Surveying the BECCS Landscape

Part of the EFI Report Series
Bioenergy with Carbon Capture and Storage: Sowing the Seeds of a Negative-Carbon Future

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The Energy Futures Initiative advances technically grounded solutions to climate change through evidence-based analysis, thought leadership, and coalition-building. Under the leadership of Ernest J. Moniz, the 13th U.S. Secretary of Energy, EFI conducts rigorous research to accelerate the transition to a low-carbon economy through innovation in technology, policy, and business models. EFI maintains editorial independence from its public and private sponsors. EFI's reports are available for download at www.energyfuturesinitiative.org.

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ABOUT THIS STUDY

This report is a systematic review of the literature to understand the key opportunities and challenges associated with bioenergy with carbon capture and storage (BECCS), a broad set of systems that integrate the use of energy derived from biomass with the capture and long-term storage of carbon. BECCS has received much attention due to its potential to remove greenhouse gas emissions from the atmosphere; however, there are uncertainties regarding BECCS pathways that may have adverse economic, social, and environmental impacts. While BECCS can potentially decarbonize numerous sectors, including agriculture, forestry, electricity, waste, and industry, BECCS deployment in practice has been limited, and the actual emissions reduction potential of a given project depends on the project's exact configuration, given the varying technical potential of BECCS projects in different geographic regions. Additionally, both the opportunities and challenges for rural and environmental justice communities are underexplored.

The Energy Futures Initiative (EFI) conducted this review as the first phase of a study on the potential contributions of BECCS in achieving the U.S. goal of net-zero greenhouse gas emissions by midcentury. Building on the previous work on carbon dioxide removal and carbon capture, utilization, and storage, EFI has examined the role of BECCS as a domestic decarbonization option, as well as in the context of advancing other national policy objectives such as sustainable agricultural and forestry practices and rural economic development. This report defines BECCS and its component parts; discusses the current state of BECCS and associated industries in the United States; and identifies the opportunities and challenges for BECCS. The findings of this literature review will inform the second phase of the study, which involves a deeper dive analysis into the specific issues through commissioned white papers and an expert workshop. EFI will use the insights gleaned from the literature review, white papers, and workshop discussions to develop a comprehensive national strategy and policy roadmap for BECCS.

Given the complexity and breadth of the potential suite of BECCS applications, EFI reviewed a wide array of sources including peer-reviewed studies, non-peer reviewed reports, news articles, web content, and legislative and executive documents. The search, screening, and review process was iterative as EFI gathered new knowledge throughout the research process. In total, over 300 sources were reviewed and included in this report.

TABLE OF CONTENTS

Executive Summary......1
The Importance of BECCS and CDR to Deep Decarbonization......5
Literature Review Key Findings......9
Key Issues and Areas for Future Study......12
Navigating this Report......12

What is BECCS?......13
Biomass Feedstocks......14
Wood and Wood Wastes......15
Agricultural Crops and Crop Wastes......16
Other Biomass Feedstocks......17
Biomass-to-Energy Conversion Pathways......19
Bioenergy Products and Uses......20
Carbon Capture......23
Carbon Utilization and Storage......24
Biochar Utilization......24
CO_2 Utilization......25
Geologic CO_2 Storage......25
Integration with Other Decarbonization Options......25
Technoeconomic Comparisons of Distinct Biomass and Carbon Capture Pathways......27
Economics of Biomass Sources......27
Biomass Harvesting, Transportation, and Pre-processing......28
Biomass Conversion Technology Costs......30
Carbon Capture and Compression Costs......31
CO_2 Transport and Storage Costs......32

U.S. BECCS Industry Landscape......33
Existing Industries Relevant to Future BECCS Deployment......33
Biofuels......33
Biomass Power Plants......33
Pellet Industry......35
Other Forestry Industries......35
Carbon Capture and Management Industry......37
BECCS Feedstock and Decarbonization Potential in the United States......38
BECCS Projects in the United States......40

Federal Policies and Programs to Support BECCS ... 42
Tax Incentives ... 43
Department of Energy ... 47
Department of Agriculture ... 50
The Environmental Protection Agency ... 51
Interagency Collaboration ... 52

Key Issues Identified in the Literature ... 56
GHG Accounting Methods for BECCS ... 56
Inconsistent Emissions Categories ... 57
A Focus on the Land-Use Sector ... 58
Timing Mismatch for Carbon Emissions and Removals ... 59
Can BECCS Deliver Net-Negative Emissions? ... 60
Potential for Net-Negative Emissions by Feedstock ... 60
Potential for Net-Negative Emissions by Conversion and End Use of Biomass ... 63
BECCS Supply Chain Challenges ... 64
Feedstock Supply Chains ... 65
CO_2 Transportation Infrastructure ... 66
Research, Development, and Demonstration Gaps ... 66
Feedstock RD&D ... 68
Energy Conversion RD&D ... 68
CCUS RD&D ... 68
Crosscutting RD&D ... 69
Environmental Impacts and Resource Requirements of BECCS ... 71
Local Air Quality Impacts ... 71
Water Requirements and Impacts ... 72
Land-Use Impacts of Feedstock Production ... 74
Energy Requirements ... 76
Biodiversity Impacts of Forestry Feedstock Production ... 77
Opportunities for BECCS to Enhance Forest Resilience ... 78
Socioeconomic and Environmental Justice Considerations for BECCS ... 80
Rural Economic Development Opportunities ... 80
Public Acceptance and Environmental Justice ... 81

Appendix ... 88
Technological Readiness of Different Pathways ... 88
Commercial BECCS Pathways ... 88
Pre-commercial BECCS Pathways ... 90
Pilot and Demonstration Stage BECCS Pathways ... 92
Technologically Uncertain BECCS Pathways ... 94

References ... 96

LIST OF FIGURES

Figure 1: Carbon Flows from BECCS....1
Figure 2: BECCS Pathway CO_2 Abatement Cost Estimates (\$/tCO_2)....5
Figure 3: The Role of BECCS in Limiting Global Warming to 1.5°C....7
Figure 4: BECCS Global Carbon Removal Potential Estimates (Percent of Net 2018 GHG Emissions)....8
Figure 5: BECCS U.S. Carbon Removal Potential Estimates (Percent of Net 2018 GHG Emissions)....8
Figure 6: Components of BECCS....13
Figure 7: U.S. Sources and End Uses of Biomass in 2014....14
Figure 8: Current and Future Annual U.S. Biomass Feedstock Production Estimates....19
Figure 9: U.S. Bioenergy Facilities by Capacity, 2014....23
Figure 10: From Farms and Forests to Factories: Integrating BECCS with Other Decarbonization Pathways....26
Figure 11: Price of Biomass Feedstocks at Different Levels of Feedstock Production....28
Figure 12: Harvesting Costs of Biomass Wood....29
Figure 13: Logistical and Transportation Costs for Non-Wood and Wood Feedstocks....29
Figure 14: Average Delivered Costs of Non-Wood and Wood Feedstocks....30
Figure 15: BECCS Pathway CO_2 Abatement Cost Estimates (\$/tCO_2)....31
Figure 16: Ethanol and Biopower Plants in the United States Eligible for 45Q Credits, 2019....34
Figure 17: Pellet Mill Capacity in the United States....35
Figure 18: Total Value Added to State GDP by Forestry in the United States....36
Figure 19: Employment in BECCS-Adjacent Forestry Industries in the United States....36
Figure 20: Paper and Pulp Mills in the United States....37
Figure 21: Geographic Distribution of Biomass in the United States in 2020....38
Figure 22: Geographic Distribution of Biomass Near Potential CO_2 Storage Sites in 2020....39
Figure 23: Location of U.S. BECCS Projects....42
Figure 24: Section 45Q Tax Credit Value Available for Differing Sources and Uses of CO_2....45
Figure 25: California LCFS Credits by Fuel Type, 2011-2021....46
Figure 26: Policies and Programs to Support BECCS Deployment across Federal Agencies....48
Figure 27: Timeline of U.S. Federal Legislation Related to Biofuels and Annual Ethanol Production from 1981 to 2020....52
Figure 28: Federal Participants in an Interagency CDR RD&D Initiative....53
Figure 29: GHG Accounting for Bioenergy in Practice....59
Figure 30: Sequestration Rate and Carbon Storage Over the Age of Forests....61

Figure 31: BECCS Supply Chain and Emissions ... 63
Figure 32: Typical Biomass Supply Chain ... 65
Figure 33: Recommended RD&D Portfolio Elements and Pathways for BECCS ... 67
Figure 34: Summary of RD&D Gaps for BECCS ... 70
Figure 35: Local Air Quality Impacts of the BECCS Supply Chain ... 71
Figure 36: Water Footprints of Agricultural Feedstocks ... 73
Figure 37: Energy Flow Diagram for 100 MJ of Energy Input for Electricity- and Biofuel-Based BECCS Using Miscanthus ... 76
Figure 38: Energy Consumed to Produce 1 MWh of Low Carbon Electricity via BECCS and Coal with CCS ... 77
Figure 39: Climate-Driven Risks to Forests, Forest Management, and BECCS ... 79
Figure 40: Policy Pathways to Address Environmental Justice Considerations in BECCS Deployment ... 83
Figure 41: Pellet Mills and Environmental Justice Communities in Southeastern United States ... 85
Figure 42: Commercial Pathways for BECCS ... 89
Figure 43: Pre-commercial Pathways for BECCS ... 91
Figure 44: Pilot & Demonstration Pathways for BECCS ... 93
Figure 45: Uncertain Pathways for BECCS ... 95

LIST OF TABLES

Table 1: Operational BECCS Projects Globally ... 3
Table 2: List of Closed, Operational, and Planned BECCS Projects in the United States ... 40
Table 3: Existing Tax Incentives with Relevance to BECCS in the United States ... 43
Table 4: Estimated U.S. Biomass Potential and Equivalent CO_2 Fluxes (2040, Mt/yr) ... 60
Table 5: TRL Description for Pre-commercial Pathways ... 90
Table 6: TRL Description for Pilot and Demonstration Pathways ... 92
Table 7: TRL Description for Uncertain Pathways ... 94

LIST OF BOXES

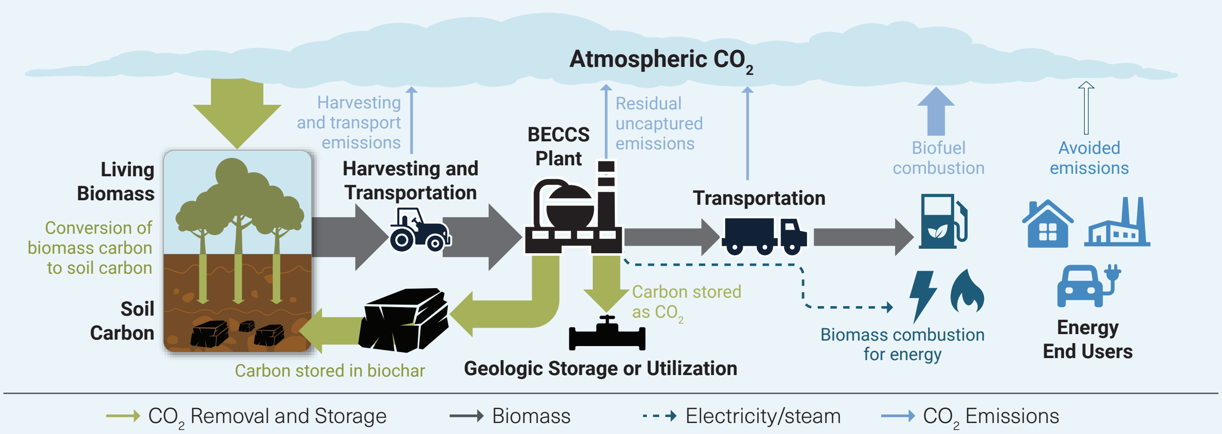
Box 1: Feedstock Terminology: Energy Crops and Biofuel Generations ... 18
Box 2: Existing Applications of BECCS for Heat and Power ... 21
Box 3: The Impact of State Policy ... 46
Box 4: BECCS Policy Proposals in the 117th Congress ... 54

Executive Summary

Bioenergy with carbon capture and storage (BECCS) refers to a set of distinct systems that share common features: a biomass feedstock, biomass-to-energy conversion and creation of a useful energy product, carbon capture, and carbon storage or utilization. Despite this clear definition, however, there is little consensus on (1) precisely which set of biomass feedstocks, conversion techniques, and carbon capture approaches should categorically be labeled as BECCS and (2) whether a project must be carbon-neutral or -negative to qualify as a BECCS project, complicating the analysis and policy environment.

BECCS has garnered attention in large part because of its potential to produce net-negative greenhouse gas (GHG) emissions, serving as a form of carbon dioxide removal (CDR). Bioenergy can produce modest emissions because the carbon that is released during combustion was previously removed from the atmosphere by photosynthesis during the growth of the plants and could be sequestered again through plant regrowth.[1] The BECCS process captures and stores some of the carbon that would otherwise be released, which can, but does not necessarily, result in net-negative GHG emissions over the process's life cycle (Figure 1).

Figure 1: Carbon Flows from BECCS[2,3]



BECCS is a set of systems that use biomass to produce energy and capture and store the embedded carbon, which can result in a net removal of greenhouse gases from the atmosphere. Plants (e.g., trees, crops) naturally absorb atmospheric carbon dioxide (CO_2) through photosynthesis and convert it into biomass carbon. BECCS involves harvesting these biomass "feedstocks" and converting them into useful energy (e.g., electricity, biofuels), while also capturing some of the carbon that would otherwise be released back to the atmosphere as GHGs. This carbon is then either used or permanently stored, either underground or in soils. Note: the width of the arrows signifies the approximate proportional share of carbon released or absorbed. Source: Adapted from Global CCS Institute, 2019 and Tanzer and Ramirez, 2019. Icons from The Noun Project.

BECCS technologies can displace emissions from fossil fuel production and consumption, and can be deployed in tandem with other decarbonization solutions, such as forestry CDR, agricultural CDR, methane mitigation, waste reduction, CCUS, bioenergy, clean fuels, clean power, and hydrogen. In addition to its climate benefits, BECCS projects have the potential to provide other environmental, economic, and jobs benefits.

While BECCS technologies build upon a well-established foundation of fully commercialized bioenergy and carbon capture, utilization, and storage technologies, a legacy of many non-technology barriers to deployment means that BECCS projects are at an earlier stage of demonstration and deployment. The handful of BECCS projects deployed globally are mostly pilot- or demonstration-scale, capturing less than 400 kilotons (kt)[a] of carbon dioxide (CO_2) a year for enhanced oil recovery (EOR) or other utilization (Table 1).[4] Most of these projects capture CO_2 from ethanol production, biomass power plants, or waste incineration. The Illinois Industrial Carbon Capture and Storage (CCS) project at Archer Daniels Midland's (ADM) Decatur, Illinois ethanol production facility—one of five projects in the United States—is the only large-scale (about 1 megaton [Mt]) BECCS facility in operation worldwide, and the only one with dedicated CO_2 storage. The project has yet to achieve its full capacity, however, and the Decatur plant still emits more CO_2 from fossil fuel combustion than it removes through BECCS.[5,6]

Policy has shaped incumbent industries that could form a foundation for BECCS. Various mandates and tax incentives have created a robust biofuels market in the U.S. transportation sector; electricity-sector regulations in Europe have incentivized the growth of U.S. wood pellet exports to supply biopower generation; and new policies such as the 45Q Carbon Oxide Sequestration tax credit and California's Low Carbon Fuel Standard (LCFS) have engendered investment in carbon transport, utilization, and sequestration systems in United States.[7,8,9] The creation of a full-scale BECCS industry, both in the United States and globally, will be contingent on new, dedicated policy.

a This report uses SI units and prefixes throughout; "tons" (t) refers to metric tons unless otherwise specified. In a few instances figures will use non-SI units, which are noted. Biomass is measured in dry metric tons (also referred to as "bone dry"), a metric ton of biomass at 0 percent moisture. In some cases, other sources use energy-equivalent dry tons to directly compare feedstocks with different heat contents and conversion efficiencies.

Table 1: Operational BECCS Projects Globally[10]

Name	Sponsors	Sector	Country	Year	Feedstock	Carbon Captured ($MtCO_2$/yr)	Carbon Disposition
Arkalon CO_2 Compression Facility	Conestoga Energy Partners	Ethanol Production	United States	2009	Corn, sorghum	0.29-0.31	EOR
OCAP[11]	Linde	Ethanol Production and Oil Refinery	Netherlands	2011	Corn	0.4*	Utilization
Bonanza Bioenergy CCUS EOR	Conestoga Energy Partners	Ethanol Production	United States	2012	Corn, sorghum	0.10-0.16	EOR
Husky Energy Lashburn and Tangleflags CO_2 Injection Project[12]	Cenovus Energy,[13] Lashburn and Tangleflags	Ethanol Production	Canada	2012	Corn, non-food quality grain	0.09	EOR
Twence CO_2/Sodium Bicarbonate Plant[14]	Twence	Waste-to-Energy	Netherlands	2014	Residual waste	0.003	Utilization
Calgren Renewable Fuels CO_2 Recovery Plant	Calgren Renewable Fuels, AirLiquide	Ethanol Production	United States	2015	Corn, sorghum, agricultural waste	0.15	Utilization (Liquefied for use in food, beverage, manufacturing)
Lantmännen Agroetanol Purification Facility[15]	Lantmännen	Ethanol Production	Sweden	2015	Wheat, starch-rich residues	0.15-0.2	Utilization
Alco Bio Fuel Bio-Refinery CO_2 Recovery Plant[16]	Alco Bio Fuel	Ethanol Production	Belgium	2016	Corn	0.1	Utilization
Cargill Wheat Processing CO_2 Purification Plant	Cargill	Ethanol Production	United Kingdom	2016	Wheat	0.1	Utilization
Saga City Waste Incineration Plant	Saga City	Waste-to-energy	Japan	2016	Municipal waste	0.003	Utilization

(continued)

Name	Sponsors	Sector	Country	Year	Feedstock	Carbon Captured ($MtCO_2$/yr)	Carbon Disposition
Illinois Industrial Carbon Capture & Storage	ADM	Ethanol Production	United States	2017	Corn	0.52-1.0	Geologic storage
AVR CO_2 Capture Plant[17]	AVR	Waste-to-energy	Netherlands	2019	Residual waste	0.06	Utilization
Drax BECCS Plant[18]	Drax	Power Generation (coal and biomass)	United Kingdom	2019	Compressed wood pellets	0.00003**	Not specified
Stockholm Exergi AB[19]	Stockholm Exergi	Combined Heat and Power	Sweden	2019	Biomass, residual waste	0.8 (anticipated)***	Not specified
Charm Industrial[20]	Charm Industrial	Bio-oil Production	United States	2020	Waste biomass	0.001 (total)	Not specified
Mikawa Post Combustion Capture Demonstration Plant[21]	Sigma Power Ariake Co. Ltd.	Power Generation (coal and biomass)	Japan	2020	Palm kernel shell	0.18	Not specified

