contributing to BiCRS in the United States.

Lower Great Lakes: The Lower Great Lakes region has the highest CO_2-removal potential in the United States, with a removal rate of approximately 119 million tonnes of CO_2 per year for around $82/tonne. This accounts for approximately 14% of the total CO_2-removal potential in the United States using low-moisture biomass. The combination of the high density of low-moisture biomass resources and abundant geologic storage makes the Lower Great Lakes region an ideal location for biorefinery processes that maximize CO_2 removal per tonne biomass, such as gasification to H_2. We find the majority (85%) of BiCRS CO_2 generated would be directly injected or transported over short distances by trucks, contributing to favorable logistics and economics.

Southeast: The southeast also shows great potential for removing approximately 70 million tonnes of CO_2 per year at a low cost of $69/tonne. The Southeast region benefits from abundant forestry resources and the availability of carbon crops that can be cultivated on marginal and abandoned land. Moreover, biorefineries in the Southeast region can be co-located with geologic storage areas, allowing for short CO_2 transportation distances.

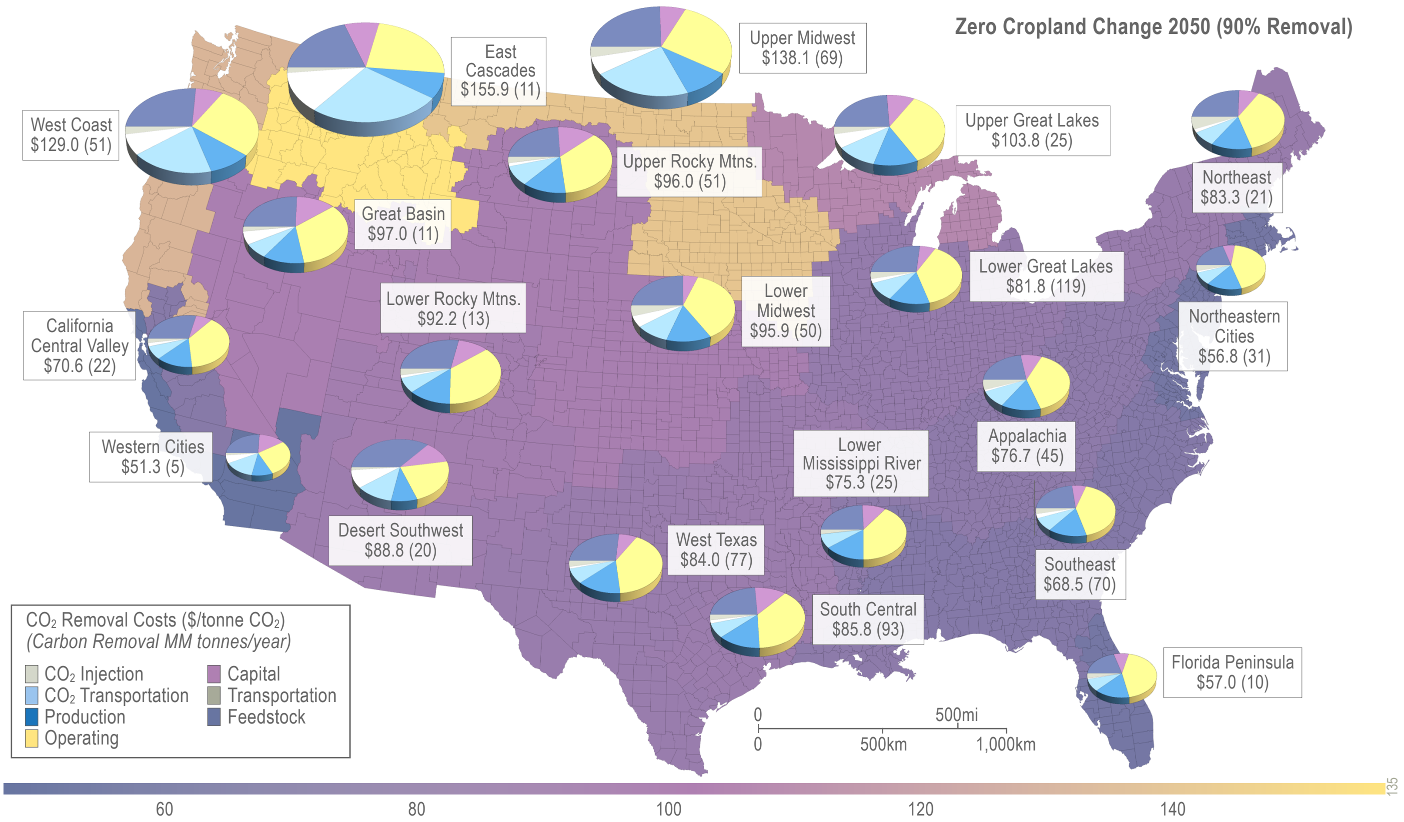


Figure 6-45. *Carbon-removal cost breakdown by region (Number in parenthesis represents total removal potential in million tonnes of CO_2 per year). Average CO_2-removal cost across different regions in United States utilizing 2050 zero-cropland-change biomass that could achieve 90% carbon-removal capacity (related to total biomass availability) at minimal cost ($/tonne CO_2). CO_2-removal cost includes costs for biomass collection and transportation, capital and operating costs for biorefinery, revenue from selling bioproducts, and costs for CO_2 capture, transportation, and injection.*

Midwest (Upper and Lower Midwest): The Midwest region, which includes both the Upper and Lower Midwest, offers abundant biomass availability, particularly agricultural residue. We have estimated that a total of 119 million tonnes of CO_2 can be removed annually in the Midwest (69 million tonnes in Upper and 50 million tonnes in Lower). When comparing removal costs, the Lower Midwest exhibits a relatively lower cost of $96/tonne, whereas the Upper Midwest has a higher cost of $138/tonne. The primary reason for this cost difference is the higher biomass density in the Lower Midwest, resulting in lower feedstock-supply cost. However, note that the Lower Midwest lacks geologic storage, which necessitates the use of pipelines to reduce CO_2-transportation costs compared to the Upper Midwest and other regions.

Our BILT results indicate that building gasification-to-H_2 biorefineries is the lowest cost option in both the Upper and Lower Midwest due to their high carbon-removal efficiency per tonne of biomass and the potential for substantial revenue from H_2 production. However, existing fermentation biorefineries in this area may create opportunities for liquid-fuel production. Additionally, our BILT optimization suggests that moving biomass resources from the Midwest to the Gulf Coast can be more economical than transporting CO_2. Alternatively, expanding CO_2 trunk lines to connect with the main pipeline network could facilitate the establishment of more biorefineries in the Midwest. Wet-waste utilization in the Midwest is considerable due to the large quantities of manure available, particularly swine manure.

Gulf Coast Areas (South Central, West Texas, and Florida Peninsula): Gulf Coast areas, such as the South-Central region, West Texas, and the Florida Peninsula, possess a substantial biomass supply and abundant geologic storage capacity. Collectively, they have the potential to remove a total of 181 million tonnes of CO_2 per year (93 million tonnes in the South-Central region, 77 million tonnes in West Texas,

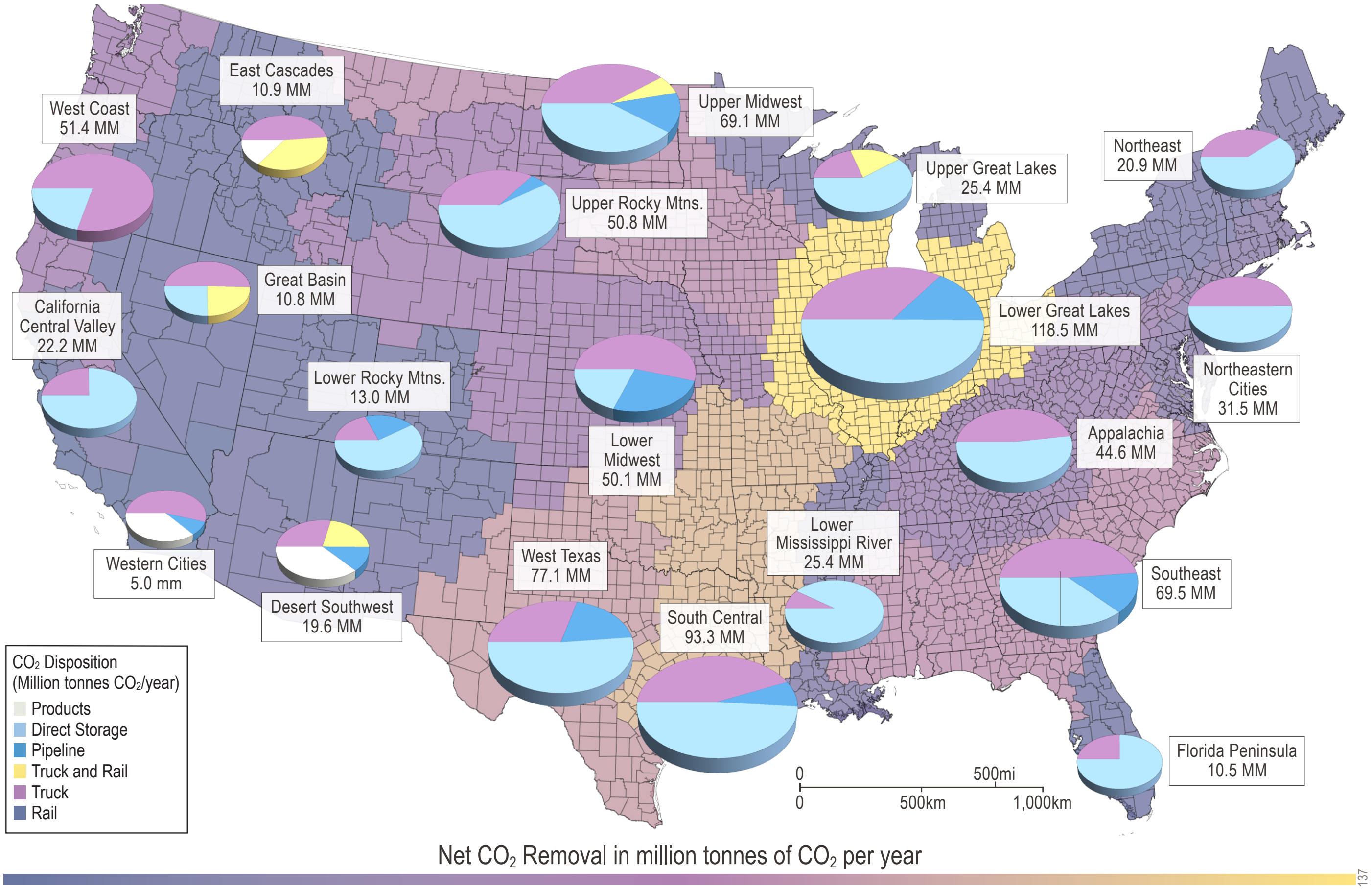


Figure 6-46. *CO_2 transportation modes across different regions. Pie size and black-font value represent total net CO_2-removal potential. Colors in the pie chart indicate different transportation modes: purple for truck, yellow for truck and rail, darker blue for pipeline, and light blue for direct injection and storage. Total net CO_2-removal potential is estimated by utilizing 2050 zero-cropland-change biomass that could achieve 90% carbon-removal capacity (related to total biomass availability) at minimal cost (\$/tonne CO_2).*

and 11 million tonnes in the Florida Peninsula). Removal costs in these regions range from \$57/tonne (Florida Peninsula) to \$86/tonne (South Central). The presence of geologic storage and pipelines plays a crucial role in facilitating cost-effective transportation of CO_2.The low removal costs in the Florida Peninsula are due to biomass transportation and low biomass costs (e.g., due to high density of MSW).