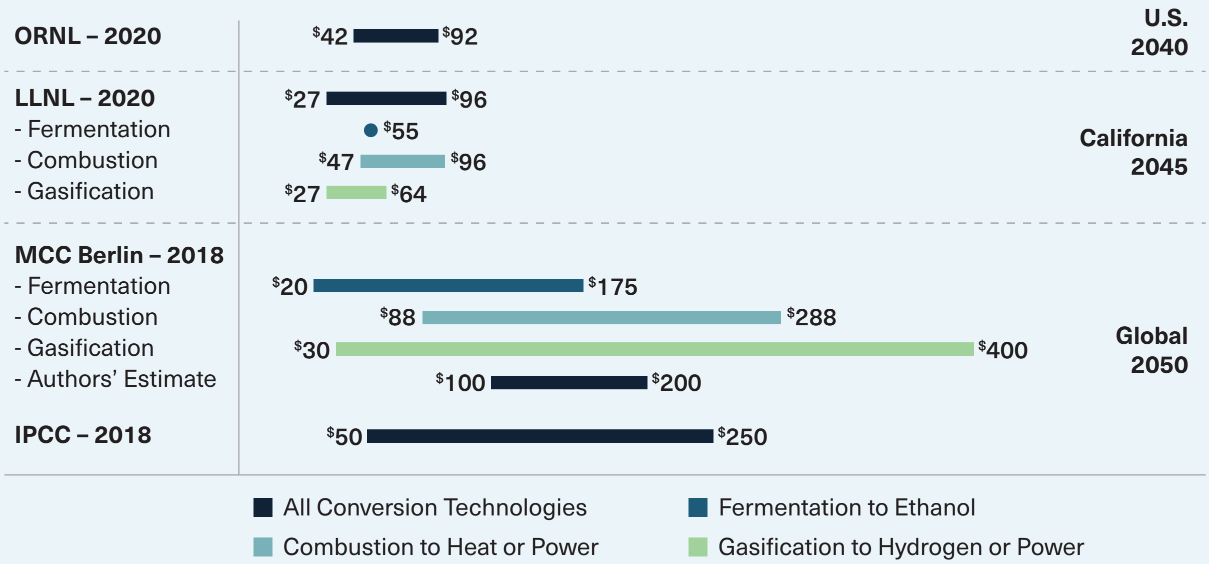
** The OCAP plant receives its CO_2 from a fuel refining facility (hydrogen production) and from an ethanol production plant. Only part of the total CO_2 (400 kt/yr) qualifies as bioenergy with carbon capture and utilization.*

*** The project is currently releasing CO_2 after its capture, but the long-term plan is to focus on offshore storage as part of the Zero Carbon Humber project.*

**** The Stockholm Exergi AB project is currently in its pilot phase and plans to capture its first kilogram of CO_2 by 2025. Once the plant achieves normal operations, it is expected to capture 0.8 $MtCO_2$/yr.*

Current estimates for BECCS carbon removal costs range widely from $20 per metric ton of CO_2 (tCO_2) to $400/$tCO_2$; estimates vary for different feedstocks, conversion and capture technologies, and system configurations (Figure 2).[22] Projects with access to abundant, cheap biomass, feedstock production co-located with energy conversion, and proximity to geologic storage can achieve lower cost and may be economic today. However, innovation in technologies, policies, and business models—both to bring down the cost of BECCS projects and to facilitate explicit valuation of their climate (i.e., CDR) benefits—will be required to make widespread deployment commercially viable.

Figure 2: BECCS Pathway CO_2 Abatement Cost Estimates ($/$tCO_2$)[23,24,25,26]



Cost estimates for BECCS projects range from $20/$tCO_2$ to $400/$tCO_2$ removed. These estimates vary widely across literature and differ by geographic scope, time, and technology. Costs for most BECCS projects in the United States are expected to be less than $100/$tCO_2$ by 2040. *Source: Data from Langholtz et al., 2020 (ORNL), Baker et al., 2020 (LLNL), Fuss et al., 2018 (Mercator Research Institute on Global Commons and Climate Change, Berlin [MCC Berlin]), and IPCC, 2018.*

THE IMPORTANCE OF BECCS AND CDR TO DEEP DECARBONIZATION

In the 2018 *Special Report on Global Warming of 1.5°C (SR1.5)*, the Intergovernmental Panel on Climate Change (IPCC) found robust differences between the impacts to natural and human systems from global warming of 1.5 degrees Celsius over pre-industrial global temperatures and the impacts from warming of 2 degrees Celsius (and higher).[27] Limiting global temperature increase to a 1.5-degree target requires global CO_2 emissions to reach net-zero by 2050 and be net-negative thereafter.[28] BECCS as a form of CDR is projected to be important to achieving these targets.

Without CDR—i.e., removal of carbon from the atmosphere and oceans and subsequent storage—net-negative emissions are impossible to reach.[29] CDR can also help achieve interim targets more quickly and affordably by compensating for difficult-to-decarbonize sectors with few mitigation options (e.g., heavy industry, aviation, and agriculture). CDR serves as an important complement to mitigation strategies, not a substitute. Substantial reductions in emissions from fossil fuel use and other sources will still be necessary.

CDR includes natural pathways, such as afforestation and agricultural soil management, and technological[b] pathways, such as BECCS and direct air capture (DAC).[30] BECCS is a major part of the CDR equation in IPCC's *SR1.5* scenarios: all scenarios that limit warming to 1.5 degrees use some form of negative emissions, including up to 8 gigatons (Gt) of annual emissions removals via BECCS by 2050.[31] Even more BECCS deployment is required in scenarios with higher overshoot.[c] For context, the total amount of mitigation or removal required to reach net-zero at the time of IPCC's analysis was 42 Gt; 8 Gt is approximately the gross CO_2 emissions from fossil fuels and cement in 2019 of the United States and the European Union (EU) combined.[32]

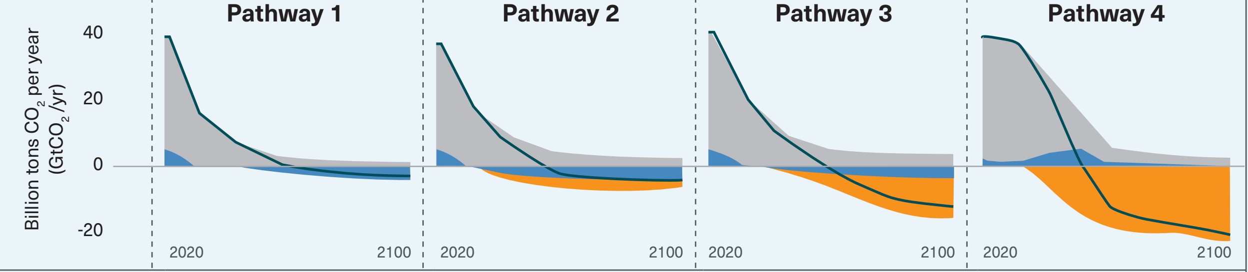
BECCS is favored in IPCC scenarios in part because it is the technological CDR solution most often included in integrated assessment models (IAMs). IPCC expects BECCS to occupy a less prominent role in future modeling as other CDR pathways become better understood and incorporated into IAMs.[33] The illustrative IPCC scenarios (Figure 3) have different constraints on the amount of BECCS allowed, with lower-BECCS scenarios requiring a faster shift away from fossil fuels and a steeper decline in total energy demand. Subsequent modeling from other sources, such as the International Energy Agency (IEA), has also indicated a need for gigaton-scale BECCS.[34] Other research has shown how BECCS can help meet global climate targets at lower cost.[35] However, as other CDR pathways become better understood and incorporated into IAMs, IPCC expects BECCS to occupy a less prominent role in future modeling.[36]

BECCS is also crucial to net-zero scenarios because it occupies a unique middle ground in the CDR landscape. BECCS pathways could potentially provide greater and more permanent carbon removal on a global scale than natural solutions, which are limited by land availability and which store carbon on a shorter timescale. Other technological methods, such as DAC, share BECCS's ability to scale, but currently are more costly (and could continue to be in the future).[37] This combination of qualities gives BECCS distinct value, but achieving necessary CDR levels to reach net-zero will likely require using BECCS as part of a portfolio of CDR options.

b BECCS is sometimes referred to as a "technologically enhanced natural CDR" (i.e., a hybrid of natural and technological CDR), but is grouped here with technological pathways, following the IPCC.

c I.e., scenarios in which global temperature increase exceeds 1.5 degrees before returning to that level.

Figure 3: The Role of BECCS in Limiting Global Warming to 1.5°C[38]



	Pathway 1	Pathway 2	Pathway 3	Pathway 4
Scenario description	Innovation leads to lower energy demand	Sustainable development at a global scale	Emissions reductions due to innovation in production	GHG-intensive lifestyles continue, leading to high energy demand
2050 energy demand vs. 2010	32% less	2% more	21% more	44% more
Fossil fuel consumption	Decreases rapidly and drastically and nears zero by 2100	Decreases regularly	Decreases gradually	Stays stable then decreases
CDR used	Afforestation only, no CCS (or BECCS)	Afforestation and limited BECCS	Afforestation and moderate BECCS	Less afforestation and widespread BECCS

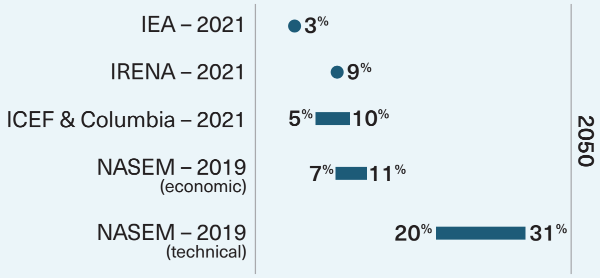
Fossil fuels | AFOLU | BECCS | Net emissions

IPCC modeling includes BECCS in three of four modeled pathways, with BECCS introduced by 2030 in all three scenarios. With immediate emissions reductions in the near-term, fewer GHG removals from BECCS are required by midcentury (as shown in Pathway 2). When mitigation is delayed (as shown in Pathway 4), substantial GHG removal is required to meet net-zero emissions by 2100. ***Note****: AFOLU = agriculture, forestry, and other land use. Afforestation is included in this category along with other emissions sources and sinks. Source: IPCC, 2018.*

A key question is whether BECCS has a technical potential commensurate with the need for CDR projected by IPCC and others. Global projections for the potential abatement from BECCS range from 1.3 $GtCO_2$ /yr to 15 $GtCO_2$ /yr (or 3 percent to 31 percent of 2018 net GHG emissions[d]) in 2050 (Figure 4). The main constraints on technical potential are feedstock availability and CO_2 storage or use options; varied estimates of potential rely on differing assumptions about these variables.

d GHG emissions data includes land-use change emissions.

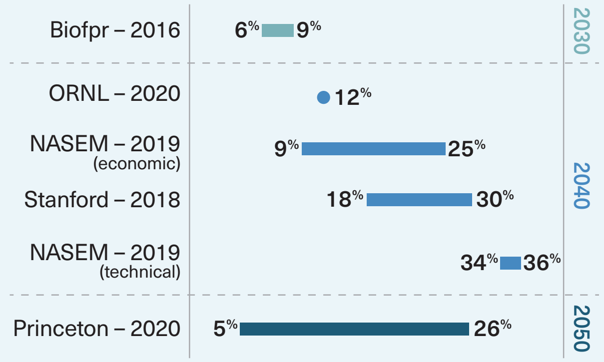
Figure 4: BECCS Global Carbon Removal Potential Estimates (Percent of Net 2018 GHG Emissions)[39,40,41,42,43]



Global projections for BECCS potential abatement range from 1.3 $GtCO_2$/yr to 15 $GtCO_2$/yr in 2050, the equivalent of 3 percent to 31 percent of 2018 global net GHG emissions of 48.9 $GtCO_2$ (which includes both emissions and removals from land-use change and forestry). The estimates vary widely based on different assumptions of feedstock availability, costs, financial incentives, and favorable policies made by each study. Source: Data from IEA, 2021, IRENA, 2021, Sandalow et al., 2021 (ICEF & Columbia), and NASEM, 2019.

The Biden administration's recent commitment to reducing economywide GHG emissions by at least 50 percent by 2030—along with the longer-term goal of net-zero GHG emissions by 2050—highlights the importance of rapid deployment of CDR technologies in the United States. Various studies have estimated the emissions-reduction potential of BECCS in the United States to be between 0.3 $GtCO_2$/yr and 2.2 $GtCO_2$/yr across various timeframes—possibly enough to bring U.S. emissions one-third of the way to net-zero (Figure 5).[e]

Figure 5: BECCS U.S. Carbon Removal Potential Estimates (Percent of Net 2018 GHG Emissions)[44,45,46,47,48,49]



Five studies show that the United States can reduce emissions via BECCS technologies by 0.3 $GtCO_2$/yr to 2.2 $GtCO_2$/yr, the equivalent of 5 percent to 36 percent of 2018 net GHG emissions of 5.9 $GtCO_2$ (which includes both emissions and removals from land use, land-use change, and forestry). The estimates vary depending on timeframe and assumptions regarding feedstock availability, costs, incentives, and policies. Source: Data from Rogers et al., 2016 (Biofpr), Langholtz et al., 2020 (ORNL), NASEM, 2019, Baik et al., 2018 (Stanford), and Larson et al., 2020 (Princeton).

The United States may also play a role in BECCS deployment by exporting biomass. The country is already a net exporter of ethanol (top destinations are Canada, Brazil, and India) and the largest supplier of wood pellets to the EU's burgeoning biomass industry.[50,51] Three-quarters of all pellets produced in the United States in 2020 were exported.[52] Europe may need to rely on either continued biomass trade (both intraregional and external) or non-BECCS options to meet its CDR needs. One estimate puts Europe's emissions abatement potential from BECCS at just 0.2 Gt, or 5 percent of current emissions—half of the 10 percent the European Commission says will need to be addressed through CDR.[53] The United States'

e For reference, 2.2 Gt is equivalent to the total emissions from the transportation and residential buildings sections in 2019, or the energy-related CO_2 emissions of the seven highest-emitting states combined (TX, CA, OH, PA, LA, IL, FL).

role in future BECCS trade will be highly dependent on both its own policy as well as the policy of potential trading partners, such as Europe; different studies have projected that the United States could become either an exporter or an importer of biomass for use in BECCS projects.[54,55]

LITERATURE REVIEW KEY FINDINGS

Several themes emerged from this systematic review of the literature, cutting across technologies, policies, industries, infrastructure, and biomass feedstocks related to BECCS. The key findings below provide insights for further research to better understand the opportunities and challenges for BECCS deployment in the United States.

BECCS encompasses a wide range of technologies; many potential pathways are underexplored and require additional analysis. BECCS is a set of systems encompassing biomass feedstocks, conversion processes, end uses, and carbon capture approaches. The focus in the literature is largely on adding carbon capture to wood-based power and ethanol production, but there are many other applications with potential climate, environmental, and socioeconomic benefits. BECCS systems that produce other energy products—such as renewable natural gas (RNG) and hydrogen—or harness other forms of carbon storage—such as biochar—represent underexplored and underdeveloped decarbonization pathways. Increased interest in CDR by the research community has emphasized the importance of the carbon removal value of BECCS projects rather than solely their energy output. This, in part, has led to the development of the term biomass carbon removal and storage (BiCRS), which covers both energy and non-energy pathways for sequestering biogenic carbon.

IAMs include significant CDR from BECCS, but the achievable scale of deployment is highly uncertain. CDR is needed to reach net-zero goals, and BECCS has the potential to play a significant role in meeting those needs as one among other CDR pathways. BECCS deployment features prominently in modeling of global deep decarbonization pathways, but its presence in the modeling is best understood as a placeholder for a broad suite of CDR options. BECCS has an important niche among CDR options because of (1) greater permanence and more scaling potential than natural solutions and (2) lower cost and higher technological readiness than other technological solutions. Modeling studies project the need for massive global BECCS deployment, up to 8 $GtCO_2$/yr by 2050. However, the real-world deployment potential for BECCS may be constrained far below these estimates by limited by feedstock availability, access to CO_2 infrastructure and disposition options, and socioeconomic or environmental limitations.[56,57] Global projections for the emissions abatement potential of BECCS in 2050 range from 1.3 $GtCO_2$/yr to 15 $GtCO_2$/yr, or 3 percent to 31 percent of 2018 net GHG emissions.[58,59,60,61,62] BECCS can also help the United States move towards its climate goals, but the potential size of its contribution is unclear; various studies estimate that BECCS can reduce U.S. emissions in 2050 by 0.3 $GtCO_2$/yr to 2.2 $GtCO_2$/yr, the equivalent of 5 percent to 36 percent of 2018 GHG emissions.[63,64,65,66,67,68]

Emission reductions and environmental impacts of BECCS projects are project-specific, and not all BECCS projects are carbon-negative. The amount of carbon removed from the atmosphere over the life cycle of a BECCS project is highly circumstantial, depending on factors such as geography, land-use change, feedstock characteristics, energy conversion technology, and carbon capture approach. These circumstances can result in any given project having net-positive or net-negative GHG emissions. Additionally, the literature found both potential environmental benefits and drawbacks associated with BECCS projects related to its effects on land, water, air quality, energy consumption, biodiversity, and forest resilience. The precise impacts depend on the project circumstances, such as the environmental and social conditions of the location and the timeframe of the project.

Current GHG accounting rules are limited in fully capturing the systemwide changes in emissions and removals from BECCS. Establishing more robust GHG accounting rules would reduce risks and uncertainty for project developers seeking to secure carbon credits or incentives for BECCS projects and could promote investment in BECCS technologies. Developing such rules and identifying the full emissions impact of any process or product, however, is enormously complicated and requires making difficult decisions on scope and methodology. The nature of BECCS as a set of pathways encompassing multiple sectors makes these calculations even more complex.

The scientific and policy communities regularly highlight several specific issues related to GHG accounting for BECCS. First, GHG accounting rules are inconsistent as to whether and how specific sources of emissions are included when estimating the overall emissions impact of BECCS pathways. Second, a typical GHG accounting simplification—counting all bioenergy-related emissions in the land-use sector and assuming zero emissions at point of combustion—shifts the most important emissions measurement burden from the energy sector to the land-use sector where measurement, recording, and verification is far more complex and requires numerous contestable assumptions. The focus on land-use emissions is further complicated by the difficulty of determining the counterfactual use of that land. Third, system boundaries are typically drawn narrowly on the feedstock supply chain and disposition, though some authors recommend including induced effects in the broader economy. Lastly, whether the temporal distribution of emissions and removals is an important consideration when accounting for BECCS emissions remains in dispute.

The current U.S. BECCS industry is limited, but has potential for significant growth. While there are only five BECCS projects in operation in the United States today, the country has several characteristics that make it suitable for BECCS deployment including well-established relevant industries (e.g., biofuels, biopower, forestry, agriculture, wood pellet production, and pulp and paper), significant natural resources (e.g., biomass and geologic storage), and growing policy support (e.g., the newly extended 45Q tax credit and the Energy Act of 2020). The BECCS industry is still in its early stages of development and deployment because of costs; the lack of research, development, and demonstration (RD&D) funding; and the variability of its geographical application (i.e., regional variations in biomass availability, supply chains, regional demand for energy output, and CO_2 storage potential).

Abatement cost estimates range from $20/t$CO_2$ to $400/t$CO_2$, which vary depending on feedstocks, conversion and capture technologies, and system configurations. Globally, 16 pilot or demonstration-scale BECCS projects exist today; all but one of which capture less than 400 kt of CO_2 per year.

Expanded biomass supply chains and CO_2 infrastructure are needed to support a national BECCS industry; coordinating this infrastructure with other decarbonization pathways offers economies of scope and scale. A key challenge to growing a BECCS industry in the United States is that biomass supply, feedstock pre-processing facilities, bioenergy conversion facilities, and CO_2 storage locations are rarely co-located, requiring distinct infrastructure to transport specific feedstocks, energy products, and/or CO_2; co-location of BECCS projects with other decarbonization pathways could leverage shared CO_2 infrastructure and make those projects more economical. Part of the appeal of BECCS pathways is that they sit at the intersection of many different decarbonization solutions, such as forestry CDR, agricultural CDR, methane mitigation, waste reduction, CCUS, bioenergy, clean fuels, clean power, and hydrogen hubs. Because there are tradeoffs between developing economies of scale and creating local or regional BECCS supply chains, BECCS projects must be developed with careful consideration of local circumstances.

BECCS pathways present rural economic development opportunities. Today, more than a million people are employed in bioeconomy industries like forestry, pulp and paper, and bioenergy.[69] Increased demand for biomass feedstocks can stimulate rural economies and the entire supply chain for BECCS could create economic opportunities for communities living near forests or other feedstocks. BECCS projects could create a market for biomass that helps offset declining demand from traditional forest products industries. By creating an additional demand for wood for bioenergy pellets, BECCS could provide a boost to regions that have suffered economic losses and provide an opportunity to repurpose existing human capital in sectors like pulp and paper.

BECCS pathways face opposition; there is need for approaches to BECCS that address environmental justice (EJ) concerns. CCUS and CDR are often seen as “false solutions” to addressing climate change that could diminish society’s urgency for more benign opportunities for direct emissions reductions.[70,71,72,73,74] There are environmental concerns about the impact of BECCS projects on air, water, and noise pollution, as well as safety concerns about geologic storage. Previous studies have tended to focus on international EJ concerns, rather than on U.S.-specific issues. Multiple EJ issues need to be addressed, such as environmental impacts; disproportionate siting in vulnerable communities; and categorical opposition to technologies like bioenergy and CCUS.

Federal programs have focused on bioenergy and CCUS distinctly; there is opportunity in existing programs and policies to address BECCS directly. BECCS is beginning to appear more often in legislation, public policies, and federal programs, but these efforts are not commensurate with a scale-up to a gigaton-scale industry. Growing the BECCS industry enough to have a meaningful impact on U.S. emissions will require support and expertise from multiple agencies, making federal interagency collaboration paramount. There is both opportunity and precedent for such collaboration. For example, the Biomass Research and Development Initiative (BRDI) could be revitalized as part of federal BECCS efforts going forward. New interagency collaborations could be undertaken as well. There is also a need for bioenergy policy and CCUS policy to work in tandem, rather than in their current silos.

KEY ISSUES AND AREAS FOR FUTURE STUDY

The key findings from this literature review show that several economic, environmental, and social issues need to be addressed in order to deploy BECCS in the United States at the scale called for in most climate studies. After discussion with the study advisory board, EFI commissioned four papers to examine the following key issues in greater detail during the second phase of this study:

- The opportunities for BECCS to contribute to sustainable and resilient forests in the Western United States;[f]
- An evaluation of the socioeconomic and environmental justice impacts of the BECCS industry;
- GHG accounting issues and means of ensuring BECCS contributes to net-zero or net-negative emissions; and
- Sustainable sourcing of U.S. biomass feedstocks for BECCS projects.

These commissioned papers will inform an expert workshop that will culminate in a comprehensive final report exploring the opportunities, challenges, and policies needed to support the thoughtful deployment of BECCS in the United States—a deployment that will work to achieve national goals for climate, resiliency, sustainable agriculture, energy security, and rural economic development.

NAVIGATING THIS REPORT

This report is divided into three sections as follows:

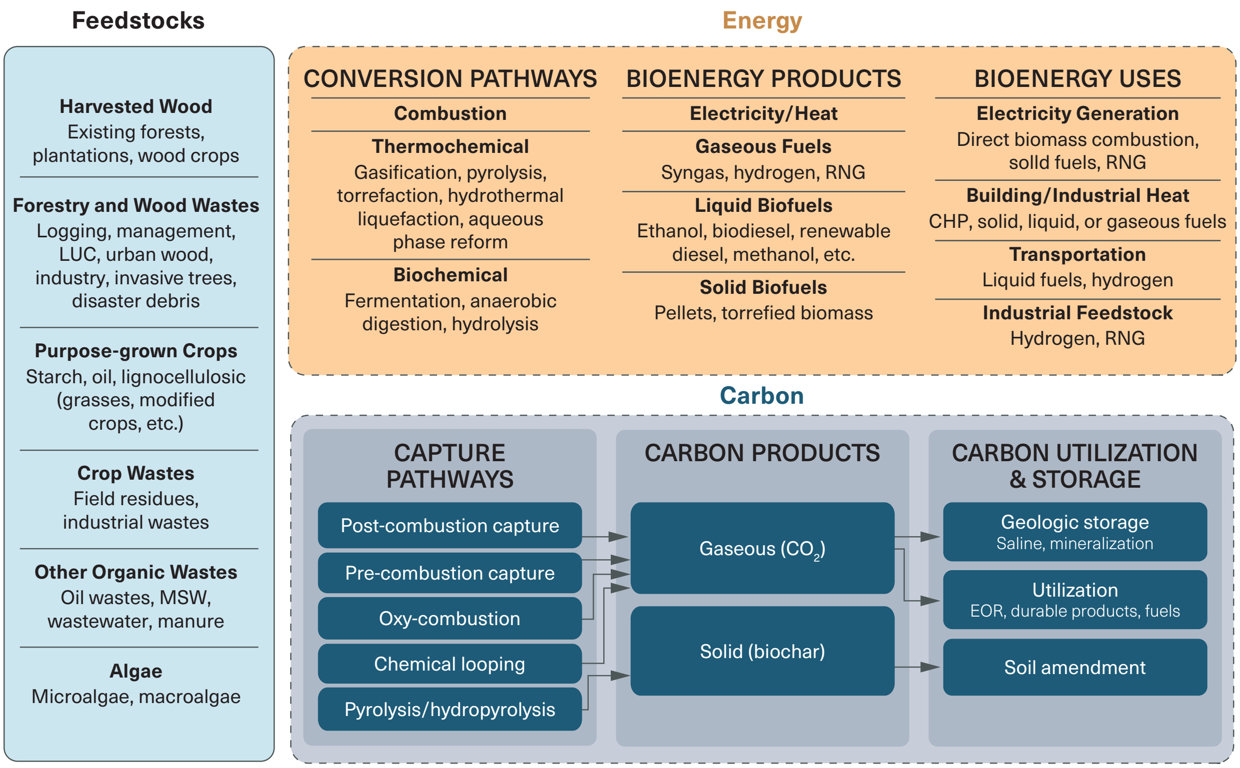
- **What is BECCS?**: a review of BECCS pathways, looking at the range of feedstocks, biomass-to-energy conversion options, bioenergy products and uses, and the options for CCUS as well as the potential benefits of BECCS through integration with other decarbonization options and technoeconomic comparison of a variety of BECCS pathways;
- **The U.S. BECCS industry landscape**: provides a comprehensive review of the industry landscape for the deployment of BECCS in the United States including existing industries relevant to future BECCS deployment, BECCS feedstock and decarbonization potential, existing BECCS projects, and federal policies and programs to support BECCS; and
- **Key issues identified in the literature**: discusses major issues identified from a systematic review of the literature. This includes GHG accounting methods for BECCS, supply chain challenges, RD&D gaps, environmental impacts and resource requirements, and socioeconomic and EJ considerations.

f The West is a region of particular interest both because of its high percentage of public forest ownership (compared to other regions, such as the Southeast) and its ongoing struggle with forest fires.

What is BECCS?

BECCS is not one single technology but a set of systems that share common features. Specific BECCS configurations can vary greatly, producing different types of energy from different feedstocks and storing or using carbon in different forms. Figure 6 shows the variety of potential BECCS feedstocks, conversion pathways, products, and uses. This section details various options for BECCS within these components, with a particular focus on current practices and potential future deployment in the United States.

Figure 6: Components of BECCS



BECCS encompasses several systems that include harvesting and converting biomass feedstocks into bioenergy products that can be used in multiple sectors as well as the capture, transport, use, or storage of CO_2 produced during the biomass conversion process. The combination of these components can result in a system with net-negative emissions. Abbreviations: LUC = land-use change, i.e., conversion of forests to non-forest land and wood/wood waste; RNG = renewable natural gas; MSW = municipal solid waste; EOR = enhanced oil recovery.

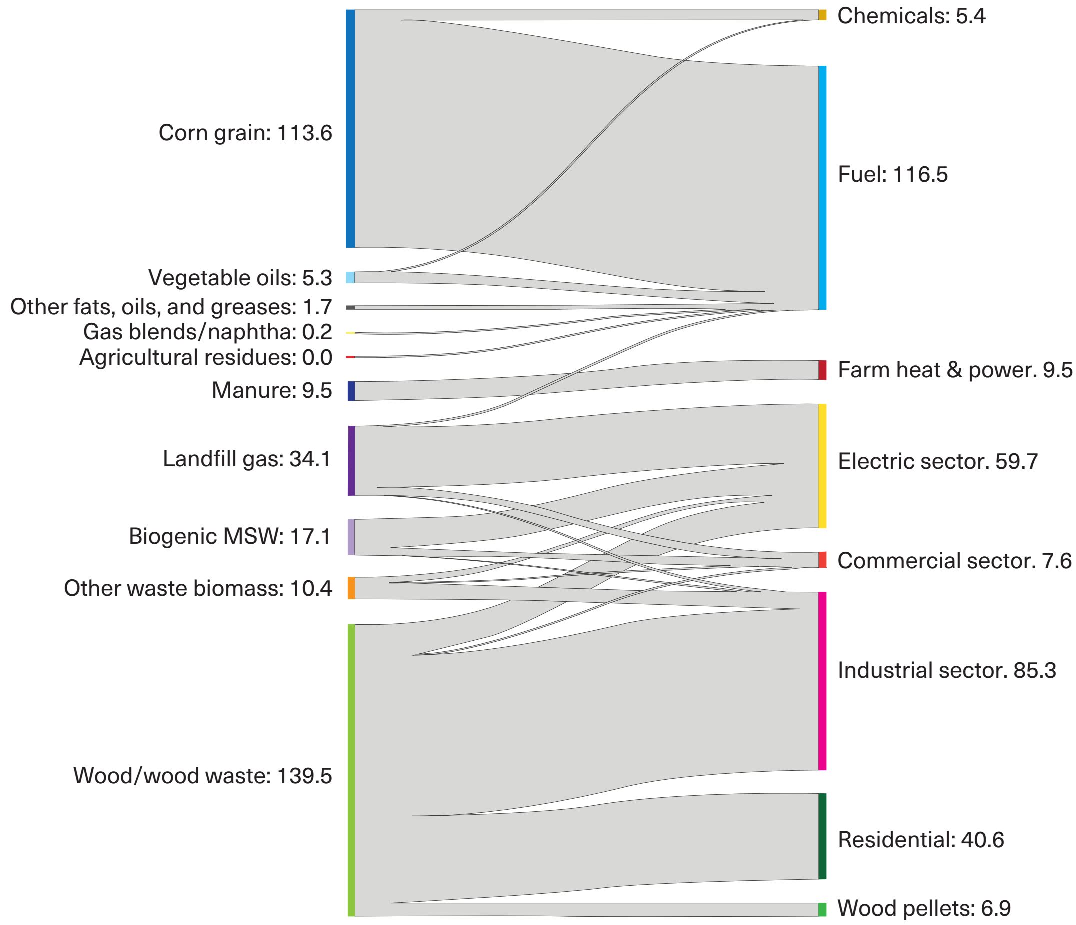
BIOMASS FEEDSTOCKS

Any form of biomass, paired with a viable conversion technology, can serve as the fuel source for BECCS. In this report, feedstocks have been grouped into six major categories:

- Harvested wood;
- Forestry waste and other wood wastes;
- Purpose-grown non-wood crops;
- Agricultural wastes;
- Other organic wastes; and
- Algae.

The vast majority of current bioenergy production and consumption occurs without carbon capture. Corn (mainly for ethanol) and wood/wood wastes (for thermal energy across multiple sectors) supply the majority of biomass in the United States (Figure 7).[75] They comprised 34 percent and 42 percent, respectively, of bioenergy feedstocks in 2014 (on an energy basis).

Figure 7: U.S. Sources and End Uses of Biomass in 2014[76]



The two largest current sources of bioenergy—corn for ethanol and wood and wood waste for heat and power—are also major candidate feedstocks for BECCS projects. Units are millions of bioenergy-equivalent dry metric tons. Source: DOE, 2016.

In general, the choice of biomass supply involves tradeoffs between "dedicated" feedstocks grown and harvested specifically for energy use and waste and "byproduct" resources (e.g., biogenic wastes from forestry, agriculture, industry, and municipal systems). While both dedicated and waste feedstocks are currently used for bioenergy, waste biomass may be the preferred feedstock for BECCS projects. Waste feedstocks tend to have lower production costs and do not require incremental land or resources. Harnessing of waste resources for energy can also have environmental and climate benefits.[77] Waste biomass costs and availability, however, are inherently limited by the quantities of waste produced and the dynamics of other markets.

Theoretically, purpose-grown or -harvested biomass has massive potential—for example, all food and fiber crops could be converted to crops for bioenergy, and all forests could be harvested for bioenergy use—but those scenarios are neither realistic nor desirable.[78] In fact, concerns about direct and indirect land-use change from dedicated feedstocks—and attendant food security, climate, environmental, and socioeconomic impacts—have limited their consideration in the BECCS literature (and may limit their future deployment).[79,80] Dedicated biomass could nonetheless be an important supplemental contributor to future BECCS feedstocks. Crops grown specifically for their energy value, for example, can improve security of supply, feedstock quality, and logistics costs (waste biomass collection is often more widely dispersed than dedicated feedstock and therefore is more expensive to collect and transport).[81,82]

Wood and Wood Wastes

In today's bioeconomy, energy is generated from wood combustion and used for heat (for industry and buildings) or for power generation.[83] The paper and wood products industries are the largest consumers of wood energy in the United States, accounting for 43 percent of consumption in 2014. Wood is one of the easiest feedstocks to collect, store, and transport; it can be converted into energy-dense and easily transportable forms (e.g., pellets) prior to combustion.[84] Wood can also be converted into fuels like ethanol or biochar, but these processes are less widespread.[85]

Most feedstocks for wood energy in the U.S. come from **wood wastes**, a large proportion of which are logging residues. These residues consist of less desirable wood that is harvested during logging for conventional timber markets that supply industries such as pulp and paper and wood products.[86] This less desirable wood—such as limbs, tops, and whole trees not suited to higher-value uses—is often repurposed for bioenergy.

Other sources of wood wastes include:

- Removals due to forest management (e.g., thinning) of both working and non-working forests;
- Removals due to conversion of forests to non-forest uses;
- Waste products from wood industries (e.g., sawdust, black liquor);
- Urban wood waste, including discarded durable goods (e.g., furniture) and construction debris;
- Invasive tree species; and
- Natural disaster debris.[87,88,89]

If not diverted for bioenergy or other profitable or convenient use, wood wastes in forests are often burned or left to decay, and urban wood waste is typically sent to landfill—all pathways that return GHGs to the atmosphere.[90,91] Using wood waste feedstocks is desirable because of their low production cost and small incremental environmental effects; the cost and environmental impact of clearing the trees would have been incurred even if these waste streams were not used as a feedstock. In addition, creating a market for these wastes can promote thinning to manage the density of forests, which can result in higher carbon uptake, less water demand, and less vulnerability to water stress, insect outbreaks, and wildfire.[92,93] High costs for collection and transportation, however, pose a challenge to increasing the use of wood waste.

A minority of current wood feedstocks come from what the DOE terms "whole-tree biomass:" **harvested wood** that comes from existing forests or plantations specifically for energy use.[94] DOE defines whole-tree biomass as harvests from stands where no wood is harvested for conventional timber, distinguishing it from logging residues and thinnings.[95] While the use of harvested wood is not common in the U.S. today, it could potentially be an important resource if BECCS deployment increases demand for wood. Another candidate feedstock source is the cultivation of trees that are fast-growing (e.g., poplar) or widely harvested already (e.g., pine) on agricultural land, rather than forestland.[96,97] These wood crops are sometimes categorized as "energy crops," grouped together with purpose-grown non-wood crops (see Box 1). The technical potential of harvested wood is vast, but it has potential downsides as a feedstock, including the loss of carbon-storage potential, detrimental effects on the local environment and ecology, and land-use concerns.[98,99] Wood wastes are much more commonly used for bioenergy production than whole-tree biomass today: high-quality logs are used for high-value products like building materials and are generally not an economic option as a bioenergy source.[100]

Agricultural Crops and Crop Wastes

Other biomass feedstocks come from **purpose-grown non-wood crops** (sometimes called "energy crops;" see Box 1). These non-wood (or "herbaceous") crops have a high total potential, but require land, water, and fertilizer, and must compete with other uses of agricultural land, especially the production of food and fiber. The most common use of crop biomass in the United States is for the production of liquid transportation fuels: ethanol from corn and biodiesel from soybeans.[101] Other starch crops (e.g., sugarcane, sorghum) or oil crops (e.g., sunflower, canola) can also be used to produce ethanol and biodiesel, respectively.[102] Other energy uses for these crops—such as combustion of vegetable oils, anaerobic digestion to produce biogas, or aqueous phase reforming of starch crops—are less common in the United States, and span a range of technological readiness levels.[103,104]

Another set of purpose-grown agricultural crops are lignocellulosic crops.[a] They are optimized for energy production rather than food production and include perennial grasses (e.g., switchgrass, miscanthus) and modified food crops (e.g., energy cane).[105] These crops avoid the negative impacts that food crops have on biodiversity, soil carbon, and water.[106] Many IAMs assume BECCS

a Wood is also a source of lignocellulosic biomass; wood as an energy crop is discussed under "harvested wood."

deployment will lean heavily on these crops.[107] Despite a concerted policy effort to commercialize a lignocellulosic bioenergy industry, these feedstocks are not widely deployed.[108] High-yield lignocellulosic crops like miscanthus can have positive or negative environmental impacts depending on how they are managed.[109]

Agricultural crop wastes can provide a feedstock for many of the same conversion processes as purpose-grown crops.[110] These wastes are sometimes combusted today for thermal energy.[111] They include field residues (the parts of crops left behind after harvesting, which are often burnt for disposal) and processing residues (from food production or other agricultural product industries). Like wood wastes, crop wastes represent a large, underutilized biomass resource with all the benefits and challenges listed above for waste biomass. In addition, removing residues from fields risks soil degradation because agricultural residues left in place can break down and fertilize soils.[112]

Other Biomass Feedstocks

Other organic wastes can provide feedstocks for specific bioenergy processes. Oil wastes, such as used cooking oil and animal fats, can be converted to biodiesel or renewable diesel—though there are not currently viable technologies to capture carbon from this process.[113] Municipal solid waste (MSW) is used today for energy generation. Thermal power is generated from incineration (known as waste-to-energy [WtE]) and landfill biogas can be captured and combusted or converted to RNG. The organic fraction of MSW—including food and yard waste—can also be separated out for bioenergy conversion.