West Coast: The West Coast has abundant forestry resources, and the need for forest restoration to reduce wildfire risk. A challenge in this region is the limited availability of geologic storage for CO_2. In the modeled BILT optimization, only 20% of the captured CO_2 is directly injected in the region, adding more costs for CO_2 transportation. Despite this limitation, the BILT optimization estimates a potential removal of 51 million tonnes of CO_2 per year in the West-Coast region. However, compared to other storage regions, the removal cost is relatively higher at \$129/tonne. This is primarily due to higher biomass costs and the increased transportation costs associated with moving the CO_2 to storage sites. To address the storage limitation, the BILT optimized solution moves biomass from the West Coast to the Central Valley and Rocky Mountain regions, which offer abundant geologic storage capacity. While the California Central Valley is closer to West Coast forestry biomass, constraints on biorefinery sizing and density in the BILT model meant additional biorefineries in the central valley could not be built. Therefore, the most economical location was the Rocky Mountain region.

Northeastern Cities: The Northeastern-Cities regions—characterized by an intermediate amount of biomass resources and some available geologic storage —have the potential to remove approximately 31 million tonnes of CO_2 per year using existing biomass sources. Our results indicate that the Northeastern Cities could have among the lowest removal costs (\$57/tonne CO_2) among all regions due to two main factors: a significant amount of MSW as a low-cost feedstock and relatively low CO_2-transportation costs in the region. A considerable amount of wet waste and existing biogas from landfills is available for carbon removal in the Northeast due to the high density of urban areas.

Capital Investments

Capital investments are a significant contributor to the levelized costs of BiCRS. **Figure 6-47** shows the capital investment for each BiCRS technology at a capacity of 1000 dry tonnes of biomass per day. HTL and fermentation are the most capital intensive due to the large number of complex operations. The levelized costs of removal for fermentation remain relatively competitive even with such high capital costs due to the high-value bioproducts generated, whereas HTL is relatively expensive due to the lower-value bioproducts. Gasification and pyrolysis are moderately capital intensive, involving a relatively small number of costly operations, as compared to fermentation which involves many costly operations. Combustion and sawmill facilities are relatively low capital intensity due to the low number of simple, low-risk operations. AD and fast pyrolysis for char and asphalt production have the lowest capital costs due to their small scales of operation and low number of simple operations.

Limitations of this Study

While we attempted to estimate supply and cost of CO_2 -removal accurately, we identified several areas where more in-depth analysis or more accurate input assumptions for specific regions may lead to significantly different results. Our assumptions about the operation of BiCRS facilities may overlook significant risks and opportunities. For example, the ability for biorefineries to adapt to biomass variability in the composition of a single feedstock is often cited as a major technical and commercial risk to large-scale deployment. Biomass variability can markedly influence process efficiency, consequently affecting the cost of carbon removal. To mitigate these uncertainties and reduce their impact on process efficiency, pretreatment methods or other adjustments to processing conditions are sometimes warranted. In our analysis, we assumed that biorefineries can accept multiple types of feedstocks, and we did not account for small differences in BiCRS process designs for these different feedstocks. To be conservative, we selected the most costly process designs as our baseline so that any feedstock can be handled. We also only considered a small range of biorefinery scales (from 1000 to 5000 tonnes biomass per

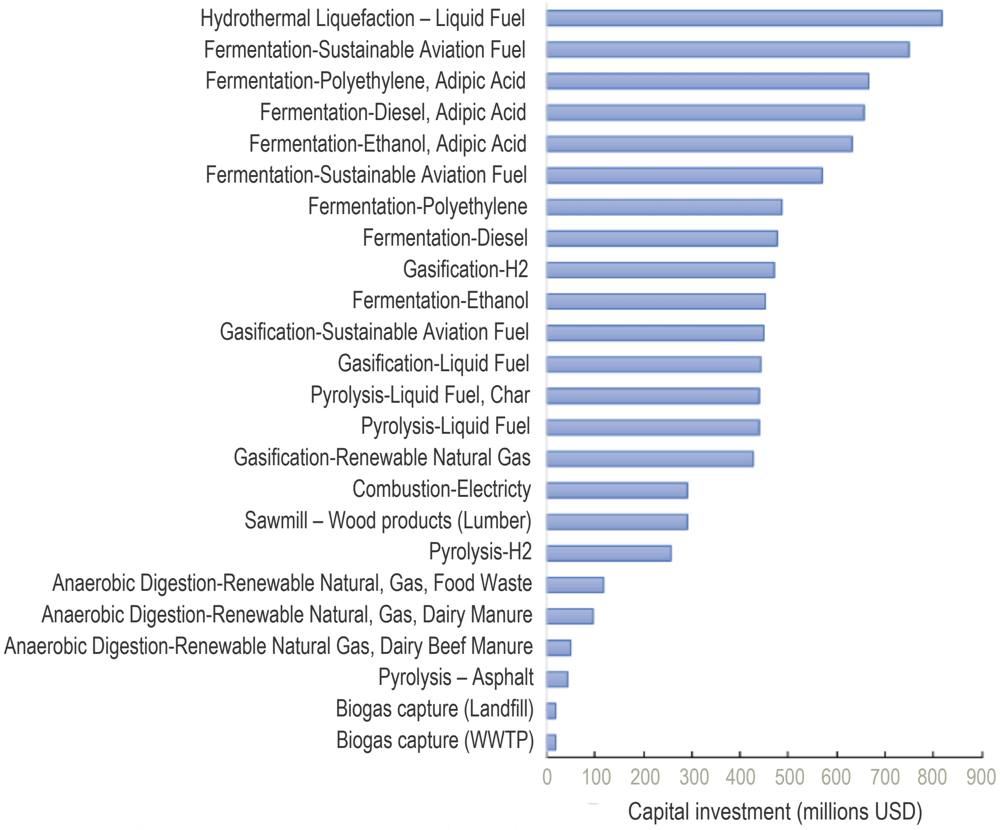


Figure 6-47. *Capital-investment costs for various BiCRS pathways based on a biorefinery with a biomass capacity of 1000 tonnes per day, presented in millions of $.*

day), which does not represent the full range of biorefinery scales demonstrated today. For example, demonstrations are currently underway of mobile pyrolysis units that operate in the field on the order of 10 tonnes per day to reduce biomass and transport costs; we also note that some corn-ethanol facilities can reach scales of 10,000 tonnes per day [118].

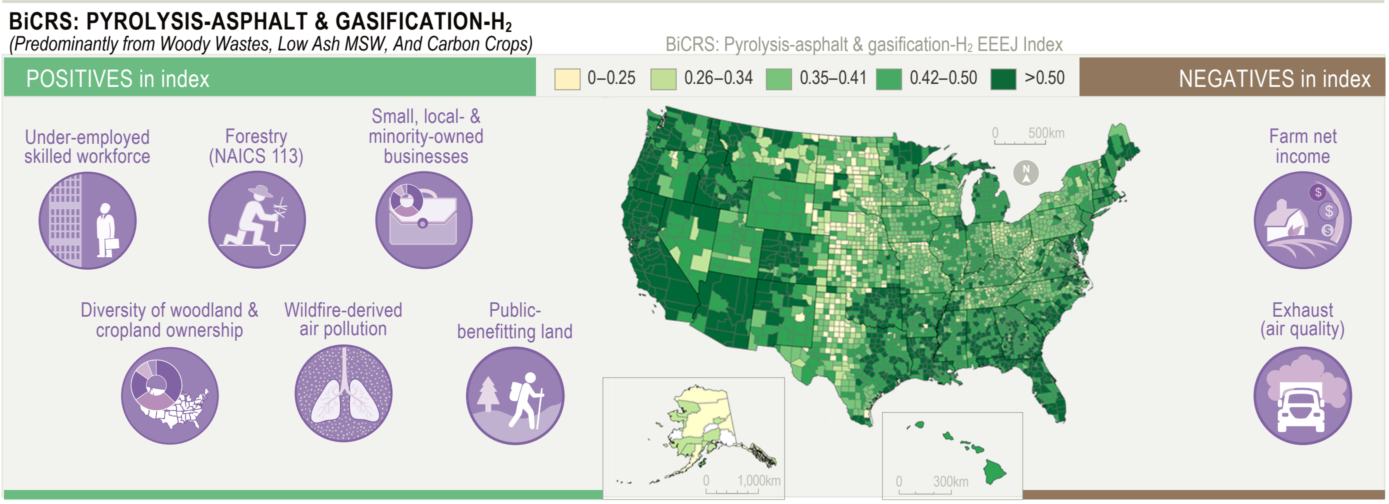
Our analysis suggests that transportation costs for biomass or CO_2 are not primary cost drivers in overall CO_2-removal costs. However, we used average US transportation costs (see **Chapter 5 –CO_2 and Biomass Transport**.); local labor costs may dramatically alter the cost breakdown for BiCRS. Similarly, we also did not capture any regional differences in the purchase prices of electricity, natural gas, or hydrogen, nor emission factors for electricity or co-product selling prices; regional differences in these assumptions could significantly affect the levelized cost of carbon removal. However, we did employ multi-year averages adjusted to cost-year 2022 to improve confidence and also captured regional differences in biomass prices. A limitation of our LCA was that we did not account for embodied emissions in the calculation of carbon removal, only direct and indirect emissions. (An alternative way to state this is that we assumed all manufacturing of equipment for biorefineries (steel, components, facility) is fully decarbonized in 2050.) Finally, we made assumptions about technical potential and market penetration that had significant impact on our results. We listed these assumptions in the text, but we want to highlight here that the technical limit of a 10% blend rate that we placed on bioasphalt greatly limited the apparent impact of this pathway due to our concerns of the technical blending level of bio-oil into asphalt, as well as limited data on carbon durability in asphalt.