Animal manure and municipal or industrial wastewater are additional sources of biogas, through the process of anaerobic digestion. These processes can have economic, environmental, and climate benefits—particularly the avoidance of methane emissions from landfills, wastewater systems, and manure—but they can also have negative impacts on local air quality.

A future bioeconomy could include **algae** feedstocks, both microalgae (phytoplankton) and macroalgae (seaweed). Algae are very efficient at photosynthesis and do not have the same land and water needs as terrestrial biomass.[114] Marine cultivation of algae can also remove carbon from the oceans—an important complement to atmospheric removal—while also reducing acidification, hypoxia, and surface warming.[115] Large-scale cultivation and processing of algae is not yet economically viable; RD&D of algae feedstocks may also have to contend with the unique technical, social, and political barriers to ocean experimentation.[116,117]

Figure 8 shows how available quantities of different biomass resources could change by 2040, including the emergence of next-generation feedstocks (see Box 1), such as algae and purpose-grown lignocellulosic crops.[118,119]

Box 1: Feedstock Terminology: Energy Crops and Biofuel Generations

The bioenergy and BECCS literatures use a variety of schema to categorize feedstocks. This report uses terms with greater definitional consensus while avoiding certain ambiguous terms.

One term used in the literature is "energy crops" (or "bioenergy crops"), which some sources define as any crop grown as a feedstock for energy (including food crops such as corn and soy).[120] Other sources, such as DOE's *2016 Billion-Ton Report: Advancing Domestic Resources for a Thriving Bioeconomy (BT16)* use the term to refer only to non-food crops, such as lignocellulosic crops.[121] Some sources, including *BT16*, also include trees grown as short-rotation crops within this category.[122] Because of this ambiguity, this report avoids the use of the term "energy crops;" the term appears only where a referenced source uses that categorization.

Another set of terms in the literature are "generations" of biofuels or biofuel feedstocks, which generally indicate different stages of technological readiness. These categorizations apply to liquid (and sometimes gaseous) fuels, rather than directly combusted feedstocks or solid fuels.[b]

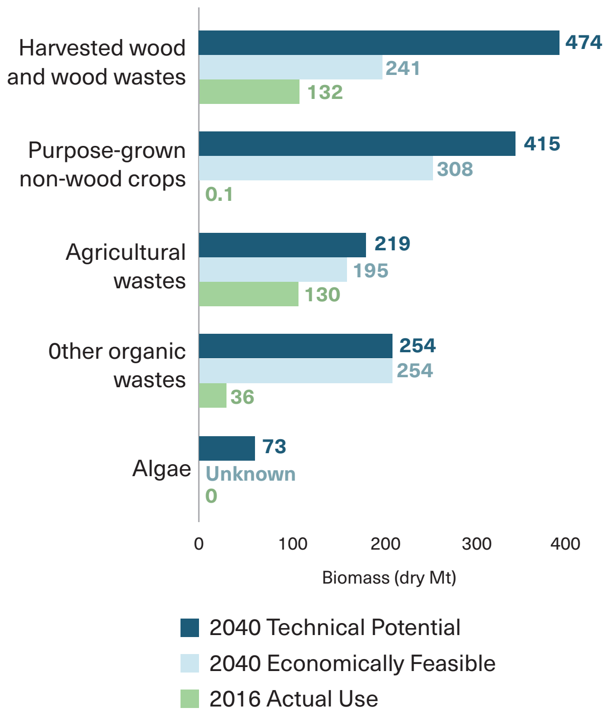
The U.S. Environmental Protection Agency (EPA) defines these categories as:

- First generation: biofuels derived from existing food sources, such as corn, sugar, soy, and animal fats (widely deployed today);
- Second generation: biofuels derived from lignocellulosic feedstocks, including wood, agricultural wastes, and herbaceous crops (commercially deployed but not yet widespread);
- Third generation: biofuels derived from algae (in early research and development [R&D]).[123]

Definitions of these generations vary and change over time; the second and third generations sometimes encompass a wider range of feedstocks.[124,125,126] Categorization is sometimes based on the conversion process or fuel produced rather than the feedstock alone.[127] Some sources have begun to refer to a fourth generation, which also lacks a consensus description. The categories "conventional" and "advanced" biofuels are sometimes used to refer to first-generation and second-generation or later fuels, respectively; federal law, however, considers all biofuels other than corn ethanol to be "advanced."[128,129,130]

b This is because some "second-generation" feedstocks for fuel production, such as wood and wood wastes, are already widely deployed in combustion applications.

Figure 8: Current and Future Annual U.S. Biomass Feedstock Production Estimates[131,132]



This graphic shows the annual technical and economically feasible potential of U.S. biomass production by feedstock in 2040 compared to actual biomass use in 2016. Roughly a million dry metric tons of biomass could be economically feasible for bioenergy use in 2040. Data from NASEM, 2018 and NASEM, 2019; estimates of technically feasible feedstock production levels were estimated using economically feasible production categories for harvested wood and wood wastes and purpose-grown non-wood crops.

BIOMASS-TO-ENERGY CONVERSION PATHWAYS

All BECCS pathways require a conversion process to turn biomass into useful energy. As with biomass feedstocks, these conversion technologies are at various stages of technological readiness. **Biochemical conversion** uses living microorganisms to convert biomass into other forms of fuel via processes like fermentation (e.g., for ethanol) or anaerobic digestion (e.g., for biogas). Some biochemical pathways are already well-understood and commercialized, whereas others (especially with new feedstocks) require further development. Currently, most BECCS facilities use biochemical conversion.[133]

Thermochemical conversion technologies—including gasification and pyrolysis—use controlled heating to decompose biomass into liquid, gaseous, and solid products. These technologies are at early stages of development.[134] Biomass can also be used for direct **combustion**; wood feedstocks may go through an intermediate step of mechanical or thermochemical conversion (e.g., densification, torrefaction) to make them more suitable for combustion. One such pre-process is pelleting, where woody biomass is converted into small pellets. Pelleting can improve combustion efficiency because conventional biomass has a relatively low energy density and high heterogeneity of inputs.[135]

BIOENERGY PRODUCTS AND USES

Bioenergy conversion can produce a variety of useful energy products such as power and heat. Biomass can be converted to liquid biofuels like ethanol that are mostly used for transportation, or gaseous fuels like hydrogen and RNG for industrial manufacturing and electricity generation. Biomass can also be processed to make non-fuel-based bioproducts. Figure 9 shows where bioenergy conversion facilities in the United States currently cluster, such as ethanol plants in the Midwest, pellet plants and industrial facilities using black liquor in the South, and WtE facilities around Northeastern population centers. A detailed description of the pathways to manufacture various bioproducts via BECCS can be found in Appendix A.

BECCS via combustion is primarily being explored to produce carbon-negative **electricity**, and it can also provide **heat** for industry or buildings. BECCS projects have been executed or planned at both power plants (using wood pellets and agricultural wastes) and WtE facilities (Box 2).

Box 2: Existing Applications of BECCS for Heat and Power

BECCS at Power Plants

Drax, an electric power generation company in the U.K., began pilot operations in 2018 for a first-of-a-kind project to capture carbon from a wood pellet-burning power plant. The company converted four of its six generating units from using coal to using biomass. Drax plans to install carbon capture equipment on two biomass units and become a carbon-negative company by 2030.[136] The first pilot began capturing 1 tCO_2/day in 2019, and the second pilot, installed in 2020, is expected to capture about 0.3 tCO_2/day. More recently, Drax announced an agreement with Mitsubishi Heavy Industries to build the world's largest carbon-capture project in power generation. With operations expected to begin as soon as 2027, Drax anticipates this BECCS facility will capture and store at least 8 million tCO_2/yr by 2030.[137]

The Mikawa Power Plant commenced its operation as Japan's first BECCS plant in 2020. The project involved retrofitting its power plant from burning coal to burning biomass in 2017. The project is expected to capture about 500 tCO_2/day generated from the combustion of biomass.[138]

BECCS at Waste-to-Energy Facilities

Currently, there are three[c] fully operational waste incineration plants with a carbon-capture system and utilization in the world—Saga City in Japan and the Twence and AVR plants in the Netherlands.[139] In Saga City, a municipal waste incineration plant captures 10 tCO_2/day and the captured CO_2 is used for local crop cultivation and algae cultures formation. Since 2019, AVR has captured CO_2 released from incineration of residual waste and has provided about 60,000 tCO_2/yr to greenhouse horticulture companies.[140] Twence has produced about 8,000 metric tons of baking soda (sodium bicarbonate) annually using the captured CO_2 from its incineration plants, which reduces annual emissions by 2,000 tCO_2 to 3,000 tCO_2.[141]

c Klemetsrud, the largest WtE plant in Norway, also launched carbon capture and storage program, but it is not fully operational as of October 2021.

Biomass can also be converted into **liquid biofuels**, which are primarily used today in transportation but could have future applications in industry and buildings. Ethanol and biodiesel are the most widely used biofuels today; several BECCS projects have already been built at ethanol refineries (usually using corn), including a large-scale plant in the United States (see Table 1).

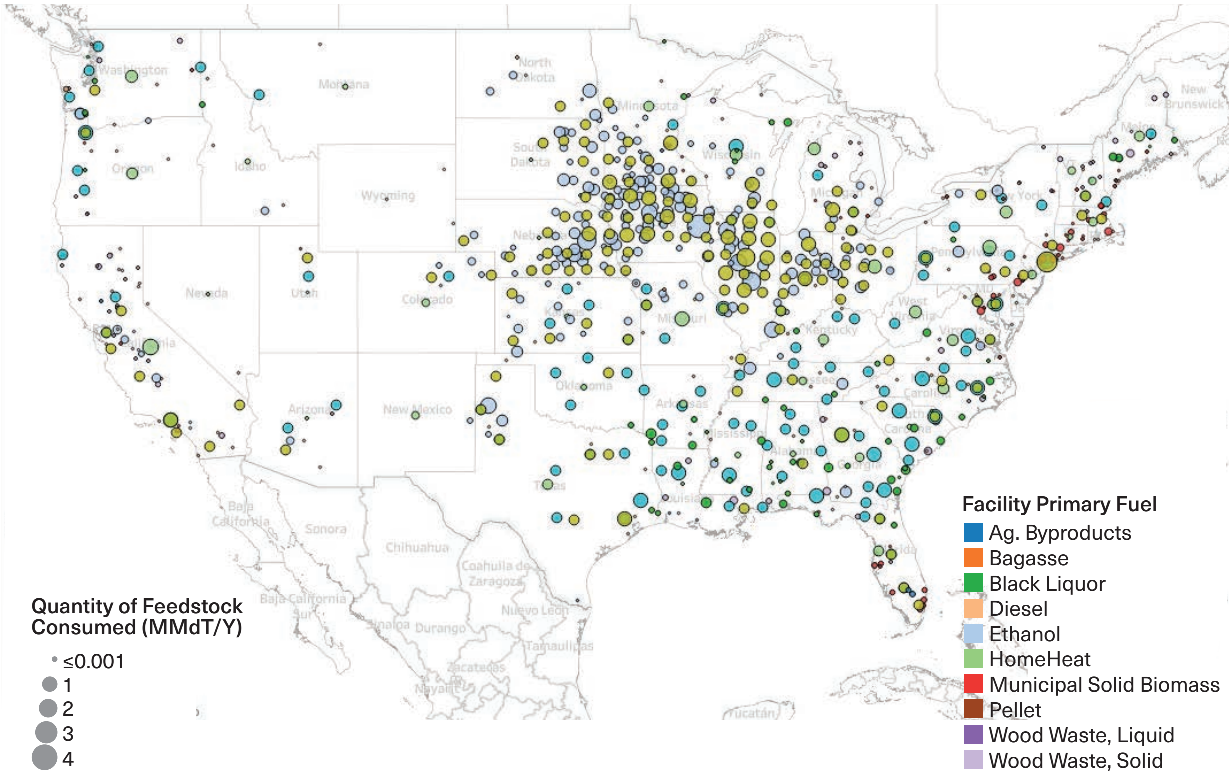
Other liquid biofuels are emerging, such as “drop-in” renewable diesel, gasoline, and aviation fuels. These fuels are produced through different conversion processes and could possibly be substituted for fossil fuels without the U.S. blend limits of current biofuels. Bio-oil, produced through pyrolysis, has multiple potential applications, including combustion, fueling engines and turbines, and upgrading to transportation fuels. “Conventional” biofuels like ethanol and biodiesel, due to their differing chemical properties and lower energy content by volume, are limited in their ability to replace fossil fuels. Most vehicles manufactured today can accommodate up to 15 percent ethanol (for gasoline vehicles) and 20 percent biodiesel (for diesel vehicles); gasoline is currently sold in the United States with no more than 10 percent ethanol and diesel with no more than 5 percent biodiesel.[142,143] Specialized vehicles and refueling infrastructure can accommodate higher blends but have limited deployment in the United States to date.

Gaseous fuels in the form of hydrogen and RNG are another important energy product. Hydrogen is a versatile energy carrier with potential uses across every energy-consuming sector. There are various conversion processes that could produce biomass-derived hydrogen, including gasification, liquid reforming, and microbial conversion.[144] Electricity produced through BECCS could also supply carbon-negative power to hydrogen production via electrolysis.[145] In addition to the general barriers facing hydrogen deployment, biomass-based production pathways face competition from fossil-derived pathways (currently the dominant mode of hydrogen production worldwide) and electrolysis—both of which have the potential for low-carbon configurations.

Apart from being used directly, biomass-derived hydrogen can also be used in methanation to produce RNG. RNG can also be produced by upgrading biogas that is produced from gasification, anaerobic digestion, or methane capture (e.g., from landfills). Like drop-in liquid fuels, RNG can be substituted directly into natural gas distribution systems. Both hydrogen and RNG are comparatively less mature than the use of biomass for electricity or liquid fuels, with limited deployment today.

Non-energy uses of biomass consist of bioproducts like plastics, industrial chemicals, lubricants, and fertilizers.[146] These industries can complement BECCS due to overlapping feedstock supply chains and carbon-capture opportunities. Some have argued that these uses (when combined with CCUS), as well as other long-lived products that can store carbon, should be grouped with BECCS into a broader CDR category of “biomass carbon removal” options.[147]

Figure 9: U.S. Bioenergy Facilities by Capacity, 2014[148]



Current bioenergy facilities are concentrated in regional clusters. The most common uses of bioenergy are corn to make ethanol and wood combusted for industrial thermal purposes or power. "HomeHeat" bubbles represent the quantity of bioenergy consumed in each state for home heating. The units are million dry short tons per year. Source: DOE, 2016.

CARBON CAPTURE

A variety of chemical and physical processes can be used to capture carbon from bioenergy processes. These pathways involve capturing the carbon in either gaseous form (as CO_2) or in solid carbon form (as biochar).

The most mature carbon capture technology is **post-combustion capture** of CO_2, in which CO_2 is chemically or physically separated from other flue gases after combustion.[149,150] Typically, post-combustion capture uses a liquid solvent (such as an amine) to remove CO_2 from other gases. Other approaches are being explored, though, including solid sorbents, membranes, cryogenic separation, and electrochemical separation.[151,152] Post-combustion capture can be applied to large-scale facilities that combust biomass or biofuels (e.g., RNG) for heat or power. Post-combustion capture technologies can also be used for other conversion processes that produce CO_2, such as fermentation. An advantage of post-combustion capture is that the capture technology can be retrofitted onto existing plants, decreasing capital costs and facilitating near-term deployment of CO_2 capture.[153]

There are other processes for capturing carbon as CO_2. **Pre-combustion capture** involves gasification, in which the biomass or fuel undergoes a chemical or thermochemical process that produces "syngas" composed of hydrogen and carbon monoxide (CO).[154] CO can then be converted to CO_2 via the water-gas shift reaction, and then removed with a solvent as in post-combustion capture. The **oxy-combustion** (combustion in a nearly pure oxygen environment) and **chemical looping** processes both produce a flue gas stream mostly composed of CO_2 and water; removing the water (dehydration) results in pure CO_2.[155,156]

Capture of carbon in solid form involves combusting biomass in the absence of air (pyrolysis) or in the presence of hydrogen (hydropyrolysis). This process can be used to produce gaseous or (primarily) liquid biofuels, but also results in the production of biomass-derived charcoal, known as **biochar**.[157] Biochar is itself a useful energy product, but can also serve as a form of carbon storage when applied to agricultural soils.[158]

CARBON UTILIZATION AND STORAGE

After capture, carbon requires a disposition pathway. It can either be stored, such as via geologic sequestration of CO_2, or put to productive economic use (utilization).

Biochar Utilization

While biochar can be burned or gasified for energy, its value as a carbon capture medium is primarily in its ability to be used as a soil amendment.[159] There is already a small commercial market for biochar in the United States, most of which is used for agricultural purposes.[160] Carbon stored as biochar can remain in the ground for centuries. Biochar is also being pursued as a CDR pathway independent of BECCS because it improves soil fertility and crop productivity, increasing natural carbon uptake and storage by plants and soils.[161] Biochar has other potential economic, environmental, and climate benefits, including decreasing nitrous oxide and methane emissions from soils, reducing fertilizer requirements, improving moisture retention, increasing soil microbes, and reclaiming degraded soils.[162]

CO_2 Utilization

Captured CO_2 also has a variety of utilization options. The most widespread utilization method today is EOR. CO_2 captured from fossil fuel power plants or ethanol production plants is transported to oil fields and injected into wells to extract more oil. Some existing BECCS plants already use their CO_2 for EOR, or for other options that utilize CO_2 directly such as greenhouse agriculture and food and beverage production. CO_2 can also be converted through chemical, biochemical, or geochemical processes into long-lived products like concrete or polymers. Additionally, CO_2 can be “recycled” into chemicals and fuels, replacing more carbon-intensive production processes.

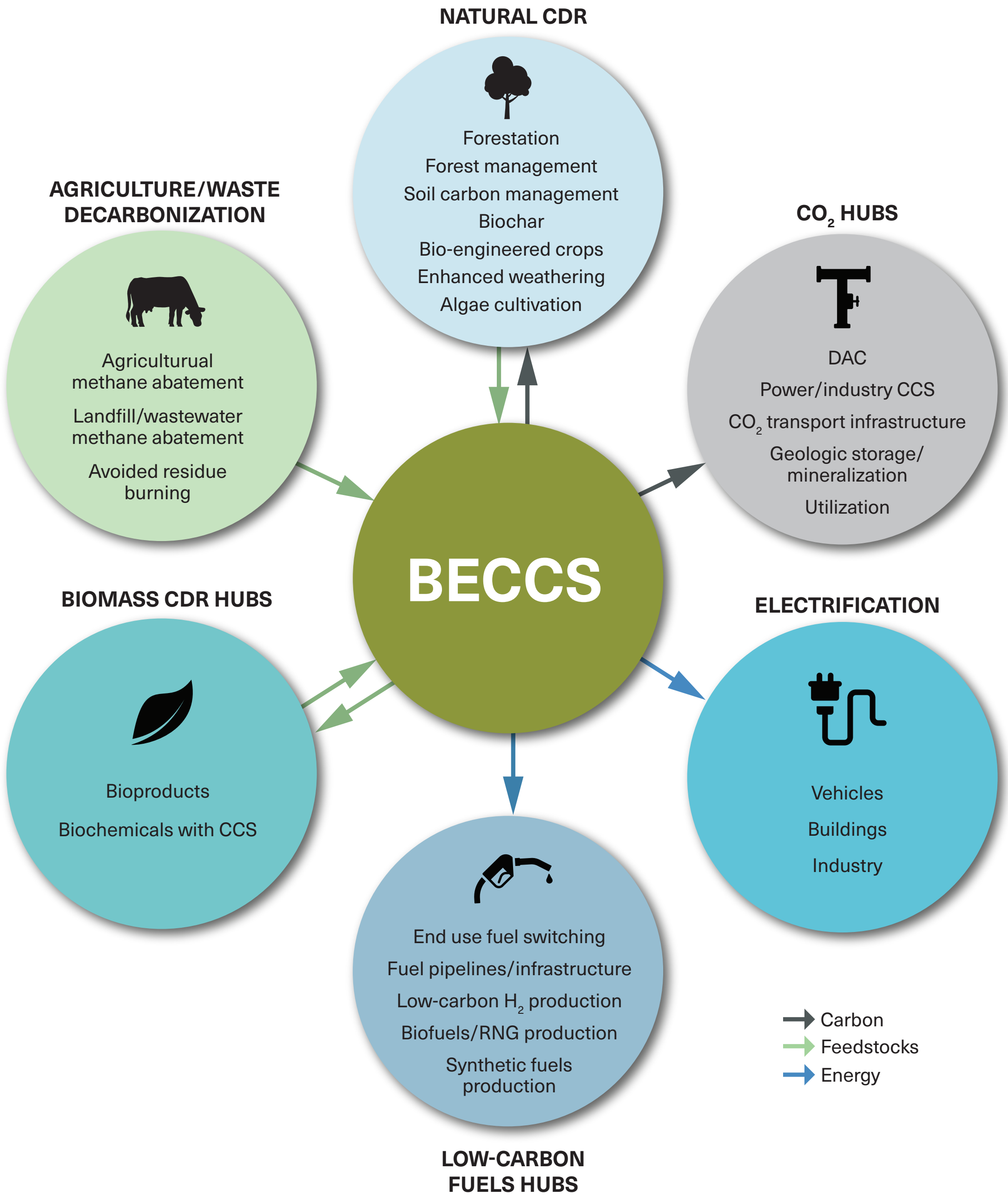
Geologic CO_2 Storage

CO_2 from BECCS can be stored in deep geologic formations that retain CO_2 for thousands of years.[163] After CO_2 is captured, it must be compressed and either injected on-site or transported to an area with suitable geology. CO_2 transportation can occur via pipeline, ship, rail, or on-road trucks. CO_2—in a fluid (supercritical) state—can be permanently stored in geologic formations that possess two characteristics: a thick reservoir that is both porous and permeable to handle large volumes and injections, and a cap with high breakthrough pressure and low permeability to maximize retention.[164] Examples of suitable geology include saline aquifers and depleted oil and gas reservoirs. CO_2 can also be stored in reactive mineral formations, such as basalt or peridotite. This form of sequestration relies more on mineralization than physical trapping and can use either CO_2 in a supercritical state or dissolved in water.

INTEGRATION WITH OTHER DECARBONIZATION OPTIONS

In addition to its primary benefits—CDR and low-carbon energy—BECCS can also contribute to economywide decarbonization through integration with other climate mitigation strategies (Figure 10). One potential strategy is co-location with other carbon-capture sources (e.g., point-source capture, hydrogen production, DAC), utilization, and storage to form CO_2 management hubs.[165] These hubs leverage shared infrastructure, benefit from risk and cost sharing, and can be facilitated by public-private partnerships. The hubs concept could also be extended to biofuel products of BECCS, such as hydrogen, which could be produced alongside other clean fuel production facilities. BECCS-to-power configurations can also benefit broader decarbonization efforts, providing reliable power available upon demand that could enable deployment of variable renewable generation and electrification of energy end uses. Policymakers and project developers, however, should ensure that co-location of BECCS with other low-carbon energy facilities (or of multiple BECCS projects) does not contribute to the overburdening of communities or disadvantaged groups that face disproportionate amounts of pollution or competition for land use.

Figure 10: From Farms and Forests to Factories: Integrating BECCS with Other Decarbonization Pathways



BECCS sits at the intersection of many decarbonization strategies, including natural carbon solutions, methane abatement, CCUS, low-carbon power, and low-carbon fuels (such as hydrogen). This figure shows how both BECCS feedstock collection and BECCS energy conversion facilities can be integrated with these other strategies. Strategies and policies for BECCS scale-up can maximize these synergies.

BECCS can also be integrated with other CDR pathways or natural climate solutions, such as conservation, restoration, and improved land management actions that increase carbon storage or avoid GHG emissions. Some CDR strategies—such as reforestation, forest management, biochar application, and algae cultivation—could themselves be integral parts of BECCS systems, either on the feedstock end or the carbon-storage end. Others—such as agricultural soil management, enhanced weathering in soils, and bioengineering of crops and trees for carbon removal—could further improve the life cycle negative emissions of BECCS projects and provide other co-benefits. For example, enhanced weathering stabilizes and increases soil pH and the pool of soil nutrients. Along with biochar, it also enhances nutrient retention and optimizes soil hydrology. These effects enable and improve biomass growth.[166,167]

BECCS also contributes to decarbonization through avoiding emissions. Energy produced from BECCS projects can substitute for fossil fuel energy, avoiding emissions from both their use and production. Using waste biomass or biogas can avoid waste emissions—e.g., methane from livestock manure, MSW, and wastewater; CO_2 from burning of agricultural and forestry residues—that would otherwise be emitted to the atmosphere. BECCS could also help avoid land-use change emissions by providing an economic incentive to maintain forests and grasslands, rather than converting them to other uses.

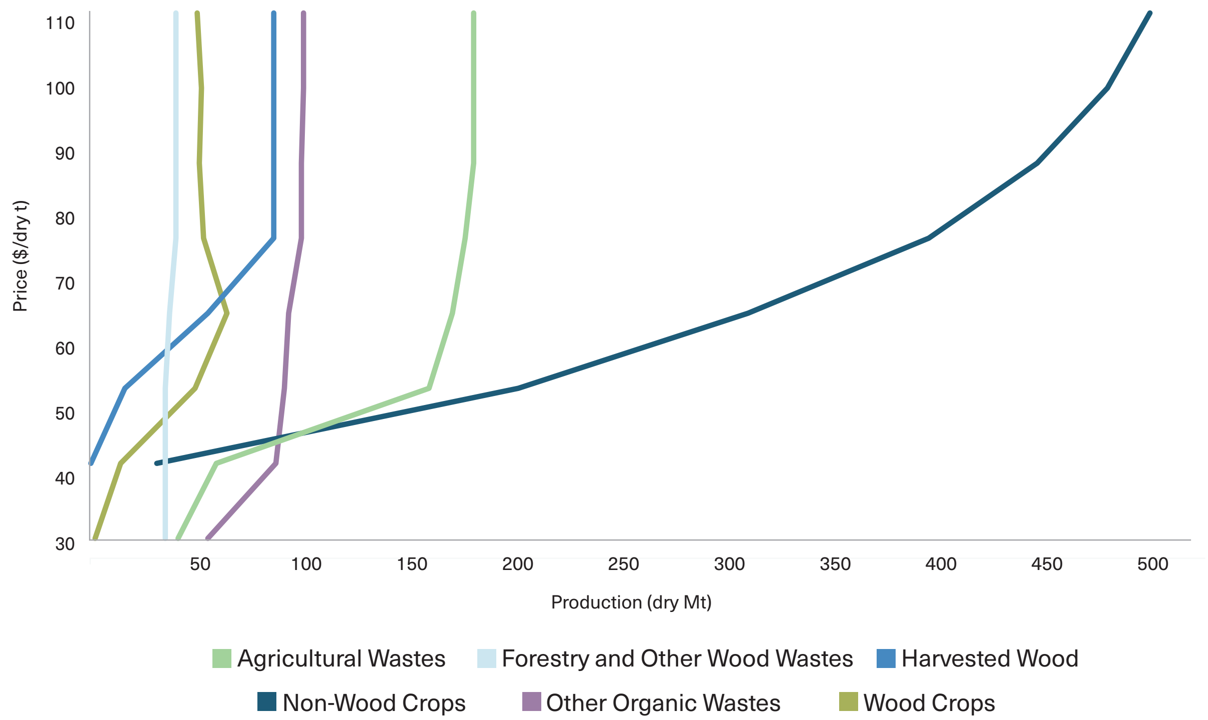
TECHNOECONOMIC COMPARISONS OF DISTINCT BIOMASS AND CARBON CAPTURE PATHWAYS

High costs are a major impediment for CDR technologies like BECCS.[168] BECCS technologies encompass multiple systems, each at different stages of technological readiness. The cost of a BECCS project will vary by feedstock, conversion method, capture technology, and byproduct.

Economics of Biomass Sources

Biomass feedstock prices in the United States vary by feedstock type, as shown in Figure 11.[169] Within each category of feedstocks, prices vary by individual biomass sources. Prices also depend on the quantity of feedstock needed.[170] At low feedstock quantities, prices could be lower because cheaper biomass sources could be used first; at high feedstock quantities, prices could be higher because more expensive biomass sources would be used. Agricultural wastes, forestry and other wood wastes, and other organic wastes could meet near-term small-scale BECCS demand cost-effectively at a price of under $44/dry metric ton of biomass.[171] At higher price points, however, other resources might be competitive with waste feedstocks, including harvested wood, woody crops like poplar, and herbaceous crops like switchgrass. BECCS could also grow to a point where waste biomass alone cannot meet demand, requiring the production of these other dedicated feedstocks.

Figure 11: Price of Biomass Feedstocks at Different Levels of Feedstock Production[172,173]

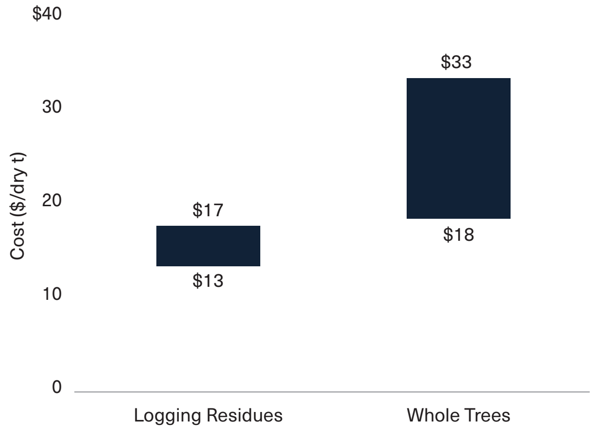


Prices of biomass feedstock generally increase with feedstock quantity because the cheapest biomasses are used up first. In the near term, when low levels of biomass feedstock are required, wastes can meet the feedstock demand for BECCS. In the longer term, BECCS may necessitate production of purpose-grown, non-wood crops like miscanthus and switchgrass. These non-wood crops could replace wood crops at higher prices, resulting in lower production levels for wood crops as prices exceed $65/dry metric ton. Source: DOE, 2016.

Biomass Harvesting, Transportation, and Pre-processing

Harvesting costs vary by biomass type and harvesting style. Generally, it is more economical to collect forestry wastes, such as logging residues that are left behind after commercial timber has been harvested, than to harvest whole trees.[174] Figure 12 shows that harvesting logging residues costs between $13/dry metric ton and $17/dry metric ton while harvesting whole trees costs between $18/dry metric ton and $33/dry metric ton.[175] Clear-cut logging—when all trees are removed—is less expensive than forest thinning—where trees are partially cut.[176]

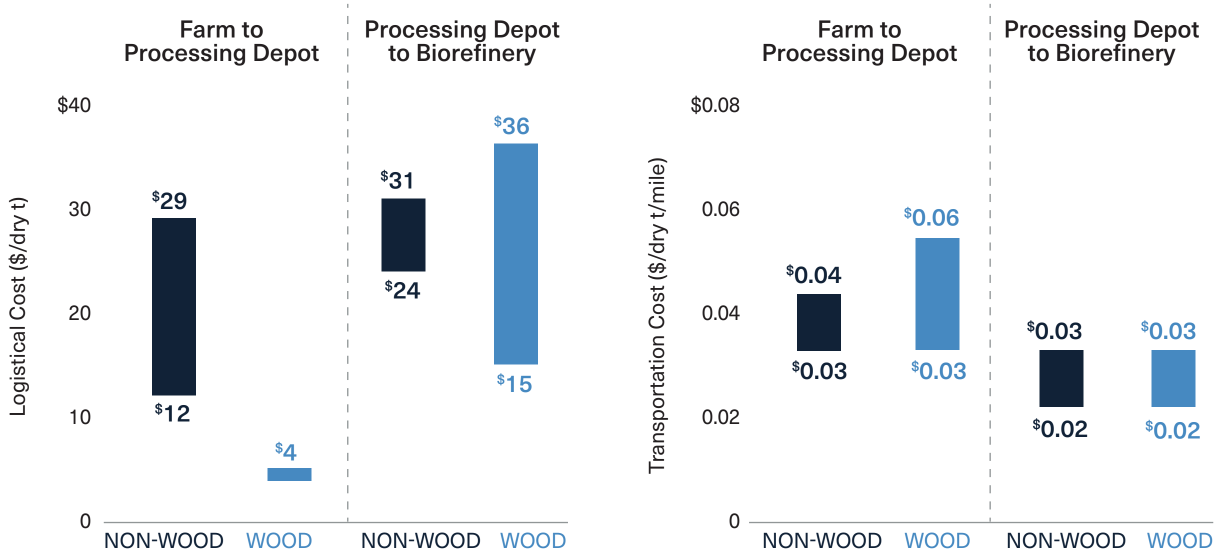
Figure 12: Harvesting Costs of Biomass Wood[177]



Logging residues left after commercial timber collection can be harvested at lower cost than whole tree biomass. The lower-bound estimates reflect the costs of harvesting after clear-cut logging; the upper-bound estimates reflect harvesting costs after thinning. Source: Data from DOE, 2016.

Agricultural feedstocks are typically harvested, collected, and stored at the farm before being transported (usually by truck) to a depot for pre-processing.[178] After grinding, drying, and densifying, the feedstocks are transported to a conversion facility.[179] Logistical costs, including storage, loading, unloading, handling, and pre-processing costs, and transportation costs, which represent the costs of moving a dry metric ton of biomass a certain distance (from one facility to another), differ by the type of feedstock—non-wood or wood—and by individual feedstock type (Figure 13) .[180] Wood crops, in their unprocessed form, usually have lower logistical costs than non-wood crops. Coppice and non-coppice wood crops have lower and higher pre-processing costs, respectively, when compared to non-wood crops.

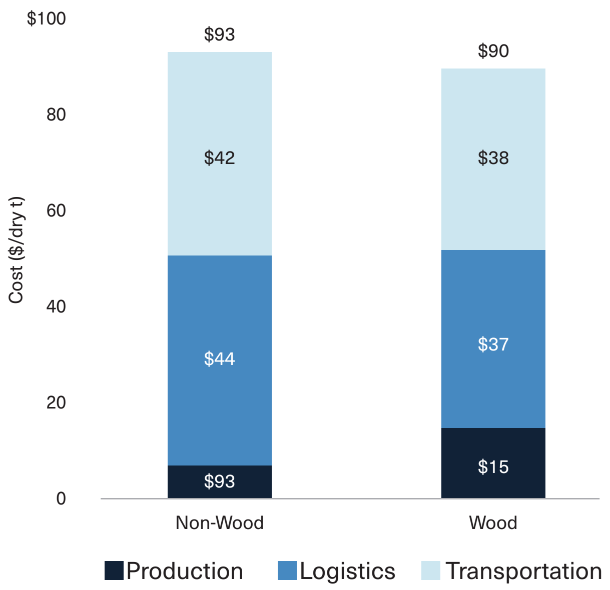
Figure 13: Logistical and Transportation Costs for Non-Wood and Wood Feedstocks[181]



Non-wood feedstocks comprise purpose-grown non-wood crops like miscanthus; wood feedstocks consist of harvested wood like poplar. Logistical costs, i.e., costs related to storage, loading, unloading, handling, and pre-processing, of non-wood and wood feedstocks vary by individual feedstocks; logistical costs for wood feedstocks could be lower or higher than those for non-wood feedstocks. Transportation costs depend on both distance and mass. Wood feedstock transportation costs could be greater than or equal to those for non-wood feedstocks. Upper and lower bounds of transportation costs reflect loaded and empty trucks respectively. Source: Data from DOE, 2016.

Delivered costs of feedstocks include various harvesting, pre-processing, and transportation costs. Figure 14 shows the weighted average of delivered costs of non-wood and wood agricultural feedstocks, including the proportions comprised by production, logistics, and transportation costs. While wood feedstocks have higher average transportation costs than non-wood feedstocks, non-wood feedstocks have higher delivered costs.

Figure 14: Average Delivered Costs of Non-Wood and Wood Feedstocks[182]

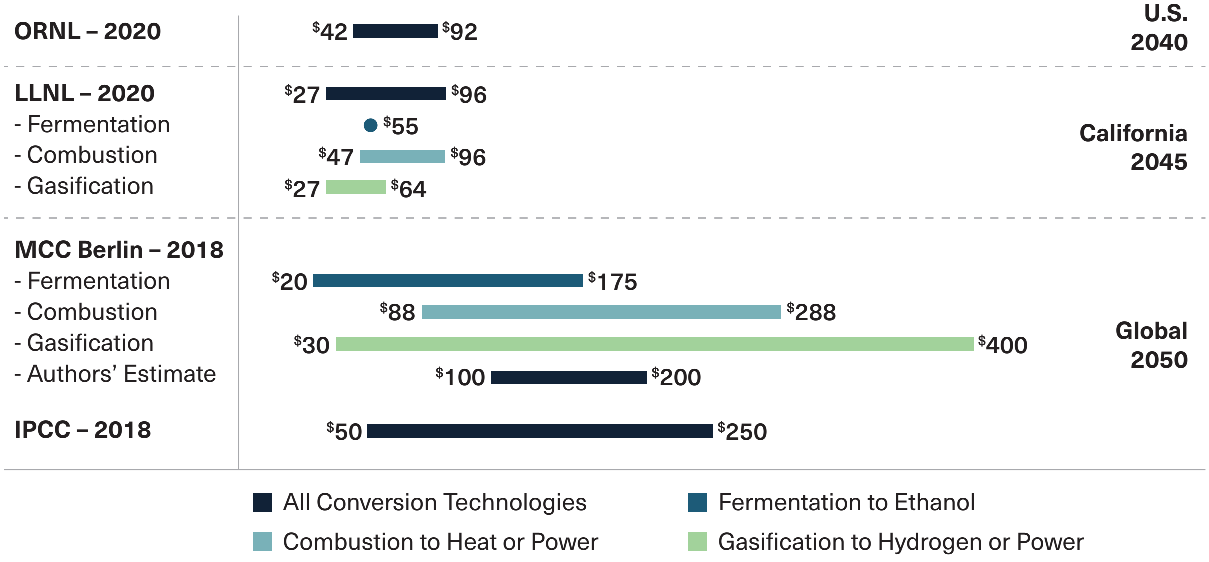


Both wood and non-wood feedstocks can cost upwards of $90 per dry metric ton. Production and logistical costs of non-wood feedstocks can be higher than those of wood feedstocks, but transportation costs can be higher for woody feedstocks. Source: Data from DOE, 2016.