BiCRS through Socioeconomic and Environmental Perspectives

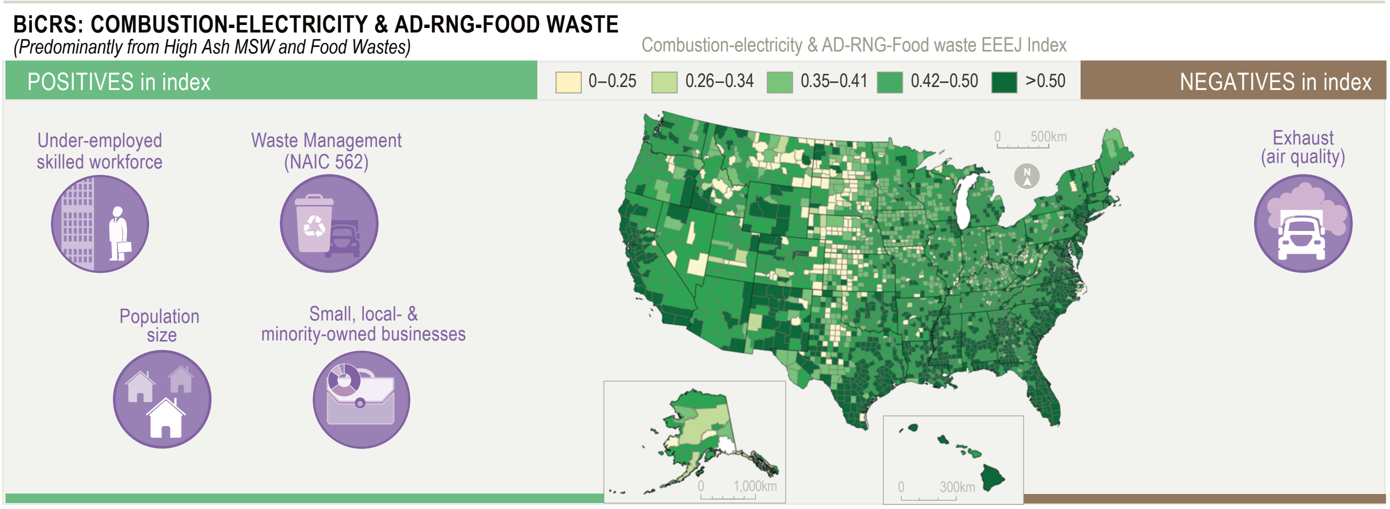
The diversity of BiCRS feedstocks and conversion methods analyzed in this chapter each have opportunities for co-benefits and potential negative impacts. In this section, we compare the trade-offs for each and highlight opportunities for the maximization of co-benefits and the avoidance or minimization of potential negative impacts (**Table 6-22**). *The key potential co-benefits for BiCRS-based CO_2 removal are creating economic value for waste streams that are otherwise disposed of in a manner that creates pollution—such as PM2.5-generating woody-waste burns or eutrophication of water supplies from excess manure application—and providing jobs for underemployed, skilled workforces* [119-121]. By prioritizing counties with the highest woody-waste-burning-derived PM2.5 and nitrate pollution, persistent job-loss trends, and county reliance on relevant sectoral job losses, policymakers could maximize the environmental and economic co-benefits of BiCRS-based CO_2 removal. The overarching potential negative impacts of BiCRS-based CO_2-removal methods, however, are further entrenching pollution-inducing industries and inequitable siting of waste-based industrial facilities in vulnerable communities, which are least equipped for advocacy or emergency response. Without parallel development of community capacity to engage in project development from an informed place of power and the development of community-approved monitoring, reporting, and verification (MRV) guidelines, BiCRS facilities risk contributing to historical and ongoing environmental injustices in the United States (e.g., [122, 123]). By investing in community capacity building around BiCRS-based CO_2 removal in regions highlighted by this report as having greater BiCRS-based CO_2-removal potential, decision makers could increase community support for projects, which is key to this industry's successful scale-up. Using renewable-energy projects as an analog, previous research has shown that if a project faces local opposition, there is an ~50% chance that it will be cancelled permanently and an ~34% chance that it will incur costly delays in permitting [124]. Due to the urgency of climate change and the potential that BiCRS has in helping the United States meet its CO_2-removal goals, BiCRS projects cannot afford to waste time or resources with stoppage or delays. Thus, it is paramount that projects be strategically proposed in counties that have the capacity and interest to engage, with early engagement from the onset, and stand to maximally benefit from the project with minimal risk.

An average 'EEEJ index' value, presented here for each county and every feedstock as well as for industrial BiCRS facilities, could allow project developers to efficiently synthesize socioeconomic and environmental data relevant to DOE's EEEJ goals [125], (for methods, see **Chapter 9 – EEEJ**). In these indices, values closer to 1 represent high opportunities for co-benefits and values closer to 0 represent lower likelihood for co-benefits and potentially greater challenges pertinent to EEEJ considerations. The impact of each variable, positively or negatively, on the overall EEEJ index value is presented in **Figure 6-48**. Following the construction of each index, a comparison to the Center for Disease Control's 'Social Vulnerability Index' (SVI) was conducted to assess for potential biases in the index toward vulnerable counties (**Figure 6-49**). Evaluating SVI alongside this report's 'EEEJ index' may be useful for agencies and project developers in determining potential priorities, such as protecting a region's most vulnerable communities from air pollution or careful considerations around developing an industrial presence in a county least equipped to respond to potential negative impacts, if they occur. By assessing these indices alongside one another, we found a positive correlation between regional SVI and wet-waste feedstocks, which are predominantly driven by CAFOs, with only three outlying regions from this trend. This result indicates an abundance of manure wastes in some of the United States' most vulnerable regions and that targeted capacity building to avoid further pollution entrenchment be undertaken to ensure just BiCRS scale-up in regions such as the Southeast, California Central Valley, and South Central. Dry wastes and MSW did not exhibit this same relationship, so BiCRS processing with these two feedstocks are potentially less likely to be sited with biases in vulnerable regions overall. BiCRS facilities, conversely, were optimized based on recent job-loss trends in relevant sectors and exhibited a weakly negative correlation with SVI, indicating that there are already regions with underemployed, skilled workforces with the social bandwidth to engage in BiCRS facility scale up, such as the Upper Rocky Mountains, Upper Midwest, and Lower Midwest. Closer examination of the socioeconomic and environmental contexts considered for each county identified here can be found in **Chapter 9 – EEEJ**.

A

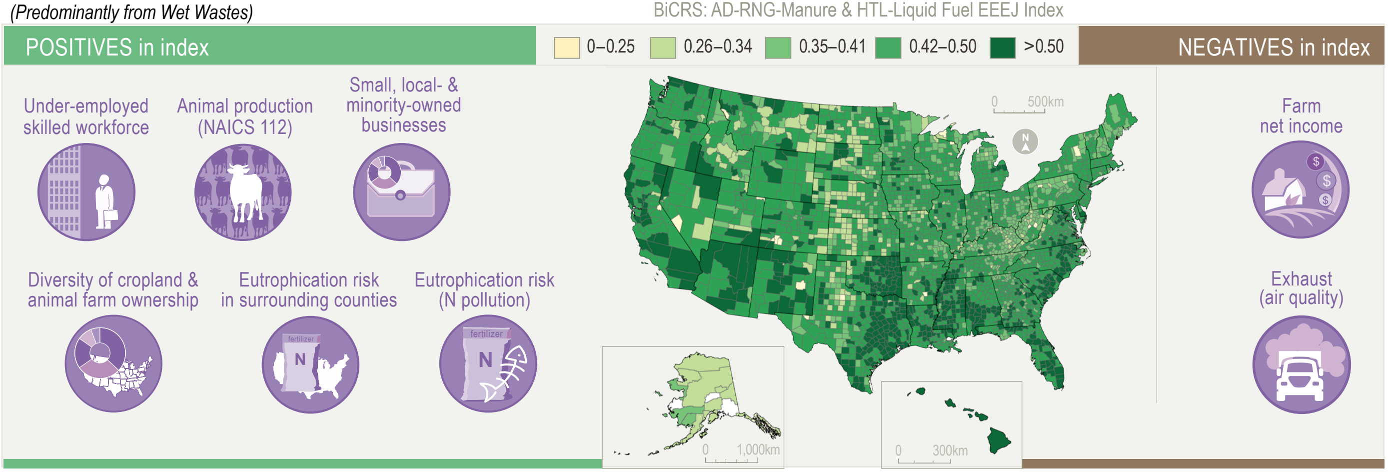


B



C

BiCRS: AD-RNG-MANURE & HTL-LIQUID FUEL
(Predominantly from Wet Wastes)



D

BiCRS: CONVERSTION FACILITIES
(Regardless of Conversion Method)

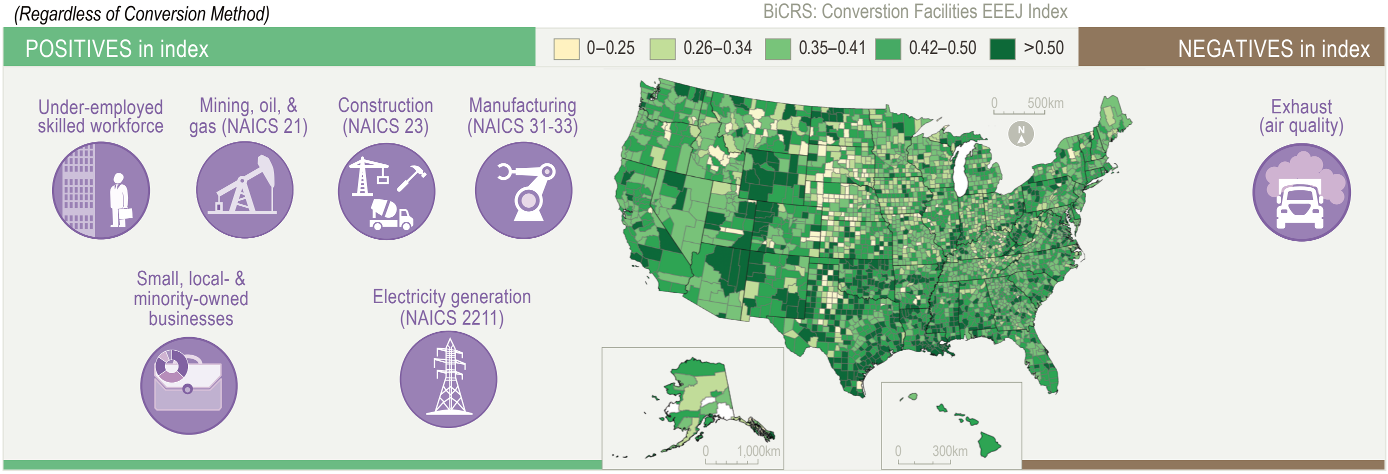


Figure 6-48. *(A – D). Maps of the EEEJ indices for BiCRS feedstock sources (A – C) and feedstock-agnostic facilities (D). These EEEJ index values are depicted alongside variables that contributed, positively or negatively, to each index. The index is normalized from 0 to 1, where higher values represent a potentially greater opportunity for socio-economic co-benefits, including reemployment of skilled workforces. Higher values also represent a smaller potential for negative impacts, such as further entrenching overly dense CAFOs or traffic/air pollution issues related to biomass transport – depicted by diesel-derived PM2.5.*

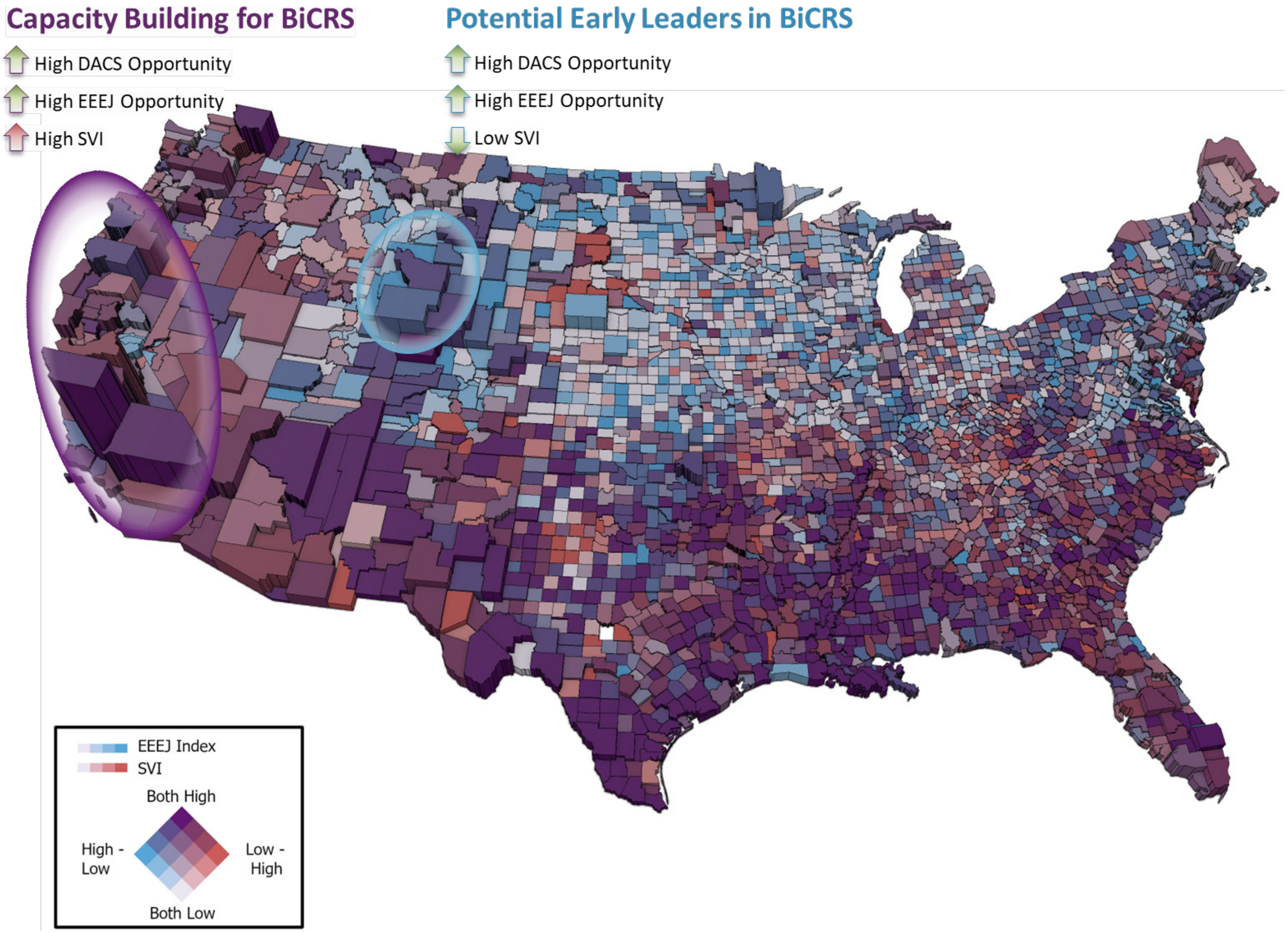


Figure 6-49. *Map of EEEJ index for BiCRS facilities (blue) and the CDC's Social Vulnerability Index (red) for the United States. The height of counties in this map represents potential capacity for CDR, relative to the average cost. The CDR potential:cost ratio reflected in the heights of counties were calculated based on the '90% removal target from zero cropland change' scenario from the BiCRS summary's **Figure 6-37**. The taller counties in the map have greater CDR potential: cost ratios. The map is annotated to reflect this report's hypothesis around BiCRS: if a county has high opportunity for co-benefits and low social vulnerability, then they may be better poised to become early leaders in the practice. Similarly, counties with high opportunity for co-benefits, but also high social vulnerability, may benefit from investments in local capacity building to engage on the topic of BiCRS.*

Table 6-22. *BiCRS Energy Equity and Environmental Justics (EEEJ). Trade-off tables for selected biomass types.*

LOW-MOISTURE AGRICULTURAL RESIDUES AND WASTE	
Potential **Co-benefits** to Communities & Options for Maximizing Potential Co-benefits	Potential **Negative** Impacts to Communities & Options for Minimizing Potential Negative Impacts
Improved air quality from less biomass burning Focus BiCRS adoption to regions that extensively practice crop and rangeland burning to maximize air-quality improvements [119].	Competition for alternative uses of woody waste Projects can strive to find synergy with existing programs that incentivize the use of woody biomass for the retention of soil moisture [126]
	Increased fertilizer usage Utilize cover-cropping strategies to maintain nutrients in the soil and reduce fertilizer costs [127].
	Soil Loss Removals can be kept within limits recommended by the USDA's NRCS or the Revised Universal Soil-Loss Equation and the Wind-Erosion Prediction System [12].
Additional income for farmers Compensation to farmers can cover not just the direct costs of residue production, but also the indirect costs from the loss of nutrients and soil health [128].	Traffic impacts from transport Optimize for routes through regions not identified as being unduly impacted by traffic [129]
Direct job creation and/or retention Develop BiCRS facilities close to the biomass source to provide additional long-term sustainable livelihoods to the local community [130]. Focus on projects in which the existing workforce has expertise relevant to geologic carbon storage and are exposed to job loss from the net-zero transition [12].	Increased PM2.5 emissions from diesel trucks Use zero-emission vehicles for trucking, especially in highly trafficked areas [131].
Indirect job creation and/or retention Mirror the Build America, Buy America Act for non-federal projects to stimulate greater job growth in domestic manufacturing and induced jobs [132, 133]. Counties looking to support employment growth can consider the increase in new jobs correlated with activities similar to MSW diversion into a BiCRS facility [134]	Overpromised/unrealized performance Perform baseline assessment such that results can be compared against a rigorous counterfactual [130].

HIGH-MOISTURE AGRICULTURAL WASTE	
Potential **Co-benefits** to Communities & Options for Maximizing Potential Co-benefits	Potential **Negative** Impacts to Communities & Options for Minimizing Potential Negative Impacts
Reduced nutrient pollution and eutrophication risk Develop BiCRS hubs to share capital and transportation costs between local manure providers and incentivize use instead of dumping [135].	Persistence, entrenchment, or worsening of water pollution Encourage adoption of nutrient management/separation through increased oversight or financial incentives to reduce over-application of nutrients to nearby fields by farmers [136].
Reduced CH4 emissions Develop BiCRS hubs co-located with usage that limit the transport distance and opportunity for CH4 leaks [135].	Increased dominance of large industrial operations Decrease systemic power imbalances by disseminating technical expertise, improving supply-chain access, and providing government support to small- and medium-scale operations [137].
Direct job creation and/or retention Develop BiCRS facilities close to the biomass source to provide additional long-term sustainable livelihoods to the local community. Focus on projects in which the existing workforce has expertise relevant to geologic carbon storage and are exposed to job loss from the net-zero transition [130, 138].	Overpromised/unrealized performance Perform baseline assessment such that results can be compared against a rigorous counterfactual [130].
Indirect job creation and/or retention Mirror the Build America, Buy America Act for non-federal projects to stimulate greater job growth in domestic manufacturing and induced jobs [132, 133]. Counties looking to support employment growth can consider the increase in new jobs correlated with activities similar to municipal solid waste diversion into a BiCRS facility [134].	
Reduced hydrogen sulfide (H2S) pollution Manure can be quickly moved to a BiCRS facility to minimize local H2S pollution. Sites using AD can consider additives (e.g., waste iron powder) that can reduce H2S generation while increasing biogas production [139].	

MUNICIPAL SOLID WASTE (MSW)	
Potential **Co-benefits** to Communities & Options for Maximizing Potential Co-benefits	Potential **Negative** Impacts to Communities & Options for Minimizing Potential Negative Impacts
Reduced methane production in landfill Recycling can be applied to the extent feasible, followed by diverting as much waste as possible from landfills to a BiCRS pathway [140].	Uncertain air emissions Gasification or pyrolysis of MSW can be implemented instead of incinerators to reduce toxic residues [141]. Prior to commercial-scale planning, air-pollution profiles from pilot facilities with representative waste streams can be documented alongside air-modeling studies [142]
Reduced pressures for new landfill construction Land-limited communities with landfills nearing the end of their usable life [143] can prioritize development of a BiCRS facility that utilizes MSW [141].	Water demand Preferentially gasify waste to hydrogen (instead of direct use for energy generation) to reduce water consumption [144].
Remediation of landfills Landfills that have demonstrated leaching of pollutants into local waters can be remediated by treatment of MSW through a BiCRS facility [145].	Potentially viewed as deterrence to recycling Set regulations or incentives to maximize viable recycling before implementing MSW-based BiCRS.
Preserved property values Counties that are nearing the end of their landfill's storage (EPA, 202 3) can prioritize implementing a BiCRS strategy with MSW as a feedstock to preserve property values, which have been shown to decrease as a function of proximity to a landfill [146].	Increased public distrust Local officials and project developers can engage with the local community early in the design process [147].
Direct job creation and/or retention Develop BiCRS facilities close to biomass sources to provide additional long-term sustainable livelihoods to the local community (130). Focus on projects in which the existing workforce has expertise relevant to geologic carbon storage and are exposed to job loss from the net-zero transition [12, 138].	Overpromised/unrealized performance Perform baseline assessment such that results can be compared against a rigorous counterfactual [130].
Indirect job creation and/or retention Mirror the Build America, Buy America Act for non-federal projects to stimulate greater job growth in domestic manufacturing and induced jobs [132, 133]. Counties looking to support employment growth can consider the increase in new jobs correlated with activities similar to MSW diversion into a BiCRS facility [134].	

FORESTRY BIOMASS	
Potential **Co-benefits** to Communities & Options for Maximizing Potential Co-benefits	Potential **Negative** Impacts to Communities & Options for Minimizing Potential Negative Impacts
Improved air quality Divert forest and logging waste from areas of high burn probability [148] to BiCRS to reduce air pollution for downwind communities [149].	Competition for alternative uses of woody waste Projects can strive to find synergy with existing programs that incentivize the use of woody biomass for the retention of soil moisture [126].
Local energy production for rural areas Prioritize the use of woody biomass to reduce fossil-fuel-based energy and hydrogen production [150].	Water demand Preferentially gasify waste to hydrogen (instead of direct use for energy generation) to reduce water consumption [144].
Improved wildlife habitat Apply thinning techniques in a patchwork to foster the highest levels of diversity [151].	Uncertain impacts on soil Perform pilot studies on targeted areas to assess soil impacts prior to full adoption, as results vary strongly between locations [152].
Direct jobs Focus on counties with a declining logging workforce to yield the greatest employment co-benefits [150].	Competition with timber industry To avoid competition with timber markets, small-diameter trees from thinning and harvest residues can be prioritized for BiCRS, while commercially viable timber could enter the market [153].
Indirect jobs An open-source economic model to forecast potential indirect job creation can be incorporated in pre-project community benefit discussions [154].	
Mitigate drought Stress In drought-prone areas, moderate-to-heavy thinning of basal area to improve growth of broadleaf trees during drought and post-drought recovery of conifers [155].	