Biomass Conversion Technology Costs

Cost estimates of biomass conversion depend on the technology and processes used to convert the energy in biomass into more usable forms. These forms include fermentation, gasification, and combustion, as shown in Figure 15. Fermenting biomass to produce ethanol with carbon capture could cost around $55/t$CO_2$ in California, while the cost of biomass gasification in the state ranges from $27/t$CO_2$ to $64/t$CO_2$.[183,184] Combustion-based BECCS costs slightly more than fermentation or gasification—$47/t$CO_2$ to $96/t$CO_2$ in California and $42/t$CO_2$ to $92/t$CO_2$ in the United States.[185,186] Fermentation costs are lower than the upper-bound estimates for combustion or gasification because the CO_2 concentration in fermentation is much higher than in the latter two conversion methods.[187]

Figure 15: BECCS Pathway CO_2 Abatement Cost Estimates ($/$tCO_2$)[188,189,190,191]



Cost estimates for BECCS projects range from $20/$tCO_2$ to $400/$tCO_2$ removed. These estimates vary widely across literature and differ by geographic scope, time, and technology. Costs for most BECCS projects in the United States are expected to be less than $100/$tCO_2$ by 2040. Source: Data from Langholtz et al., 2020 (ORNL), Baker et al., 2020 (LLNL), Fuss et al., 2018 (Mercator Research Institute on Global Commons and Climate Change, Berlin [MCC Berlin]), and IPCC, 2018.

Carbon Capture and Compression Costs

The cost of capturing carbon depends on the concentration of carbon in the flue stream. Many sources anticipate carbon capture costs for BECCS projects to be on par with or less than those for fossil fuel generation sources.[192] Ethanol production via biomass fermentation emits a higher concentration of CO_2 (~100 percent) and is less costly (e.g., $30/$tCO_2$ in California) than fossil fuel sources like coal- and gas-fired plants.[193] Capturing CO_2 from U.S. coal-fired power plants is estimated to cost between $52/$tCO_2$ to $60/$tCO_2$.[194] Capture costs for wood-based power generation and coal-fired generation are expected to be similar because some biomass plants are co-fired with or converted from coal; at least one study uses coal power plant capture costs as a proxy in a BECCS cost analysis.[195,196]

There are also costs incurred in installing carbon capture and related infrastructure. One study estimated that adding carbon capture to a bioenergy plant could double the facility's capital costs.[197] Captured CO_2 must also be compressed for transportation; the cost to capture and compress CO_2 at currently operating biorefinery plants is estimated to be between $25/$tCO_2$ and $32/$tCO_2$.[198]

CO_2 Transport and Storage Costs

The cost of CO_2 transport and storage varies depending on a number of local factors, including the quantity of CO_2 transported and stored, the transport distance, the geological characteristics and location of storage site, the rate of injection, monitoring assumptions, and the regulatory landscape.[199,200] The IPCC Fifth Assessment Report estimated CO_2 transport and storage costs to be in the range of $10/t$CO_2$ on average across the globe; more recent IAMs suggest that onshore pipeline transport and storage costs globally could vary from $4/t$CO_2$ to $45/t$CO_2$.[201] One analysis of the European market found that CO_2 storage costs were similar for storage in saline aquifers and depleted oil and gas fields, while costs were higher for offshore sites than for onshore sites.[202] Previous EFI analysis of key U.S. regions estimated the net cost for CO_2 infrastructure—including capture, transportation, and storage costs as well as the cost offset by the 45Q tax credit—to be $1.15/t$CO_2$ in the Gulf of Mexico, $7.19/t$CO_2$ in Wyoming, $7.26/t$CO_2$ in the Ohio River Valley, and $3.61/t$CO_2$ in California.[203,204]

U.S. BECCS Industry Landscape

The U.S. BECCS industry today is nascent, with only five projects in operation. Decarbonization analyses, however, project a substantial role for BECCS in achieving net-zero goals. The United States is well-positioned to spearhead BECCS deployment due to established industries including biofuels, forestry, agriculture, and pulp and paper. BECCS can also rejuvenate local economies by creating new jobs and generating additional revenue. All these factors are important foundations upon which the BECCS industry can grow.

EXISTING INDUSTRIES RELEVANT TO FUTURE BECCS DEPLOYMENT

The presence of several relevant industries in the United States could support the deployment of BECCS. The United States already has a robust bioenergy industry, producing both biofuels for transportation and biopower for heat and electricity.[205] In nearly all cases today, these industries produce energy products from bio-based feedstocks without capturing the associated emissions. Well-established forestry industries could provide feedstocks (e.g., waste streams), infrastructure (e.g., logging equipment), workforce expertise, and other components of supply chains to underpin a BECCS industry.

Biofuels

The United States has an established biofuel production and distribution industry and is the largest producer and exporter of ethanol in the world.[206] The biofuels industry directly employs 100,000 people across the country.[207]

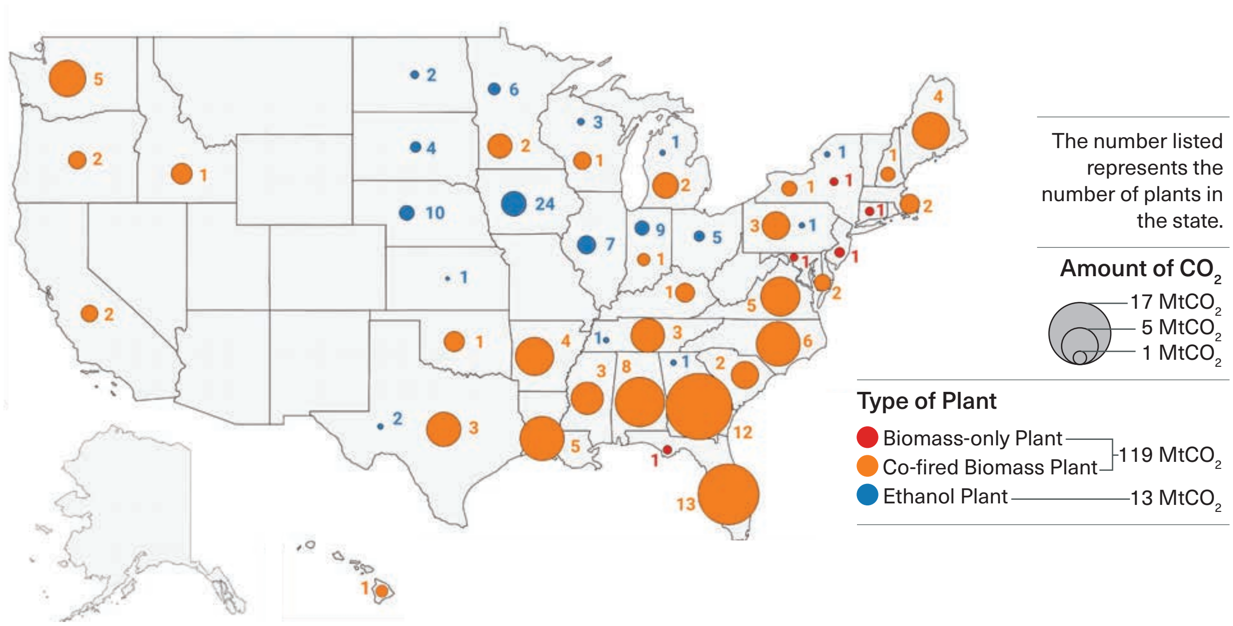
There is a potential opportunity to incorporate CCUS into biofuels production because the CO_2 generated during biofuels production has high purity and can be captured at relatively lower costs.[208] Biofuels like ethanol, produced using BECCS processes, are similar to conventional petroleum fuels and can be transported via established shipping infrastructure like oil tankers.[209] Trade of ethanol today, however, is limited to a relatively small number of partners, which currently limits the number of ports and shipping routes available to ethanol produced via BECCS processes.

Biomass Power Plants

The United States has generated electricity from biomass for over a century.[210] Due to relatively low energy density, high costs, and policy uncertainty, biopower has struggled to compete with other forms of electricity generation in recent years. Consequently, only 1.4 percent of all electricity generated in 2020 came from biomass.[211]

There were 787 biomass power plants[a] in the United States in 2019.[212] Existing plants can be retrofitted with—and new plants can be built with—carbon-capture technologies. Carbon-free electricity produced via biopower-based BECCS can be transmitted via the existing electrical grid. Biofuel and biomass power plants emitting more than 100,000 $MtCO_2$ and 500,000 $MtCO_2$ respectively are eligible for the Section 45Q Carbon Oxide Sequestration tax credit[b] if they capture CO_2 emissions (Figure 16). This eligibility includes power plants that co-fire a combination of biomass and fossil fuels.

Figure 16: Ethanol and Biopower Plants in the United States Eligible for 45Q Credits, 2019[213,214]



Power plants and ethanol plants that emit more than 500 $ktCO_2$/year and 100 $ktCO_2$/year respectively are eligible for the 45Q tax credit. Smaller plants would also be eligible if they utilize CO_2 rather than store it geologically. As of 2019, there were 78 ethanol and 101 biopower plants eligible for 45Q tax credits in the United States. Most ethanol plants are in the Midwest; most biopower plants are in the Southeast. Co-fired biopower plants burn a combination of biomass and fossil fuels. Total annual CO_2 emissions from eligible plants in 2019 were 119 $MtCO_2$ from biopower plants (98 $MtCO_2$ from biomass and 22 $MtCO_2$ from fossil fuels) and 13 $MtCO_2$ of biogenic emissions from ethanol plants. Source: Data from EPA FLIGHT, 2021 and eGRID, 2021.

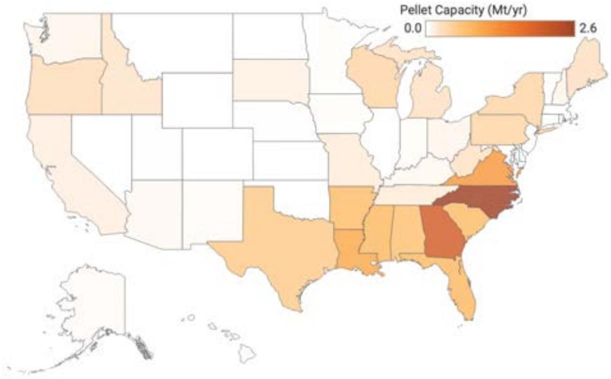
a Only 663 biomass plants were operated to generate energy (heat or power) in 2019.

b Originally established in 2008, the Section 45Q tax credit in the U.S. Internal Revenue Code is a tax incentive for dedicated geological CO_2 storage, CO_2 for EOR, and CO_2 utilization. The credit provides incentives for storage or utilization of any carbon oxides. CO_2 is the most common such compound, but others (like carbon monoxide) are possible, if not likely in practice.

Pellet Industry

The United States has an established pelleting industry (Figure 17), with about 37 percent of those wood pellets being burned for domestic energy consumption.[215,216] Pellets can be used for cooking and for space and water heating in the residential and industrial sectors.[217] The majority of wood pellet production facilities—predominantly in the Southeast—supply feedstock to biomass projects in Europe.[218] Enviva, the world's largest producer of industrial wood pellets, owns and operates many such plants. The largest user of Enviva's pellets is the Drax Power Station in the U.K. (Box 2). Due to the U.K.'s favorable policy environment toward bioenergy, U.S. wood pellet exports grew sevenfold between 2012 and 2017.[219]

Figure 17: Pellet Mill Capacity in the United States[220]



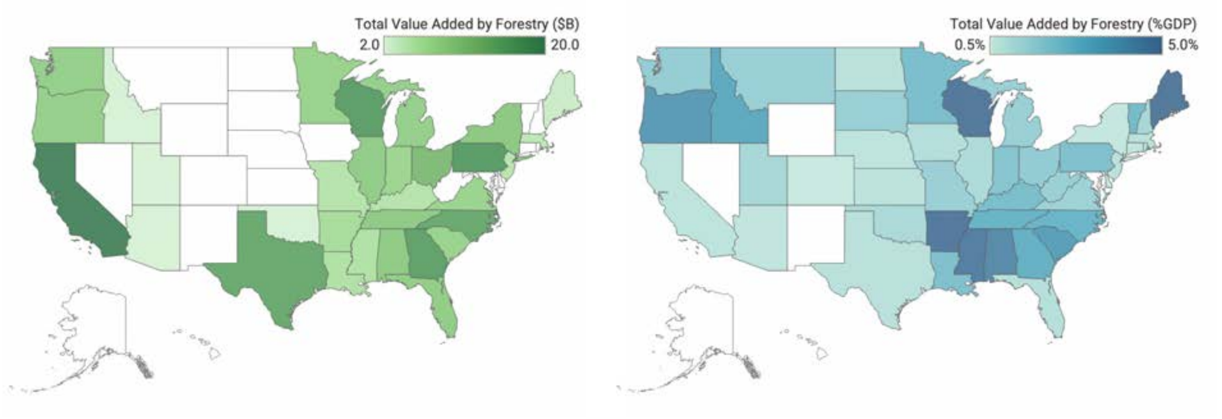
Pellets are a popular source of energy, used for firewood and to power water heaters, ovens, and industrial and residential heating. There are 122 wood pellet mills in the United States spread across 36 states. Pellet mill capacity is greatest in the Southeast, with the Northwestern Forests, Mid-Atlantic, and the Great Lakes regions also contributing significant capacity. Source: Data from the Biomass Magazine website.

Other Forestry Industries

Apart from the established bioenergy industry, other biomass-based forestry industries, including logging, paper and pulp, and wood products, can play a role in the growth of BECCS in the United States.[c] Forestry industries directly employ more than one million people and add more than $100 billion to the U.S. gross domestic product (GDP); including indirect economic impacts, forestry contributes a total of four million jobs and $400 billion to the economy (Figure 18).[221,222] Forestry industries contribute to every state's economy, but the Southeastern states, Wisconsin, Maine, and Oregon are most dependent on forestry.[223]

c Forestry industry sectors include forest products like timber; commercial logging; sawmills; plywood, wood furniture, and other wood product manufacturing; paper, paperboard, and pulp mills; and sanitary paper products.

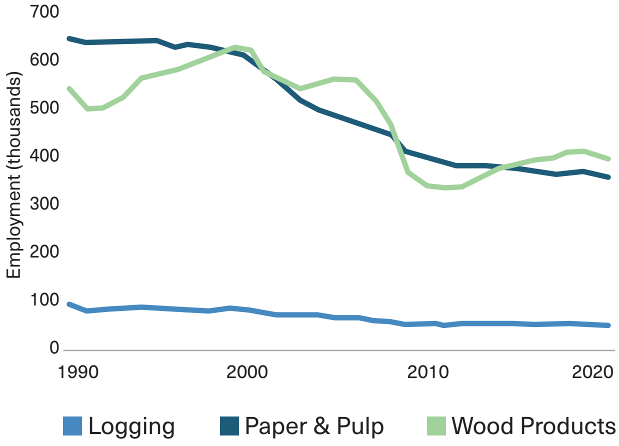
Figure 18: Total Value Added to State GDP by Forestry in the United States[224]



Forestry adds billions of dollars to the GDP of 31 states; forestry's contribution to the GDP of California and Pennsylvania was nearly $20 billion in 2016 (left). Forestry contributes at least 0.5 percent of the GDP of 44 states; Southeastern states, along with Wisconsin, Maine, and Oregon, depend on forestry for 3 to 5 percent of their GDP (right). States where the total value added by forestry is less than $2 billion (left), or where forestry comprises less than 0.5 percent of state GDP (right), are shown in white. Source: Data from Pelkki and Sherman, 2020.

The decline of forestry industries due to foreign competition, displacement of print media and paper-based products with digital versions, economic downturns driving down demand for timber and timber products, and other factors has led to job losses among skilled workers in these sectors and stranded forestry assets that could be used for BECCS projects (Figure 19).[225,226] The logging industry[d] has seen a 50 percent decline in total number of jobs over 30 years; the wood products industry[e] has seen an smaller drop in labor (about 20 percent) over the same period.[227] By creating demand for more wood for bioenergy pellets, BECCS can provide a boost to regions that have suffered economic losses.

Figure 19: Employment in BECCS-Adjacent Forestry Industries in the United States[228]



BECCS-adjacent forestry industries, such as logging, paper and pulp, and wood products, have seen a fall in employment over the past 30 years. These industries are key to employment in and economies of many regions around the United States; mill closures have had significant economic impacts on those areas. BECCS can rejuvenate these local economies by creating a demand for skilled labor previously employed by these industries. Source: Data from BLS, 2021.

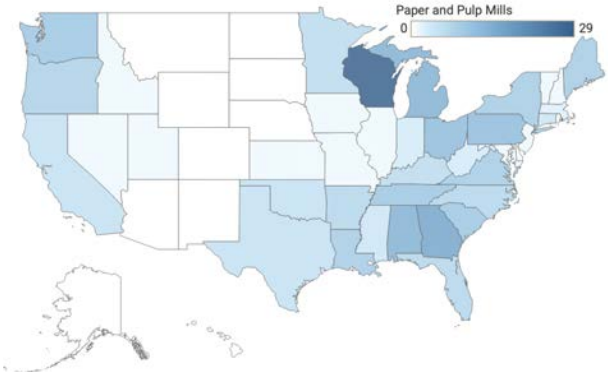
d North American Industry Classification System (NAICS) Code: 1133

e NAICS Code: 321

The paper and pulp industry has also experienced regular mill closures and a continuous decline in employment.[229,230] Mill closures have eliminated demand for low-grade wood, and without a market for this wood, an important economic incentive for removing poor-quality trees from forests is lost. Harvesting only high-grade wood can lead to a long-term decline in the quality of the forest stocks and forest composition.[231]

The BECCS industry can create a market for this stranded, low-grade wood, which can act as a pellet feedstock for BECCS projects, incentivizing landowners to maintain these forests and potentially generating new, rural jobs.[232,233] New pellet mills are often built near closed paper mills due to the availability of a trained workforce, infrastructure, and feedstock. Existing paper mills are scattered all over the United States, but most are clustered in four regions—the Northwest, the Midwest, the Southeast, and the Northeast (Figure 20).[234]

Figure 20: Paper and Pulp Mills in the United States[235]



There are many pulp and paper mills in forested parts of the Northwest, the Midwest, the Southeast, and the Northeast. These mills are located mostly in rural areas, and the paper and pulp industry can provide the human capital and feedstocks needed to develop the BECCS industry. Source: The EPA FLIGHT Tool.

A study modeled the impact of the closures of two paper mills in Louisiana and Alabama and discovered that for each job lost at the paper mill, three additional jobs were lost in other sectors.[236] The economic impacts of mill closures spilled into neighboring states and resulted in value-losses of hundreds of millions of dollars. The paper also evaluated the economic impact of opening a pellet mill in such counties and found that although a pellet mill creates fewer direct jobs than a pulp and paper mill, it creates more indirect jobs in forestry and logging.[237]

Carbon Capture and Management Industry

CO_2 has been captured and stored in the United States since the 1970s. As of October 2021, there are 20 operational carbon capture projects in the country.[238] Twelve of the projects are commercial-scale and eight are pilot- and demonstration-scale.[239] Forty-three additional carbon capture projects are in advanced stages of development, and one is under construction.[240] Many projects are used to capture emissions from ethanol plants, which have high-purity waste streams of CO_2.

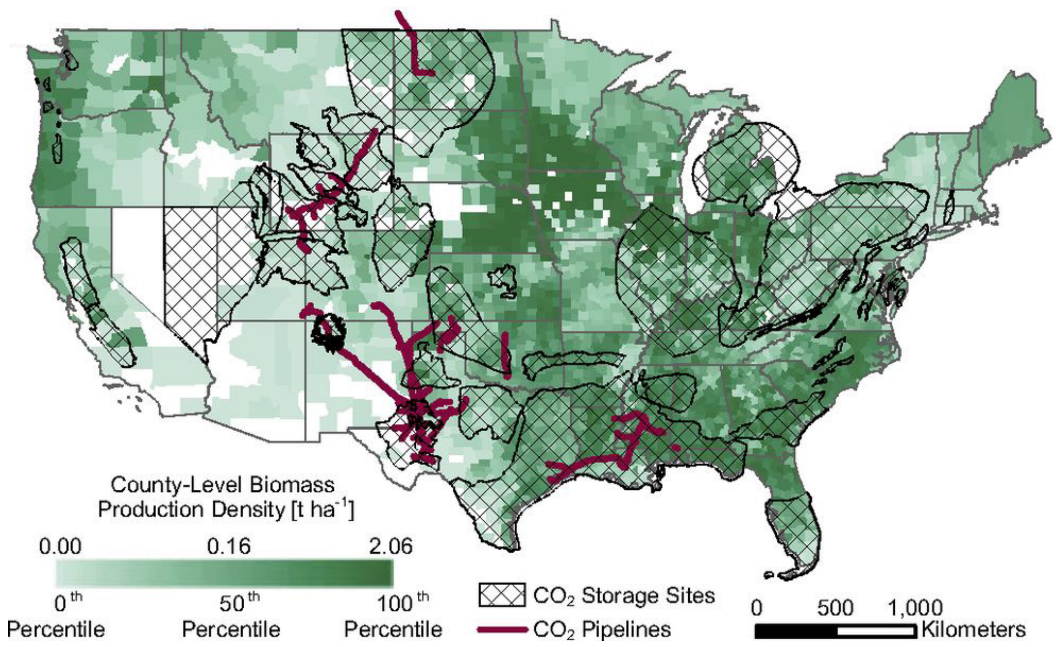
Over 4,500 miles of CO_2 pipeline connect carbon capture projects with CO_2 use and storage sites.[241] CO_2 utilization in the United States is almost entirely for EOR where CO_2 is injected underground to extract oil and gas from mature wells. The industry has recently seen the advent of companies like Summit Carbon Solutions, which offers carbon capture as a service. Summit Carbon Solutions plans to use shared CO_2 pipelines to transport and permanently store CO_2 from over 30 ethanol facilities in the Midwest.[242] Another carbon management company, Navigator CO_2 Ventures LLC, received approval to develop and construct a

1,300-mile shared CO_2 pipeline that the company estimates will connect more than 20 ethanol plants and other emitters.[243]

BECCS FEEDSTOCK AND DECARBONIZATION POTENTIAL IN THE UNITED STATES

As noted earlier, studies have estimated that the United States could reduce emissions by 0.3 $GtCO_2$/yr to 2.2 $GtCO_2$/yr (5 percent to 36 percent of 2018 U.S. emissions) across various timeframes through BECCS. Achieving such emission reductions will require substantial amounts of biomass and CO_2 storage capacity. The volume and type of feedstock available depends on the region and the year. In its *BT16* report, DOE estimated that 210 Mt/yr to 230 Mt/yr of lignocellulosic biomass would be available by 2020.[244] The geographic distribution of these resources in 2020 is shown in Figure 21. Agricultural residue is plentiful in the midwestern Corn Belt; purpose-grown crops are predominant in the southern Plains states; and woody biomass is found in the Southeast, the West Coast, and Appalachia.

Figure 21: Geographic Distribution of Biomass in the United States in 2020[245]

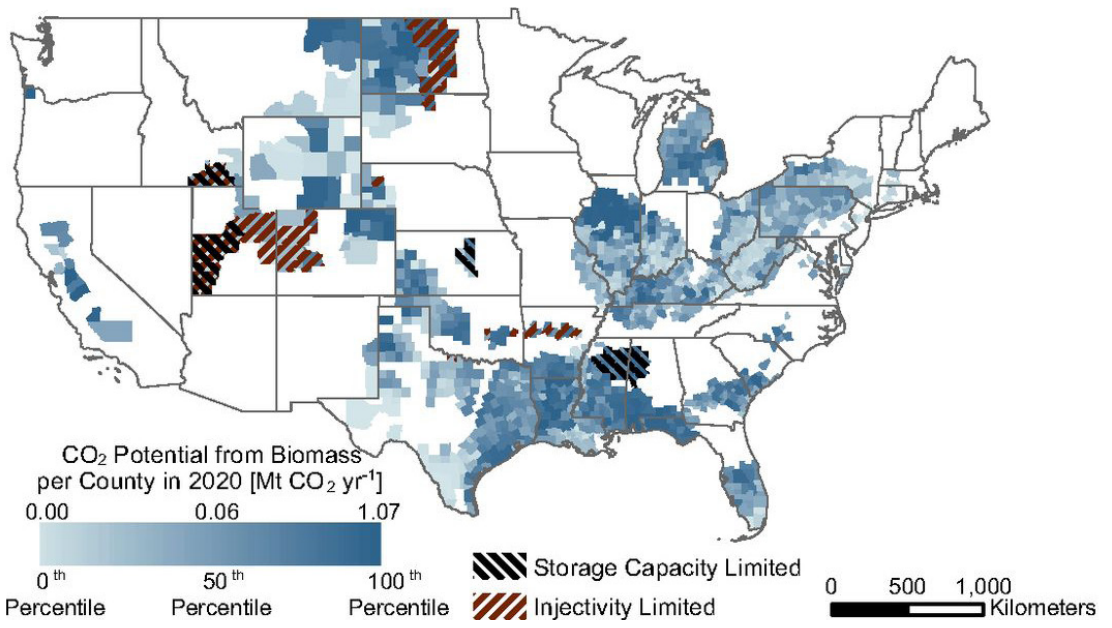


County-level biomass production density in the contiguous United States in 2020 varies by region. The largest portion of available biomass is in the midwestern Corn Belt. Potential CO_2 storage sites and existing CO_2 pipelines are also shown. Units are in metric tons per hectare. Source: Baik et al., 2018.

DOE estimates for bioenergy feedstock potential suggest that wood waste resources are near their capacity; however, there is significant potential to expand the use of harvested wood, agricultural wastes, and other wastes. Waste resources could dominate feedstock supply through 2030 at prices up to $50 per dry metric ton; purpose-grown non-wood crops could be the largest source of potential new supply at $66 per dry metric ton, the breakeven price point DOE found for a billion-ton bioeconomy (see Figure 11).[246,247]

Apart from a supply of feedstocks, BECCS also needs CO_2 storage (or utilization, though large-scale deployment will likely require some dedicated storage). The United States has a geologic storage potential of 3,000 Gt, including over 2,000 Gt in saline formations alone.[248,249] Storage capacity varies across the United States and the actual injection sites must be carefully evaluated and selected based on geologic characteristics (e.g., absence of permeable faults) and land uses around the injection well. Lack of suitable storage capacity could constrain future BECCS deployment in certain regions. Figure 22 shows areas that are ideal for both biomass growth and CO_2 storage: the best areas are northern Illinois, the Gulf, and western North Dakota. The breakdown of feedstocks grown in these counties is 41 percent agricultural residue, 44 percent woody biomass, and 16 percent purpose-grown energy crops.[250]

Figure 22: Geographic Distribution of Biomass Near Potential CO_2 Storage Sites in 2020[251]



This map highlights the CO_2 storage potential of counties with co-located biomass growth and geologic storage in 2020; promising areas are northern Illinois, the Gulf, and western North Dakota. The map also identifies potential limitations of storage capacity and injectivity. Source: Baik et al., 2018.

BECCS PROJECTS IN THE UNITED STATES

The availability of feedstocks and CO_2 storage sites, combined with the Section 45Q tax credit for carbon sequestration, has led to the deployment of BECCS in the United States. There are currently five operational BECCS projects in the United States, along with two closed projects and five in development (Table 2). These projects vary significantly in their size, carbon-capture potential, and end-use of captured carbon.

Table 2: List of Closed, Operational, and Planned BECCS Projects in the United States[252]

Name	Status	Sponsors	Location	Year	Feedstocks	Output	Carbon Captured ($MtCO_2$/yr)	Carbon Use
Russel CO_2 Injection Plant[253]	Closed	ICM	Russel, KS	2003 - 2005	Corn	Ethanol	0.007 (total)	EOR
Illinois Basin – Decatur Pilot Project[254,255]	Closed	ADM, MGSC, Illinois State Geological Survey	Decatur, IL	2011-2014	Corn	Ethanol	0.3	Geologic storage
Arkalon CO_2 Compression Facility[256]	Current	Conestoga Energy Partners	Liberal, KS	2009	Corn, sorghum	Ethanol	0.29-0.31	EOR
Bonanza Bioenergy CCUS EOR[257]	Current	Conestoga Energy Partners	Garden City, KS	2012	Corn, sorghum	Ethanol	0.10-0.16	EOR
Calgren Renewable Fuels CO_2 Recovery Plant[258]	Current	Calgren Renewable Fuels, AirLiquide	Tulare, CA	2015	Corn, sorghum, agricultural waste	Ethanol	0.15	Use - Liquefied for use in food, beverage, manufacturing
Illinois Industrial Carbon Capture & Storage[259]	Current	ADM	Decatur, IL	2017	Corn	Ethanol	0.52-1.0	Geologic storage
Charm Industrial[260]	Current	Charm Industrial	San Francisco, CA	2020	Waste biomass	Bio-oil	0.001 (total)	Geologic storage
Mendota Project[261]	Planned	Clean Energy Systems, Schlumberger New Energy, Chevron, Microsoft	Mendota, CA	2022	Agricultural waste	Syngas (hydrogen), power	0.3	Geologic storage
Green Plains[262]	Planned	Summit Carbon Solutions	Shenandoah, IA; Atkinson, NE; Central City, NE; York, NE; ND	2024	Corn	Biofuel	1.9	Geologic storage
Aemetis Carbon Capture and Sequestration[263]	Planned	Aemetis, ATSI, Baker Hughes	Modesto, CA	TBD	Waste biomass	Ethanol, RNG, renewable diesel	1.6	Geologic storage
Biorecro and EERC project[264]	Planned	Biorecro, EERC	ND	TBD	Corn	Ethanol syngas	0.001-0.005	Geologic storage

(continued)

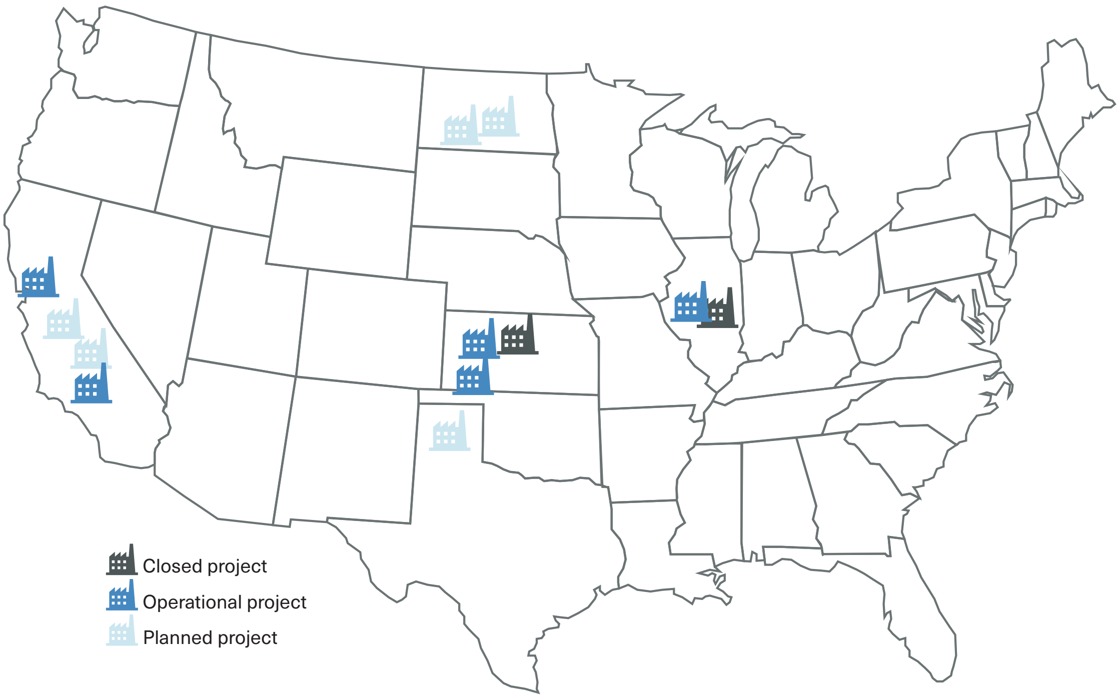
Name	Status	Sponsors	Location	Year	Feedstocks	Output	Carbon Captured ($MtCO_2/yr$)	Carbon Use
New Energy Freedom Biomass Refinery[265]	Planned	New Energy Blue	Mason City, IA	TBD	Crop residue (cornstalks and wheat straw)	Ethanol, lignin	1.0	Soil Carbon Sequestration
Occidental and White Energy[266]	Planned	Occidental Petroleum, White Energy	Hereford and Plainview, TX	TBD	Corn, sorghum	Ethanol	0.60-0.70	EOR
Red Trail Energy CCS Project[267]	Planned	Red Trail Energy	Richardton, ND	TBD	Corn	Ethanol	TBD	Geologic storage

***Note**: Planned projects are those that were publicly announced before October 2021 in the United States. There may be additional planned projects at the time of this report's release that are not included in the table as a result.*

BECCS projects are located throughout the Midwest and California since most feedstocks and outputs are tied closely to the ethanol industry and its supply chain (Figure 23). Although most projects produce ethanol, they differ in the end uses for captured carbon. Some projects facilitate carbon utilization in areas like food and beverage manufacturing or in agriculture to increase soil carbon uptake. Other projects either sequester the carbon or transport it to oil fields for EOR.

The largest operational BECCS project in the world is the ADM Illinois Industrial CCS facility that can capture up to 1 $MtCO_2$/yr.[268] The CO_2 generated from ethanol fermentation is injected into a layer of sandstone under the facility, making it the only large-scale project capturing CO_2 for permanent geologic storage. It cost $441 million, of which $281 million came from the DOE. In its three years of operation, however, the plant has never captured more than 52 percent of its potential.[269]

Figure 23: Location of U.S. BECCS Projects



BECCS projects are primarily located in the Midwest and California. The status and location data of these U.S. BECCS projects are based on EFI analysis of publicly available project information, which is listed in Table 2. Sources: Map from the Noun Project.

FEDERAL POLICIES AND PROGRAMS TO SUPPORT BECCS

Few current federal policies and programs directly address BECCS, though there are some existing tax incentives, programs, and policies with relevance to BECCS that are found mainly across three federal agencies—DOE, Department of Agriculture (USDA), and the EPA. States have had a hand in shaping the current policy landscape for BECCS as well (see Box 3). There are also policies that indirectly support the industry by focusing on one component of BECCS.

Federal policy on bioenergy has existed since at least 1978, when the Energy Tax Act of 1978 established the first biofuel subsidy. Federal support for CCUS RD&D began in 1997.[270,271] Other BECCS-adjacent programs have even deeper roots, such as the Forest Inventory and Analysis Program, which was created in 1928.[272] Since then, federal bioenergy programs have proliferated and have been instrumental in developing today's bioenergy market.[273] A 2016 report by the interagency Biomass Research and Development Board detailed over 40 offices across the Board's seven agencies[f] contributing to bioeconomy RD&D.[274] CDR more generally has garnered recent support in federal legislation, such as the Energy Act of 2020.[275]

f The Departments of Agriculture, Energy, Defense, Interior, and Transportation; the EPA; and NSF.

Table 3: Existing Tax Incentives with Relevance to BECCS in the United States[276,277]

Tax Credit	Eligibility	Credit Amount in 2021	Expiration Date (as of Oct. 2021)
45Q Carbon Oxide Sequestration Credit	Power plants: must capture at least 500 ktCO_2. Other industrial facilities and direct air capture: must capture at least 100 ktCO_2.	Geological sequestration: \$31.77/MtCO_2 EOR or qualified use: \$20.22/MtCO_2	January 1, 2026 (start construction)
Alternative Fuel Excise Tax Credit	Entities liable for the federal excise tax on sale/use of RNG (among other fuels) in motor vehicles.	\$0.50/gallon	December 31, 2021
Alternative Fuel Infrastructure Tax Credit	Owners of fueling equipment for qualified ethanol and biodiesel blends.	30 percent of installed equipment	December 31, 2021
Alternative Fuel Mixture Excise Tax Credit	Entities liable for the federal excise tax on sale/ use of fuel blends containing petroleum and alternative fuels, including bio-/renewable diesel.	\$0.50/gallon	December 31, 2021
Biodiesel Income Tax Credit	Sellers who use biodiesel or renewable diesel as an on-road fuel.	\$1.00/gallon	December 31, 2022
Biodiesel Mixture Excise Tax Credit	Fuel blenders who sell or use a mixture of bio-/ renewable diesel and petroleum diesel.	\$1.00/gallon	December 31, 2022
Production Tax Credit (PTC)	Electricity generation from biomass, landfill gas, and WtE facilities (among others). This includes open- and closed-loop biomass facilities.	Open-loop biomass electricity: 1.3 cents/kWh Closed-loop biomass electricity: 2.5 cents/kWh	December 31, 2021
Second Generation Biofuel Producer Tax Credit	Producers of biofuels from lignocellulosic or algae feedstocks.	\$1.01/gallon	December 31, 2021

This table summarizes the existing federal tax credits for biomass-based motor vehicle fuels, biomass use in electricity production, and CCUS facilities in the United States. The credit amount for each tax incentive is based on policies as of October 2021 and subject to change in the future. Source: Alternative Fuels Data Center, 2021.