Conclusion

BiCRS Impacts on Land, Soil, and Carbon Removal in the United States

We have presented a range of land-use, biomass, and technology options where BiCRS can play a major role in large-scale CO_2 removal in the United States, while helping to meet other regional and national goals. We found that the supply of BiCRS biomass can be increased significantly beyond current biogenic wastes and agricultural residues by planting carbon crops on non-cropland, thus avoiding commodity price increases. We found that a substantially higher CO_2-removal potential is achievable with higher land-use efficiency—both through BiCRS and through increased soil-carbon storage—if a small percentage of current cropland is converted to the production of carbon crops as described for our maximum-economic-potential assessment. Further study is needed to understand the level of risk for carbon leakage associated with conversion of current cropland in the United States. We present a summary of impacts in **Table 6-23**, showing tradeoffs in land use, soil carbon (see Chapter 3 – Soils), commodity-price impacts, and BiCRS' carbon-removal potential. To realize the potential presented here, a broad range of stakeholders from communities, states, and regions will need to collaborate to overcome barriers to implementation; however, the United States has substantial biomass resources, and the 27 pathways we described can make significant impacts on US climate goals and are ready to scale today.

Table 6-23. *Summary of land area, soil, biomass, and CO_2 removal potential impacts depending on modeled approach to BiCRS biomass. Table reflects annual CO_2 removal potential from 90% removal targets with H_2 price set at \$2/kg.*

Biomass Assessment (2050)	Land Area Change	Carbon Crop Yield	Commodity Price Increase	Soil-Based CO_2 Removal Potential	Annual CO_2 Removal Potential in 2050
	(Million Ha @ \$73 Dollars/Tonne)	*(Million tonnes/year @ \$73 Dollars/ tonne)*	*@ \$73 Dollars/ tonne*	*(Million tonnes Cumulative Through 2050)*	*Million tonnes/ year from Optimized Pathway (BiCRS + Soil Carbon= Total)*
Baseline	0	0	0	0	693
Zero Cropland Change	29	133	0	18	899+4= 903
Maximum Economic Potential	25	297	6.2 % corn, 11.5% wheat, 8.3% soy	120	1219+ 6=1225

REFERENCES

1. *Intergovernmental Panel on Climate Change (IPCC). Global Warming of 1.5 °C (IPCC Special Report on Impacts of Global Warming of 1.5 °C above Pre-industrial Levels in Context of Strengthening Response to Climate Change, Sustainable Development, and Efforts to Eradicate Poverty). 2022. Cambridge University Press, Cambridge; DOI: 10.1017/9781009157940. https://www.ipcc.ch/sr15/.*
2. *Joeri Rogelj, et al., Scenarios towards limiting global mean temperature increase below 1.5 °C. Nature Climate Change, 2018.* ***8****(4): p. 325-332, https://doi.org/10.1038/s41558-018-0091-3.*
3. *Intergovernmental Panel on Climate Change (IPCC). Climate Change 2021: The Physical Science Basis. (Contribution of Working Group I to the Sixth Assessment Report of IPCC). 2021. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA; 10.1017/9781009157896. https://www.ipcc.ch/report/ar6/wg1/.*
4. *David Sandalow, et al. Biomass Carbon Removal and Storage (BiRCS) Roadmap. 2021. United States; 10.2172/1763937. https://www.osti.gov/biblio/1763937.*
5. *G. Philip Robertson, et al., Cellulosic biofuel contributions to a sustainable energy future: Choices and outcomes. Science, 2017.* ***356****(6345): p. eaal2324, https://doi.org/10.1126/science.aal2324.*
6. *Caleb M. Woodall and Colin F. McCormick, Assessing the optimal uses of biomass: Carbon and energy price conditions for the Aines Principle to apply. Frontiers in Climate, 2022.* ***4****, 10.3389/fclim.2022.993230.*
7. *C. Greig E. Larson, J. Jenkins, E. Mayfield, A. Pascale, C. Zhang, J. Drossman, R. Williams, S. Pacala, R. Socolow, EJ Baik, R. Birdsey, R. Duke, R. Jones, B. Haley, E. Leslie, K. Paustian, and A. Swa. Net-Zero America: Potential Pathways, Infrastructure, and Impact. 2020. Princeton University, Princeton, NJ; https://netzeroamerica.princeton.edu/img/Princeton_NZA_Interim_Report_15_Dec_2020_FINAL.pdf.*
8. *M. H. Langholtz, B. J. Stokes, and L. M. Eaton. 2016 Billion-Ton Report: Advancing Domestic Resources for a Thriving Bioeconomy. 2016. United States; 10.2172/1271651. https://www.osti.gov/biblio/1271651.*
9. *Timothy Seiple and Anelia Milbrandt, National Wet Waste Inventory (NWWI), V. Mendeley Data, Editor. 2020 (https://doi.org/10.17632/f4dxm3mb94.1).*
10. *U.S. Census Bureau. 2017 National Population Projections Tables: Main Series. 2017 Published by U.S. Census Bureau; Available from https://www.census.gov/data/tables/2017/demo/popproj/2017-summary-tables.html.*
11. *Rebecca Ann Efroymson and Matthew H. Langholtz. 2016 Billion-Ton Report: Advancing Domestic Resources for a Thriving Bioeconomy, Volume 2: Environmental Sustainability Effects of Select Scenarios from Volume 1. 2017. Office of Scientific and Technical Information (OSTI), 10.2172/1338837. http://dx.doi.org/10.2172/1338837.*
12. *U.S. Department of Energy (R.D. Perlack and B.J. Stokes (Leads)). U.S. Billion-Ton Update: Biomass Supply for a Bioenergy and Bioproducts Industry (Report Number ORNL/TM-2011/224). 2011. Oak Ridge National Laboratory (ORNL), Oak Ridge, TN; https://www.energy.gov/sites/prod/files/2015/01/f19/billion_ton_update_0.pdf.*
13. *Raju Pokharel, et al., Factors affecting utilization of woody residues for bioenergy production in the southern United States. Biomass and Bioenergy, 2017.* ***105****: p. 278-287, https://doi.org/10.1016/j.biombioe.2017.07.002.*
14. *Gustavo Perez-Verdin, et al., Woody biomass availability for bioethanol conversion in Mississippi. Biomass and Bioenergy, 2009.* ***33****(3): p. 492-503, https://doi.org/10.1016/j.biombioe.2008.08.021.*
15. *Fei Pan, et al., Production and cost of harvesting, processing, and transporting small-diameter (≤ 5 inches) trees for energy. Forest Products Journal, 2007.* ***58****(5): p. 47-53, https://www.fs.usda.gov/research/treesearch/30845.*
16. *Joshua Petitmermet, et al., Cost and Productivity of Tethered Cut-to-Length Systems in a Dry-Forest Fuel-Reduction Treatment: A Case Study. Forest Science, 2019.* ***65****(5): p. 581-592, https://doi.org/10.1093/forsci/fxz010.*
17. *Scott Turn, Robert Williams, and Wai Ying Chan, Resources for renewable natural gas: A Hawaii case study. Environmental Progress & Sustainable Energy, 2023.* ***42****(4): p. e14002, https://doi.org/10.1002/ep.14002.*

18. *U.S. Environmental Protection Agency (EPA). Paper and Paperboard: Material-Specific Data - Summary Table and Graph. Accessed September 2023 Published by U.S. EPA; Available from https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling/paper-and-paperboard-material-specific-data#PaperTableandGraph.*

19. *Environmental Research & Education Foundation (EREF). Analysis of MSW Landfill Tipping Fees – 2020. 2021. Retrieve from www.erefdn.org.*

20. *U.S. Environmental Protection Agency (EPA), 21st Century Complete Guide to Biogas and Methane: Agricultural Recovery, Manure Digesters, AgSTAR, Landfill Methane, Greenhouse Gas Emission Reduction and Global Methane Initiative. 2012 (https://books.google.com/books?id=WPAwswEACAAJ): Progressive Management; 417 p.*

21. *W. J. Sagues, et al., Prospects for bioenergy with carbon capture & storage (BECCS) in the United States pulp and paper industry. Energy & Environmental Science, 2020.* ***13****(8): p. 2243-2261, http://dx.doi.org/10.1039/D0EE01107J.*

22. *Daniel L. Sanchez, et al., Near-term deployment of carbon capture and sequestration from biorefineries in the United States. Proceedings of the National Academy of Sciences, 2018.* ***115****(19): p. 4875-4880, https://doi.org/10.1073/pnas.1719695115.*

23. *Uisung Lee, et al., Retrospective analysis of the U.S. corn ethanol industry for 2005–2019: implications for greenhouse gas emission reductions. Biofuels, Bioproducts and Biorefining, 2021.* ***15****(5): p. 1318-1331, https://doi.org/10.1002/bbb.2225.*

24. *Peter M. Berger, et al., Carbon sequestration at the Illinois Basin-Decatur Project: experimental results and geochemical simulations of storage. Environmental Earth Sciences, 2019.* ***78****(22): p. 1-10, https://doi.org/10.1007/s12665-019-8659-4.*

25. *John Dees, et al., Cost and Life Cycle Emissions of Ethanol Produced with an Oxyfuel Boiler and Carbon Capture and Storage. Environmental Science & Technology, 2023.* ***57****(13): p. 5391-5403, https://doi.org/10.1021/acs.est.2c04784.*

26. *John L. Field, et al., Robust paths to net greenhouse gas mitigation and negative emissions via advanced biofuels. Proceedings of the National Academy of Sciences, 2020.* ***117****(36): p. 21968-21977, https://doi.org/10.1073/pnas.1920877117.*

27. *B. P. McGrail, et al., Overcoming business model uncertainty in a carbon dioxide capture and sequestration project: Case study at the Boise White Paper Mill. International Journal of Greenhouse Gas Control, 2012.* ***9****: p. 91-102, https://doi.org/10.1016/j.ijggc.2012.03.009.*

28. *B. J. Stokes U.S. Department of Energy (M. H. Langholtz, and L. M. Eaton and (Leads)). 2016 Billion-Ton Report: Advancing Domestic Resources for a Thriving Bioeconomy, Volume 1: Economic Availability of Feedstocks (ORNL/TM-2016/160). 2016. Oak Ridge National Laboratory, Oak Ridge, TN; doi: 10.2172/1271651. http://energy.gov/eere/bioenergy/2016-billion-ton-report.*

29. *Ben P. Werling, et al., Perennial grasslands enhance biodiversity and multiple ecosystem services in bioenergy landscapes. Proceedings of the National Academy of Sciences, 2014.* ***111****(4): p. 1652-1657, https://doi.org/10.1073/pnas.1309492111.*

30. *Dileepa M. Jayawardena, et al., Comparative productivity of six bioenergy cropping systems on marginal lands in the Great Lakes Region, United States. Agronomy Journal, 2023, https://doi.org/10.1002/agj2.21416.*

31. *Ilya Gelfand, et al., Empirical Evidence for the Potential Climate Benefits of Decarbonizing Light Vehicle Transport in the U.S. with Bioenergy from Purpose-Grown Biomass with and without BECCS. Environmental Science & Technology, 2020.* ***54****(5): p. 2961-2974, https://doi.org/10.1021/acs.est.9b07019.*

32. *Sophia Murphy and Karen Hansen-Kuhn, The true costs of US agricultural dumping. Renewable Agriculture and Food Systems, 2020.* ***35****(4): p. 376-390, https://doi.org/10.1017/S1742170519000097.*

33. *Jerome Dumortier, Miguel Carriquiry, and Amani Elobeid, Where does all the biofuel go? Fuel efficiency gains and its effects on global agricultural production. Energy Policy, 2021.* ***148****: p. 111909, https://doi.org/10.1016/j.enpol.2020.111909.*

34. *Jerome Dumortier, Amani Elobeid, and Miguel Carriquiry, Light-duty vehicle fleet electrification in the United States and its effects on global agricultural markets. Ecological Economics, 2022.* ***200****: p. 107536, https://doi.org/10.1016/j.ecolecon.2022.107536.*

35. *Jerome Dumortier, Miguel Carriquiry, and Amani Elobeid, Interactions Between U.S. Vehicle Electrification, Climate Change, and Global Agricultural Markets. Environmental and Resource Economics, 2023.* ***84****(1): p. 99-123, https://doi.org/10.1007/s10640-022-00716-8.*

36. *Jerome Dumortier, Impact of agronomic uncertainty in biomass production and endogenous commodity prices on cellulosic biofuel feedstock composition. GCB Bioenergy, 2016.* ***8****(1): p. 35-50, https://doi.org/10.1111/gcbb.12238.*

37. *S. K. Sansaniwal, et al., Recent advances in the development of biomass gasification technology: A comprehensive review. Renewable and Sustainable Energy Reviews, 2017.* ***72****: p. 363-384, https://doi.org/10.1016/j.rser.2017.01.038.*

38. *European Commission. State aid: Commission approves support package for gasification plant in Finland. 2015. Brussels, European Commission. Available from https://ec.europa.eu/commission/presscorner/detail/en/IP_15_5255.*

39. *Gonçalo Lourinho, et al., Costs of Gasification Technologies for Energy and Fuel Production: Overview, Analysis, and Numerical Estimation. Recycling, 2023.* ***8****(3): p. 49, https://doi.org/10.3390/recycling8030049.*

40. *Eric D. Larson, Haiming Jin, and Fuat E. Celik, Large-scale gasification-based coproduction of fuels and electricity from switchgrass. Biofuels, Bioproducts and Biorefining, 2009.* ***3****(2): p. 174-194, https://doi.org/10.1002/bbb.137.*

41. *J. A. Garcia-Nunez, et al., Historical Developments of Pyrolysis Reactors: A Review. Energy & Fuels, 2017.* ***31****(6): p. 5751-5775, https://doi.org/10.1021/acs.energyfuels.7b00641.*

42. *Aisha Al-Rumaihi, et al., A review of pyrolysis technologies and feedstock: A blending approach for plastic and biomass towards optimum biochar yield. Renewable and Sustainable Energy Reviews, 2022.* ***167****: p. 112715, https://doi.org/10.1016/j.rser.2022.112715.*

43. *Jim Lane. The Pyromaniax, Class of 2015: The Top 10 Pyrolysis projects in renewable fuels. 2015 Published by The Digest; Available from https://www.biofuelsdigest.com/bdigest/2015/08/03/the-pyromaniax-class-of-2015-the-top-10-pyrolysis-projects-in-renewable-fuels/.*

44. *PyroWiki. Commercial Plants. Accessed September 2023 Published by PyroWiki; Available from http://pyrowiki.pyroknown.eu/index.php/Commercial_plants.*

45. *A. V. Bridgwater, D. Meier, and D. Radlein, An overview of fast pyrolysis of biomass. Organic Geochemistry, 1999.* ***30****(12): p. 1479-1493, https://doi.org/10.1016/S0146-6380(99)00120-5.*

46. *Abhijit Dutta, et al. Ex Situ Catalytic Fast Pyrolysis of Lignocellulosic Biomass to Hydrocarbon Fuels: 2019 State of Technology and Future Research (Document Number NREL/TP-5100-76269). 2020. National Renewable Energy Laboratory (NREL), Golden, CO; 10.2172/1605092. https://www.osti.gov/biblio/1605092.*

47. *Joseph Eke, Jude A. Onwudili, and Anthony V. Bridgwater, Influence of Moisture Contents on the Fast Pyrolysis of Trommel Fines in a Bubbling Fluidized Bed Reactor. Waste and Biomass Valorization, 2020.* ***11****(7): p. 3711-3722, https://doi.org/10.1007/s12649-018-00560-2.*

48. *Ningyi Su, et al., Productions and applications of bio-asphalts – A review. Construction and Building Materials, 2018.* ***183****: p. 578-591, https://doi.org/10.1016/j.conbuildmat.2018.06.118.*

49. *Xinxing Zhou, et al., Life Cycle Assessment of Biochar Modified Bioasphalt Derived from Biomass. ACS Sustainable Chemistry & Engineering, 2020.* ***8****: p. 14568-14575, https://doi.org/10.1021/acssuschemeng.0c05355.*

50. *Kelli G. Roberts, et al., Life Cycle Assessment of Biochar Systems: Estimating the Energetic, Economic, and Climate Change Potential. Environmental Science & Technology, 2010.* ***44****(2): p. 827-833, https://doi.org/10.1021/es902266r.*

51. *Ejeong Baik, et al., Geospatial analysis of near-term potential for carbon-negative bioenergy in the United States. Proceedings of the National Academy of Sciences, 2018.* ***115****(13): p. 3290-3295, https://doi.org/10.1073/pnas.1720338115.*

52. *M. R. Allen, et al., Technical Summary (https://www.ipcc.ch/sr15/resources/technicalsummary/), in Global warming of 1.5 C. (An IPCC Special Report on the impacts of global warming of 1.5 C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty), V. Masson-Delmotte, et al., Editors. 2018; DOI: 10.1017/9781009157940 Cambridge University Press: Cambridge, UK and New York, NY, USA. p. 616.*

53. *International Energy Agency (IEA). CCUS around the world. 2021. IEA, Paris, France; https://www.iea.org/reports/ccus-around-the-world.*

54. *Jun Ni, et al., A review on fast hydrothermal liquefaction of biomass. Fuel, 2022.* ***327****: p. 125135, https://doi.org/10.1016/j.fuel.2022.125135.*

55. *Lesley Snowden-Swan, et al. Wet Waste Hydrothermal Liquefaction and Biocrude Upgrading to Hydrocarbon Fuels: 2020 State of Technology (Report Number PNNL-30982). 2021. Pacific Northwest National Laboratory (PNNL), Richland, WA; 10.2172/1771363. https://www.osti.gov/biblio/1771363.*

56. *Yunhua Zhu, et al., Techno-economic analysis of liquid fuel production from woody biomass via hydrothermal liquefaction (HTL) and upgrading. Applied Energy, 2014.* ***129****: p. 384-394, https://doi.org/10.1016/j.apenergy.2014.03.053.*

57. *John P. Dees, et al., Leveraging the bioeconomy for carbon drawdown. Green Chemistry, 2023.* ***25****(8): p. 2930-2957, http://dx.doi.org/10.1039/D2GC02483G.*

58. *David Kramer, Whatever happened to cellulosic ethanol? Physics Today, 2022.* ***75****(7): p. 22-24, https://doi.org/10.1063/PT.3.5036.*

59. *Alexander H. Tullo. Dow eyes ethylene from cellulosic ethanol. 2023 Published by C&EN; Available from https://cen.acs.org/business/biobased-chemicals/Dow-eyes-ethylene-cellulosic-ethanol/101/i18.*

60. *Alvina Aui, Wenqin Li, and Mark M. Wright, Techno-economic and life cycle analysis of a farm-scale anaerobic digestion plant in Iowa. Waste Management, 2019.* ***89****: p. 154-164, https://doi.org/10.1016/j.wasman.2019.04.013.*

61. *Yeqing Li, et al., Comparison of methane production potential, biodegradability, and kinetics of different organic substrates. Bioresource Technology, 2013.* ***149****: p. 565-569, https://doi.org/10.1016/j.biortech.2013.09.063.*

62. *U.S. Environmental Protection Agency (EPA). The Benefits of Anaerobic Digestion of Food Waste At Wastewater Treatment Facilities. Accessed July 2023 Published by U.S. EPA; Available from https://www.epa.gov/sites/default/files/documents/Why-Anaerobic-Digestion.pdf.*

63. *Kamalakanta Sahoo and Sudhagar Mani, Economic and environmental impacts of an integrated-state anaerobic digestion system to produce compressed natural gas from organic wastes and energy crops. Renewable and Sustainable Energy Reviews, 2019.* ***115****: p. 109354, https://doi.org/10.1016/j.rser.2019.109354.*

64. *Jun Wong, et al., Market Potential for CO_2 Removal and Sequestration from Renewable Natural Gas Production in California. Environmental Science & Technology, 2022.* ***56****(7): p. 4305-4316, https://doi.org/10.1021/acs.est.1c02894.*

65. *Brandon Coppedge, Gary Coppedge, Dan Evans, Jim Jensen, Kathy Scanlan, Blair Scanlan, Peter Weisberg, and Craig Frear. Renewable Natural Gas and Nutrient Recovery Feasibility for Deruyter Dairy. 2012. https://climatetrust.org/wp-content/uploads/2014/07/DeRuyter-Feasibility-Study-Final-Report.pdf.*

66. *Imran Ullah Khan, et al., Biogas as a renewable energy fuel – A review of biogas upgrading, utilisation and storage. Energy Conversion and Management, 2017.* ***150****: p. 277-294, https://doi.org/10.1016/j.enconman.2017.08.035.*

67. *Jan-Olof Anderson and Andrea Toffolo, Improving energy efficiency of sawmill industrial sites by integration with pellet and CHP plants. Applied Energy, 2013.* ***111****: p. 791-800, https://doi.org/10.1016/j.apenergy.2013.05.066.*

68. *U.S. Environmental Protection Agency (EPA). Wood: Material-Specific Data. Accessed April 2023 Published by US EPA; Available from https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling/wood-material-specific-data.*

69. *Mi Hyung Kim and Han Byul Song, Analysis of the global warming potential for wood waste recycling systems. Journal of Cleaner Production, 2014.* ***69****: p. 199-207, https://doi.org/10.1016/j.jclepro.2014.01.039.*

70. *Pradip Saud, et al., Carbon impacts of hardwood lumber processing in the northeastern United States. Canadian Journal of Forest Research, 2015.* ***45****(12): p. 1699-1710, https://doi.org/10.1139/cjfr-2015-0082.*

71. *CISION. Canfor to Invest in New Sawmill in Louisiana CISION 2021 Published by Canfor Corporation; Available from https://www.newswire.ca/news-releases/canfor-to-invest-in-new-sawmill-in-louisiana-818079281.html.*

72. *D. Humbird, et al. Process Design and Economics for Biochemical Conversion of Lignocellulosic Biomass to Ethanol Dilute-Acid Pretreatment and Enzymatic Hydrolysis of Corn Stover (Report Number NREL/TP-5100-47764). 2011. National Renewable Energy Laboratory (NREL), Golden, CO; 10.2172/1013269. https://www.osti.gov/biblio/1013269.*

73. Chris Bataille, Low and zero emissions in the steel and cement industries. 2020, https://doi.org/10.1787/5ccf8e33-en.

74. Samantha Tanzer, Kornelis Blok, and Andrea Ramírez, Can bioenergy with carbon capture and storage result in carbon negative steel? International Journal of Greenhouse Gas Control, 2020. **100**: p. 103104, https://doi.org/10.1016/j.ijggc.2020.103104.

75. Aristotle Ubando, et al., Optimal integration of a biomass-based polygeneration system in an iron production plant for negative carbon emissions. International Journal of Energy Research, 2020. **44**: p. 9350-9366, https://doi.org/10.1002/er.4902.

76. Richard Bergman, et al., The carbon impacts of wood products. Forest Products Journal, 2014. **64**(7-8): p. 220-231, https://doi.org/10.13073/FPJ-D-14-00047.

77. Daniel L Sanchez, et al. Literature review and evaluation of research gaps to support wood products innovation. 2020. Joint Institute for Wood Products Innovation; https://bof.fire.ca.gov/media/9688/full-12-a-jiwpi_formattedv12_3_05_2020.pdf.

78. Aurecon. 25 King Street: Sustainable timber building design putting people at the heart. Accessed July 2023 Published by Aurecon; Available from https://www.aurecongroup.com/projects/property/25-king#:~:text=25%20King%20is%20currently%20the,of%20workplaces%20of%20the%20future.

79. Moelven. Mjøstårnet: Standing 85,4 meters tall, Mjøstårnet is officially the world's tallest timber building. Accessed July 2023 Published by Moelven; Available from https://www.moelven.com/mjostarnet/.

80. Jim Robbins. As Mass Timber Takes Off, How Green Is This New Building Material? 2019 Published by Yale Environment 360; Available from https://e360.yale.edu/features/as-mass-timber-takes-off-how-green-is-this-new-building-material.

81. Hans-Peter Schmidt, et al., Pyrogenic carbon capture and storage. GCB Bioenergy, 2019. **11**(4): p. 573-591, https://doi.org/10.1111/gcbb.12553.

82. Banjo Akinyemi and Adeyemi Adesina, Recent advancements in the use of biochar for cementitious applications: A review. Journal of Building Engineering, 2020: p. 101705, https://doi.org/10.1016/j.jobe.2020.101705.

83. Souradeep Gupta, Harn Kua, and Sd Pang, Biochar-mortar composite: Manufacturing, evaluation of physical properties and economic viability. Construction and Building Materials, 2018. **167**, https://doi.org/10.1016/j.conbuildmat.2018.02.104.

84. Ning Zeng and Henry Hausmann, Wood Vault: remove atmospheric CO_2 with trees, store wood for carbon sequestration for now and as biomass, bioenergy and carbon reserve for the future. Carbon Balance and Management, 2022. **17**(1): p. 2, https://doi.org/10.1186/s13021-022-00202-0.

85. Robert Rynk, et al., On-farm composting handbook (NRAES 54). 1992, Ithaca, NY: Northeast Regional Agricultural Engineering Service (NRAES); (https://hdl.handle.net/1813/67142); 202 p.

86. Modupe Stella Ayilara, et al., Waste Management through Composting: Challenges and Potentials. Sustainability, 2020. **12**(11): p. 4456, https://doi.org/10.3390/su12114456.

87. Sintana E. Vergara and Whendee L. Silver, Greenhouse gas emissions from windrow composting of organic wastes: Patterns and emissions factors. Environmental Research Letters, 2019. **14**(12): p. 124027, https://dx.doi.org/10.1088/1748-9326/ab5262.

88. Shuaixiang Zhao, et al., A precision compost strategy aligning composts and application methods with target crops and growth environments can increase global food production. Nature Food, 2022. **3**(9): p. 741-752, https://doi.org/10.1038/s43016-022-00584-x.

89. Shiyang Fan, et al., Heat potential, generation, recovery and utilization from composting: A review. Resources, Conservation and Recycling, 2021. **175**: p. 105850, https://doi.org/10.1016/j.resconrec.2021.105850.

90. U.S. Environmental Protection Agency (EPA). Sustainable Materials Management: Non-Hazardous Materials and Waste Management Hierarchy. 2023 Published by EPA; Available from https://www.epa.gov/smm/sustainable-materials-management-non-hazardous-materials-and-waste-management-hierarchy.

91. Dorte Krause-Jensen and Carlos M. Duarte, Substantial role of macroalgae in marine carbon sequestration. Nature Geoscience, 2016. **9**(10): p. 737-742, https://doi.org/10.1038/ngeo2790.

92. *J. Wu, D. P. Keller, and A. Oschlies, Carbon dioxide removal via macroalgae open-ocean mariculture and sinking: an Earth system modeling study. Earth Syst. Dynam., 2023.* ***14****(1): p. 185-221, https://doi.org/10.5194/esd-14-185-2023.*

93. *William J. Sagues, et al., Enhanced carbon dioxide removal from coupled direct air capture–bioenergy systems. Sustainable Energy & Fuels, 2019.* ***3****(11): p. 3135-3146, http://dx.doi.org/10.1039/C9SE00384C.*

94. *Abdulnaser M. Al-Sabaeei, et al., A systematic review of bio-asphalt for flexible pavement applications: Coherent taxonomy, motivations, challenges and future directions. Journal of Cleaner Production, 2020.* ***249****: p. 119357, https://doi.org/10.1016/j.jclepro.2019.119357.*

95. *Xuefei Zhang, et al., Preparation of bio-oil and its application in asphalt modification and rejuvenation: A review of the properties, practical application and life cycle assessment. Construction and Building Materials, 2020.* ***262****: p. 120528, https://doi.org/10.1016/j.conbuildmat.2020.120528.*

96. *Stefan Jirka and Thayer Tomlinson. State of the biochar industry 2014. 2015. A Report by the International Biochar Initiative (IBI); Available at https://biochar-international.org/state-of-the-biochar-industry-2014/.*

97. *C Drennan. Challenges and Opportunities for Wet-Waste Feedstocks–Resource Assessment. (2015). pgs.: Bioenergy (https://www.energy.gov/eere/bioenergy/articles/challenges-and-opportunities-wet-waste-feedstocks-resource-assessment).*

98. *David A. Laird, et al., Review of the pyrolysis platform for coproducing bio-oil and biochar. Biofuels, Bioproducts and Biorefining, 2009.* ***3****(5): p. 547-562, https://doi.org/10.1002/bbb.169.*

99. *Hassan A. Alabdrabalameer, et al., Big problem, little answer: overcoming bed agglomeration and reactor slagging during the gasification of barley straw under continuous operation. Sustainable Energy & Fuels, 2020.* ***4****(7): p. 3764-3772, http://dx.doi.org/10.1039/D0SE00155D.*

100. *Aurimas Bukauskas, et al., Whole timber construction: A state of the art review. Construction and Building Materials, 2019.* ***213****: p. 748-769, https://doi.org/10.1016/j.conbuildmat.2019.03.043.*

101. *Susan L LeVan-Green and Jean Livingston, Exploring the uses for small-diameter trees. Forest products journal, 2001.* ***51****(9): p. 10-21, https://www.fs.usda.gov/research/treesearch/5832.*

102. *Jose R. Serrano and Daniel Cassens, Pallet and component parts from small-diameter red oak bolts. Forest Products Journal, 2000.* ***50****(3): p. 67-73, https://www.researchgate.net/publication/294609272_Pallet_and_component_parts_from_small-diameter_red_oak_bolts.*

103. *Leif J. Jönsson, Björn Alriksson, and Nils-Olof Nilvebrant, Bioconversion of lignocellulose: inhibitors and detoxification. Biotechnology for Biofuels, 2013.* ***6****(1): p. 16, https://doi.org/10.1186/1754-6834-6-16.*

104. *Oscar Rosales-Calderon and Valdeir Arantes, A review on commercial-scale high-value products that can be produced alongside cellulosic ethanol. Biotechnology for Biofuels, 2019.* ***12****(1): p. 240, https://doi.org/10.1186/s13068-019-1529-1.*

105. *Bin Zhang, et al., Re-examination of dilute acid hydrolysis of lignocellulose for production of cellulosic ethanol after de-bottlenecking the inhibitor barrier. Journal of Biotechnology, 2022.* ***353****: p. 36-43, https://doi.org/10.1016/j.jbiotec.2022.05.006.*

106. *U.S. Energy Information Agency (EIA). Table 5.6.A in Average Price of Electricity to Ultimate Customers by End-Use Sector. Accessed July 2023 Published by US EIA; Available from https://www.eia.gov/electricity/monthly/epm_table_grapher.php?t=epmt_5_6_a.*

107. *U.S. Energy Information Agencym (EIA). Henry Hub Natural Gas Spot Price. Accessed July 2023 Published by US EIA; Available from https://www.eia.gov/dnav/ng/hist/rngwhhdA.htm.*

108. *Ryan E. Davis, et al. Process Design and Economics for the Conversion of Lignocellulosic Biomass to Hydrocarbon Fuels and Coproducts: 2018 Biochemical Design Case Update; Biochemical Deconstruction and Conversion of Biomass to Fuels and Products via Integrated Biorefinery Pathways (Report Number NREL/TP-5100-71949). 2018. National Renewable Energy Laboratory (NREL), Golden, CO, USA; 10.2172/1483234. https://www.osti.gov/biblio/1483234.*

109. *Argonne National Laboratory (ANL) Energy Systems and Infrastructure Analysis (ESIA). GREET® Model The Greenhouse gases, Regulated Emissions, and Energy use in Technologies Model. 2023 Published by ANL; Available from https://greet.es.anl.gov/.*

110. *Daniel Sanchez and Duncan Callaway, Optimal scale of carbon-negative energy facilities. Applied Energy, 2016.* ***170****: p. 437-444, https://doi.org/10.1016/j.apenergy.2016.02.134.*

111. *U.S. Energy Information Administration (EIA). Annual Energy Outlook 2022. 2022. https://www.eia.gov/outlooks/archive/aeo22/pdf/AEO2022_Narrative.pdf.*

112. *Fuel Cell and Hydrogen Energy Association (FCHEA). Road map to a US hydrogen economy. 2020. Fuel Cells Bulletin; https://doi.org/10.1016/S1464-2859(20)30532-0. https://www.fchea.org/us-hydrogen-study.*

113. *Freedonia Group. Lumber Industry Report. 2021 Published by Available from https://www.freedoniagroup.com/industry-study/lumber-4143.htm.*

114. *CISION. Global Acetone Market to Reach 7.3 Million Tons by 2026. (2021) Published by CISION; Available from https://www.prnewswire.com/news-releases/global-acetone-market-to-reach-7-3-million-tons-by-2026--301355631.html.*

115. *Grand View Research. Adipic Acid Market Size, Share & Trends Analysis Report By Application (Nylon 6, 6 Fiber, Nylon 6, 6 Resin, Polyurethane, Adipate Esters), By Region (North America, Europe, Asia Pacific), And Segment Forecasts, 2023 - 2030. 2023. https://www.grandviewresearch.com/industry-analysis/adipic-acid-market#.*

116. *Statista Research Department. Polyethylene production in the United States from 1990 to 2019 (in 1000 metric tons). 2020. https://www.statista.com/statistics/975591/us-polyethylene-production-volume/.*

117. *World Highways. U.S. asphalt market seeing future growth. 2017 Published by Available from https://www.worldhighways.com/wh6/news/us-asphalt-market-seeing-future-growth.*

118. *Alan Sherrard. ADM starts commercial-scale CCS at Decatur ethanol plant. 2017 Published by Bioenergy International; Available from https://bioenergyinternational.com/adm-starts-commercial-scale-ccs-decatur-ethanol-plant/.*

119. *George Pouliot, et al., Development of the crop residue and rangeland burning in the 2014 National Emissions Inventory using information from multiple sources. Journal of the Air & Waste Management Association, 2017.* ***67****(5): p. 613-622, https://doi.org/10.1080/10962247.2016.1268982.*

120. *Patricia M. Glibert, From hogs to HABs: impacts of industrial farming in the US on nitrogen and phosphorus and greenhouse gas pollution. Biogeochemistry, 2020.* ***150****(2): p. 139-180, https://doi.org/10.1007/s10533-020-00691-6.*

121. *U.S. Census Bureau. QWI Explorer. Accessed July 2023 Published by U.S. Census Bureau; Available from https://qwiexplorer.ces.census.gov/.*

122. *Ji-Young Son, et al., Distribution of environmental justice metrics for exposure to CAFOs in North Carolina, USA. Environmental Research, 2021.* ***195****: p. 110862, https://doi.org/10.1016/j.envres.2021.110862.*

123. *Laura McKinney and Ryan Thomson, Landfills and disasters: a geospatial analysis of environmental injustice across the Southern United States. Environmental Sociology, 2022.* ***8****(2): p. 173-186, https://doi.org/10.1080/23251042.2021.2004497.*

124. *Lawrence Susskind, et al., Sources of opposition to renewable energy projects in the United States. Energy Policy, 2022.* ***165****: p. 112922, https://doi.org/10.1016/j.enpol.2022.112922.*

125. *U.S. DOE Office of Energy Efficiency & Renewable Energy (EERE). Energy Equity and Environmental Justice. Accessed July 2023 Published by EERE; Available from https://www.energy.gov/eere/energy-equity-and-environmental-justice.*

126. *Linda Chalker-Scott, Impact of Mulches on Landscape Plants and the Environment — A Review. Journal of Environmental Horticulture, 2007.* ***25****(4): p. 239-249, https://doi.org/10.24266/0738-2898-25.4.239.*

127. *Conservation Technology Information Center (CTIC) Sustainable Agriculture Research and Education (SARE), and American Seed Trade Association (ASTA). National Cover Crop Survey Annual Report 2019–2020. 2020. SARE, CTIC, ASTA, https://www.sare.org/wp-content/uploads/2019-2020-National-Cover-Crop-Survey.pdf.*

128. *Paul W. Gallagher, et al., Supply and Social Cost Estimates for Biomass from Crop Residues in the United States. Environmental and Resource Economics, 2003.* ***24****(4): p. 335-358, https://doi.org/10.1023/A:1023630823210.*

129. *Council of Environmental Quality. Justice40 by Number of Categories Map November 2022. Published by Available from https://www.arcgis.com/apps/mapviewer/index.html?webmap=ee9ddbc95520442482cd511f9170663a.*

130. *Carbon Direct. Criteria for High-Quality Carbon Dioxide Removal. 2023. https://www.carbon-direct.com/research-and-reports/criteria-for-high-quality-carbon-dioxide-removal.*

131. *Shuai Pan, et al., The air quality and health impacts of projected long-haul truck and rail freight transportation in the United States in 2050. Environment International, 2019.* ***130****: p. 104922, https://doi.org/10.1016/j.envint.2019.104922.*

132. *The White House. Build America, Buy America Act – Federal Financial Assistance Accessed July 2023 Published by Available from https://www.whitehouse.gov/omb/management/made-in-america/build-america-buy-america-act-federal-financial-assistance/.*

133. *Josh Bivens. Updated employment multipliers for the US economy. 2003. Report, Economic Policy Institute, August; https://www.epi.org/publication/updated-employment-multipliers-for-the-u-s-economy/.*

134. *Yuan Liu, et al., Evaluating the employment impact of recycling performance in Florida. Waste Management, 2020.* ***101****: p. 283-290, https://doi.org/10.1016/j.wasman.2019.10.025.*

135. *Amy Jaffe, et al. The Feasibility of Renewable Natural Gas as a Large-Scale, Low Carbon Substitute. 2016. https://ww2.arb.ca.gov/sites/default/files/classic/research/apr/past/13-307.pdf.*

136. *Gregory M. Astill and C. Richard Shumway, Profits from pollutants: Economic feasibility of integrated anaerobic digester and nutrient management systems. Journal of Environmental Management, 2016.* ***184****: p. 353-362, https://doi.org/10.1016/j.jenvman.2016.10.012.*

137. *Zahid Hussain, Jyoti Mishra, and Emanuela Vanacore, Waste to energy and circular economy: the case of anaerobic digestion. Journal of Enterprise Information Management, 2020.* ***33****(4): p. 817-838, https://doi.org/10.1108/JEIM-02-2019-0049.*

138. *Daniel Raimi, Sanya Carley, and David Konisky, Mapping county-level vulnerability to the energy transition in US fossil fuel communities. Scientific Reports, 2022.* ***12****, https://doi.org/10.1038/s41598-022-19927-6.*

139. *Mohamed Farghali, et al., Prospects for biogas production and H_2S control from the anaerobic digestion of cattle manure: The influence of microscale waste iron powder and iron oxide nanoparticles. Waste Management, 2020.* ***101****: p. 141-149, https://doi.org/10.1016/j.wasman.2019.10.003.*

140. *E. Matthews and Nickolas Themelis. Potential for Reducing Global Methane Emissions From Landfills, 2000-2030. 2007. Available from https://gwcouncil.org/potential-for-reducing-global-methane-emissions-from-landfills-2000-2030/.*

141. *C. Mukherjee, et al., A review on municipal solid waste-to-energy trends in the USA. Renewable and Sustainable Energy Reviews, 2020.* ***119****: p. 109512, https://doi.org/10.1016/j.rser.2019.109512.*

142. *Tae-Heon Kwak, et al., Gasification of municipal solid waste in a pilot plant and its impact on environment. Korean Journal of Chemical Engineering, 2006.* ***23****(6): p. 954-960, https://doi.org/10.1007/s11814-006-0014-2.*

143. *U.S. Environmental Protection Agency (EPA). Landfill Technical Data. 2023 Published by US EPA; Available from https://www.epa.gov/lmop/landfill-technical-data.*

144. *David Lampert, et al. Development of a Life Cycle Inventory of Water Consumption Associated with the Production of Transportation Fuels (Report Number ANL/ESD15/27). 2015. Argonne National Laboratory (ANL), http://dx.doi.org/10.13140/RG.2.1.3886.9201.*

145. *Pradeep Jain, et al., Life-Cycle Inventory and Impact Evaluation of Mining Municipal Solid Waste Landfills. Environmental Science & Technology, 2014.* ***48****(5): p. 2920-2927, https://doi.org/10.1021/es404382s.*

146. *U.S. Environmental Protection Agency (EPA) Landfill Methane Outreach Program (LMOP). LMOP National Map: Landfill Gas (LFG) Energy Projects and Municipal Solid Waste (MSW) Landfills. Accessed July 2023 Published by US EPA; Available from https://www.epa.gov/lmop/lmop-national-map.*

147. *Richard Ready, Do Landfills Always Depress Nearby Property Values? Journal of Real Estate Research, 2010.* ***32****(3): p. 321-340, https://doi.org/10.1080/10835547.2010.12091279.*

148. *DOE. Community Engagement Initiatives. Published by Available from https://www.energy.gov/lm/community-engagement-initiatives.*

149. *Robert Bacon and Masami Kojima. Issues in estimating the employment generated by energy sector activities. 2011. The World Bank Sustainable Energy Department, https://citeseerx.ist.psu.edu/document?repid=rep1&type=pdf&doi=50752cfda9b2e0b887d2cd037512f2d3f659b758.*

150. *Karen C Short, et al., Spatial dataset of probabilistic wildfire risk components for the conterminous United States, 1st Edition. 2016: Fort Collins, CO, USA: Forest Service Research Data Archive (https://doi.org/10.2737/RDS-2016-0034).*

151. *Ma Yiqun, et al., Wildfire smoke PM2.5 and mortality in the contiguous United States. medRxiv, 2023: p. 2023.01.31.23285059, https://doi.org/10.1101/2023.01.31.23285059.*

152. *Francisco Aguilar and HE 'Gene' Garrett, Perspectives of woody biomass for energy: Survey of state foresters, state energy biomass contacts, and National Council of Forestry Association executives. Journal of Forestry, 2009.* ***107****(6): p. 297-306, https://www.researchgate.net/publication/233583303_Perspectives_of_Woody_Biomass_for_Energy_Survey_of_State_Foresters_State_Energy_Biomass_Contacts_and_National_Council_of_Forestry_Association_Executives.*

153. *Jake Verschuyl, et al., Biodiversity response to intensive biomass production from forest thinning in North American forests-a meta-analysis. Forest Ecology and Management, 2011.* ***261****(2): p. 221-232, https://doi.org/10.1016/j.foreco.2010.10.010.*

154. *Xinzhong Zhang, et al., The effects of forest thinning on soil carbon stocks and dynamics: A meta-analysis. Forest Ecology and Management, 2018.* ***429****, https://doi.org/10.1016/j.foreco.2018.06.027.*

155. *Eric M White. Woody biomass for bioenergy and biofuels in the United States: A briefing paper (Report Number PNW-GTR-825). 2010. USDA Forest Service Pacific Northwest (PNW) Research Station https://www.fs.usda.gov/pnw/pubs/pnw_gtr825.pdf.*

156. *James E. Henderson, Richard B. Standiford, and Samuel G. Evans. Economic contribution of timber harvesting and manufacturing to north coast redwood region counties. (2017). pgs. 371-381. In: Standiford, Richard B. and Valachovic, Yana, tech cords. Coast redwood science symposium 2016: Past successes and future direction. Proceedings of a workshop. Gen. Tech. Rep. PSW-GTR-258. Albany, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station; https://www.fs.usda.gov/research/treesearch/55455.*

157. *Julia A. Sohn, Somidh Saha, and Jürgen Bauhus, Potential of forest thinning to mitigate drought stress: A meta-analysis. Forest Ecology and Management, 2016.* ***380****: p. 261-273, https://doi.org/10.1016/j.foreco.2016.07.046.*