Tax Incentives

Various parts of the BECCS value chain—including fuels production, power production, and carbon sequestration—are eligible to receive existing tax credits (Table 3).[278]

One of the most significant incentives for near-term BECCS deployment may be the Section 45Q Carbon Oxide Sequestration credit, which provides a tax credit for each tCO_2 sequestered in geologic storage, EOR, or utilized for other purposes.[279] For facilities coming online after February 2018, eligibility is based on the capture equipment in service. For example, power plants must capture at least 500,000 tCO_2 annually to be eligible; non-power (e.g., DAC, industrial) facilities must capture 100,000 tCO_2; and facilities that emit less than 500,000 tCO_2 are eligible if they capture at least 25,000 tCO_2 for carbon utilization, rather than storage.[280] Additionally, the credit amount depends on the type of CO_2 disposition. Facilities that geologically store CO_2 can earn \$31.77/tCO_2 in 2021 and up to \$50/tCO_2 by 2026. Similarly, facilities that sequester CO_2 with EOR or a qualified use of CO_2 could earn \$20.22/tCO_2 in 2021 and up to \$35/tCO_2 by 2026 (Figure 24).[281]

Several credits are also available for the production or sale of biofuels. These include:

- The primary tax credit for sellers of liquid biofuels is the Biodiesel Income Tax Credit, which offers $1.00/gallon of biodiesel, agri-biodiesel (derived directly from virgin plant oils or animal fats, rather than waste feedstocks), or renewable diesel delivered as an on-road fuel. This means that—if the fuel is sold at retail—the individual who sold and placed the fuel in the tank is eligible for a credit on the seller's income tax liability.[282]
- Other biofuel tax credits focus on subsidies for biofuel producers. The Biodiesel Mixture Excise Tax Credit provides a $1.00/gallon tax incentive to fuel blenders who sell or use a mixture of biodiesel, agri-biodiesel, or renewable diesel and (at least 0.1 percent) petroleum diesel.[283] This tax credit helps to compensate for the higher costs of renewable diesel and biodiesel compared to petroleum diesel. The U.S. EIA found that during 2016, the tax credit's fiscal impact was $2.7 billion, as biodiesel imports reached their highest levels and domestic production increased 33 percent from 2015. These trends are expected to increase through 2021.[284] This policy and the Biodiesel Income Tax Credit were recently retroactively extended through the end of 2022.
- There is also the Second Generation Biofuel Producer Tax Credit for biofuels from lignocellulosic or algae feedstocks (see Box 1 for a discussion of the varying definitions of second-generation biofuels). Producers are eligible for up to $1.01/gallon for the sale or use of the fuel, whether on its own or blended with fossil fuels.[285]

Beyond these biofuel-specific tax credits, there are broader tax incentives that support both biofuels and other alternative fuels.

- The Alternative Fuel Excise Tax Credit is a $0.50/gallon tax credit available for many alternative fuels—including compressed or liquified gas derived from biomass (i.e., RNG)—where eligibility is based on an entity's liability for reporting and paying the federal excise tax on the fuel's sale or use in a motor vehicle.[286]
- The Alternative Fuel Mixture Excise Tax Credit applies the same incentives to alternative fuel blends including biodiesel and renewable diesel (containing at least 0.1 percent gasoline, diesel, or kerosene) on its sale or use as a fuel. The credit is applied to the blender's alternative fuel tax liability. [287]
- There is also the Alternative Fuel Infrastructure Tax Credit, under which fueling equipment—including for ethanol blends over 80 percent and biodiesel blends over 20 percent—can receive a 30 percent tax credit. This tax credit impacts all equipment installed through the end of 2021.[288]

Electricity generation from biomass, landfill gas, and WtE facilities is eligible for the renewable production tax credit (PTC).[289] The PTC currently offers a 1.3 cents/kWh corporate tax credit for open-loop biomass electricity and a 2.5 cents/kWh credit for electricity from closed-loop biomass. The PTC is set to expire in 2021 for all renewable energy technologies, so any projects must begin construction before the end of 2021 to qualify.[290] The PTC applies to the first 10 years of operation for a renewable electricity plant.[291]

Both the PTC and the Section 45Q tax credit were extended by the omnibus coronavirus relief and appropriations package in December 2020 (Consolidated Appropriations Act, 2021).[292] Proposals for further extensions and reforms were under consideration by Congress as of October 2021, as were new credits—such as a hydrogen production tax credit—that could be relevant to BECCS projects (see Box 4 on page 54).

Figure 24: Section 45Q Tax Credit Value Available for Differing Sources and Uses of CO_2

	Minimum Size of Eligible Carbon Capture Plant by Type ($ktCO_2/yr$)			Relevant Level of Tax Credit in a Given Operational Year ($\$USD/tCO_2$)									
Type of CO_2 Storage/Use	Power Plant	Other Industrial Facility	Direct Air Capture	2018	2019	2020	2021	2022	2023	2024	2025	2026	Beyond 2026
Dedicated Geological Storage	500	100	100	28	31	34	36	39	42	45	47	50	Indexed to Inflation
Storage via EOR	500	100	100	17	19	22	24	26	28	31	33	35	
Other Utilization Processes[1]	25	25	25	17[2]	19	22	24	26	28	31	33	35	

[1] Each CO_2 source cannot be greater than than 500 $ktCO_2/yr$
[2] Any credit will only apply to the portion of the converted CO_2 that can be shown to reduce overall emissions

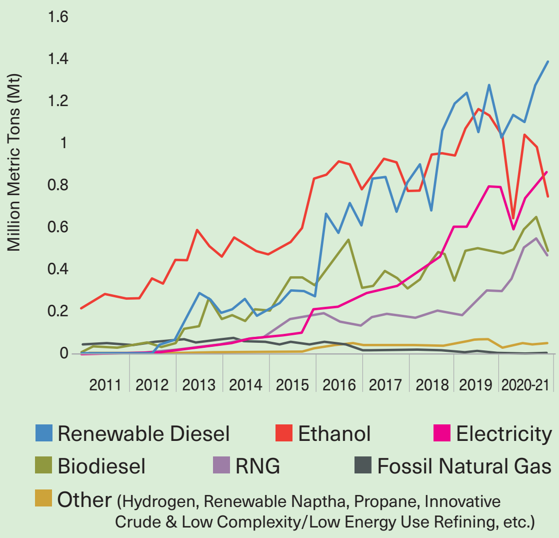
Box 3: The Impact of State Policy

In the absence of comprehensive federal climate policy, decarbonization has often been driven by the states. Two examples—the renewable portfolio standard (RPS) and California's LCFS—show how state regulation can drive the adoption or proliferation of new technologies. These policies could help promote BECCS deployment; states could also provide valuable laboratories for policy innovation in areas like CDR.

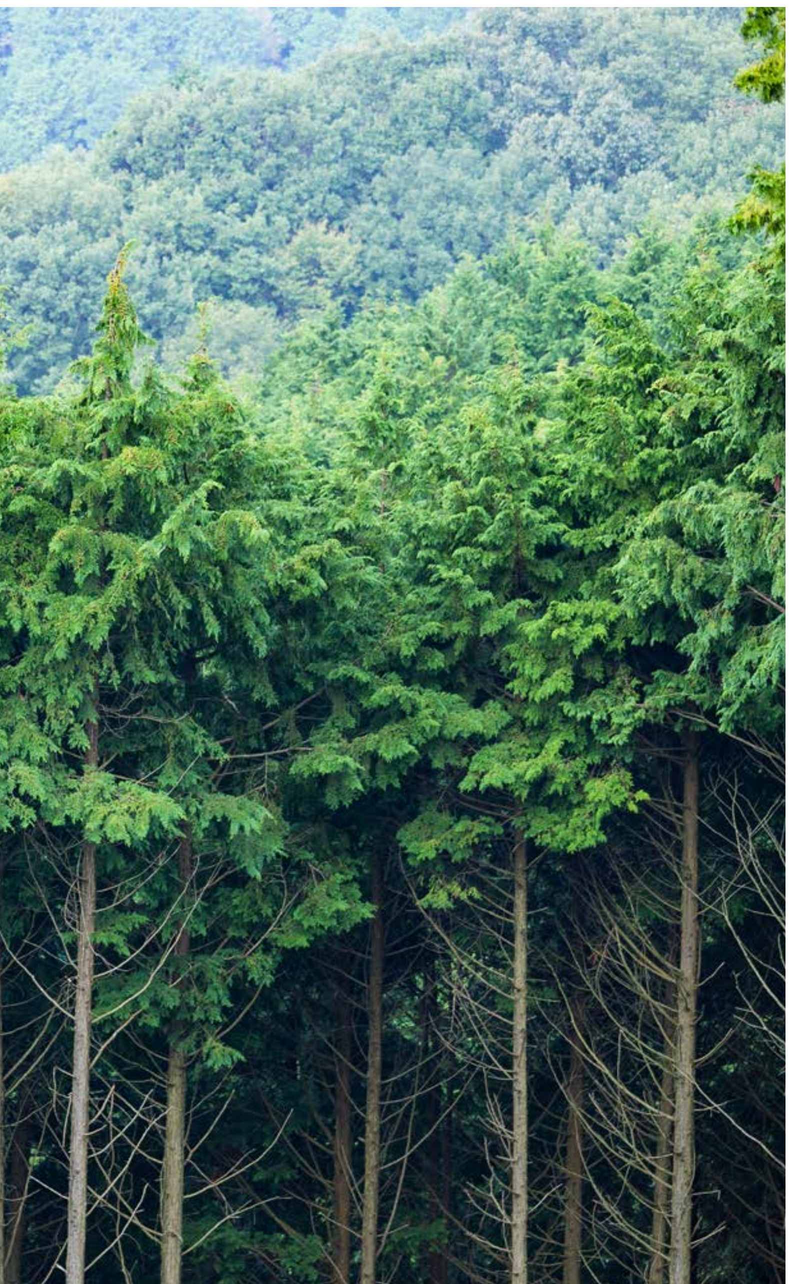
A crucial driver of the growth in renewable power—particularly wind and solar—over the past two decades has been the RPS, coupled with other state policies like net metering for solar; RPS-required generation accounted for 45 percent of the new non-hydro renewables between 2000 and 2019.[293] This growth contributes to learning-by-doing and cost declines for renewable generation, which in turn spurs growth both in RPS and non-RPS states.

California's LCFS—which requires fuel suppliers to provide fuel with declining life cycle carbon intensities or buy tradeable credits—has directly impacted BECCS development (Figure 25). The LCFS requirements have triggered demand for new types of biofuels, such as RNG and renewable diesel, creating new industries.[294,295,296,297] The Standard's CCS Protocol has not yet had the same impact in terms of actual credits generated, but multiple CCUS and CDR projects—including the Clean Energy Systems BECCS project and the 1PointFive and Carbon Engineering DAC project—are actively pursuing LCFS credits as part of their value proposition.[298,299] The LCFS is also part of a long history of innovative climate and environmental policies that California has exported, inspiring similar standards in Oregon, Washington, and Canada.

Figure 25: California LCFS Credits by Fuel Type, 2011-2021[300]



The California LCFS has driven the growth of less widely used biofuels, such as renewable diesel and RNG, that generate more credits than competitor fuels like biodiesel and fossil gas. The LCFS is just one example of how state policies can have national-level impacts on technology innovation and deployment.



Department of Energy

DOE plays a key role in BECCS innovation, hosting relevant programs from basic research through early commercialization. It is also the only agency explicitly tasked with tackling BECCS (Figure 26). The Energy Act of 2020, passed as part of the December 2020 omnibus, created a CDR RD&D program. This program is housed within the Office of Fossil Energy and Carbon Management (FECM), with participation from the Offices of Science (SC) and Energy Efficiency and Renewable Energy (EERE).[301] As part of the Energy Act of 2020, DOE's Fossil Energy program received $228.3 million for Fiscal Year 2021 in new authorizations for carbon capture demonstrations across stages of technological maturity and different types of facilities, ranging from natural gas power plants to projects in heavy industry.[302,303] DOE was also allocated continued funding for carbon storage projects and directed to establish a RD&D program focused on new utilization pathways for CO_2.[304]

Figure 26: Policies and Programs to Support BECCS Deployment across Federal Agencies

United States Department of Energy	**Biological and Environmental Research (Office of Science)**	Early-stage bioenergy research
	Office of Fossil Energy and Carbon Management	CDR RD&D lead office; CCUS RD&D
	Bioenergy Technologies Office (Office of Energy Efficiency and Renewable Energy)	Bioenergy RD&D
	Advanced Research Projects Agency–Energy	Commercializing promising technologies
	Loan Programs Office	First-of-a-kind deployment financing
	DOE National Laboratories	Innovation, public-private partnerships
	CDR Task Force (w/ USDA)	
United States Department of Agriculture	**Agricultural Research Service**	Climate Hubs; RD&D on biochar, soils, etc.
	National Institute of Food and Agriculture	External RD&D grants; Biomass R&D Initiative (w/DOE)
	Agriculture Advanced Research and Development Authority	Commercializing promising technologies
	United States Forest Service	RD&D on forestry, forest bioenergy, forest products; management of National Forest System
	Rural Development programs/ Farm Service Agency	Financial/technical assistance energy programs
	Natural Resources Conservation Service	Financial/technical assistance for land conservation
United States Environmental Protection Agency	**Safe Water Drinking Act**	Geologic storage permitting
	Renewable Fuel Standard (Energy Policy Act of 2005)	Biofuel requirements for petroleum producers
	Energy Independence and Security Act of 2007	Expanded mandate on biofuel quantity and diversificationof feedstocks in RFS

This figure is a summary of the offices or policies within DOE, USDA, and the EPA that manage programs or regulations closely connected to CDR technologies and bioenergy. Even though few federal policies and programs directly focus on BECCS today, these examples in each of the agencies present potential policy pathways for BECCS development in the United States.

The omnibus also created a CDR task force (overseen by DOE in collaboration with USDA) and appropriated $83 million in Fiscal Year 2021 toward CDR efforts at the three aforementioned DOE offices. The Energy Act's CDR RD&D and task force provisions were the first time that BECCS appeared in the U.S. Code; these newly authorized programs will not be fully implemented, however, unless Congress continues to appropriate money to fund them.[305] In addition to leading this new CDR effort, FECM oversees DOE's work on CCUS. While no specific BECCS efforts have been announced since the creation of the CDR program, FECM under the Biden administration has funded projects in related areas such as DAC and algae-based CO_2 utilization.[306,307]

The other DOE offices named in the Energy Act also have existing programs with relevance to BECCS. SC's Biological and Environmental Research (BER) program funds early-stage research on bioenergy topics; one BER program is the Bioenergy Research Centers, four research clusters that are devoted to overcoming technical barriers to lignocellulosic bioenergy feedstock production and conversion.[308] Other bioenergy RD&D is conducted under the auspices of the EERE's Bioenergy Technologies Office (BETO). BETO's current RD&D programs fund several technologies that could be useful for BECCS, including algal systems, CO_2 utilization, conversion technologies, feedstock technologies, sustainable aviation fuels, WtE, and bioenergy systems integration.[309] BETO has previously collaborated with FECM on a BECCS workshop; recent funding announcements under two different Administrations have shown a focus on large-scale carbon management, with BETO investing in projects related to algal carbon removal, CO_2 utilization, and using biomass feedstocks for ecosystem restoration.[310,311,312]

Other DOE offices may also have roles to play in BECCS RD&D, including other offices within EERE (e.g., Vehicle Technologies, Advanced Manufacturing) or SC (e.g., Basic Energy Sciences). The Advanced Research Projects Agency—Energy (ARPA-E) funds cutting-edge research in a variety of areas and helps to bridge the gap between RD&D and commercialization. Recent ARPA-E projects include ROOTS, which entails the breeding of specific plants that absorb atmospheric CO_2 to increase soil carbon content, and ECOSynBio, which supports the development of new biomass conversion systems and platforms for the downstream part of the bioeconomy supply chain—creation of fuels and other useful products.[313,314] The DOE Loan Programs Office (LPO) oversees the Title XVII Innovative Energy Loan Guarantee Program, which helps fund first-of-a-kind energy projects; it has previously provided financing for bioenergy projects such as a cellulosic ethanol biorefinery.[315]

DOE also supports innovation through its National Laboratories. The National Energy Technology Laboratory (NETL) manages many FECM projects; its Regional Carbon Sequestration Partnership and Carbon Storage Assurance Facility Enterprise (CarbonSAFE) programs have established public-private collaborations to create regional carbon-storage hubs, including projects that involve ADM's Decatur plant.[316,317] BETO has regularly funded RD&D at nine[g] of the DOE Labs.[318] The National Renewable Energy Laboratory (NREL), the only Lab directly overseen by EERE, hosts

g Argonne, Idaho, Lawrence Berkeley, Lawrence Livermore, Los Alamos, Oak Ridge, Pacific Northwest, and Sandia National Laboratories, as well as NREL.

the National Bioenergy Center and a bioenergy research program that covers topics such as technoeconomic analysis and characterization, net-zero biofuels for difficult-to-decarbonize transportation uses, and carbon capture and use from biomass using catalysis.[319] Oak Ridge National Laboratory (ORNL), an SC Lab, is another leader in the biomass space, working with BETO, BER, and USDA on topics such as feedstock supply, bioproduct sustainability, conversion technologies, and materials compatibility.[320]

Department of Agriculture

Of USDA's eight mission areas, at least four have existing programs that could benefit BECCS, including both RD&D programs and programs that provide deployment incentives (Figure 26).[321,322] The Research, Education, and Economics (REE) mission area includes the Agricultural Research Service (ARS), USDA's main RD&D arm. ARS (in conjunction with the Forest Service) hosts important RD&D efforts through USDA's Climate Hubs and its Regional Biomass Research Centers; the agency has also been a primary driver of federal biochar research.[323,324,325,326] REE also includes the National Institute of Food and Agriculture (NIFA), which supports RD&D and deployment through the Land Grant Universities and Colleges and the Cooperative Extension Service.[327] The 2018 Farm Bill created a new REE pilot program, the Agriculture Advanced Research and Development Authority (AGARDA), modeled on ARPA-E and the Department of Defense's DARPA. A fully realized AGARDA could help develop BECCS and other land-based CDR.[328]

USDA's Rural Development (RD) and Farm Production and Conservation (FPAC) mission areas are more focused on deployment. Both provide grants, loans, technical assistance, and other programs for farmers, other landowners, and rural communities. RD and FPAC's Farm Service Agency (FSA) both have energy programs devoted to providing financial assistance for bioenergy production and infrastructure.[329,330] These include FSA's Biomass Crop Assistance Program, which provides matching payments for farmers and foresters who convert their land to biomass feedstock production, and RD's Advanced Biofuel Payment Program, which pays producers for each British thermal unit produced of non-corn ethanol fuels.[331,332] FPAC's Natural Resources Conservation Service (NRCS), on the other hand, provides financial and technical assistance for land conservation or implementation of environmentally beneficial practices.[333] NRCS provides an important role in both R&D and deployment of carbon-sequestering practices on farms and forests, which could improve the life cycle emissions of BECCS systems.

USDA's Natural Resources and Environment mission area contains the U.S. Forest Service (USFS), a multifaceted agency that has many relevant roles in the development of BECCS. USFS has its own Research and Development program, responsible for forest data collection and research into forest products, biomass, bioenergy, and climate impacts.[334] Similar to NRCS, the agency provides financial and technical assistance to subnational governments and private landowners, through programs such as the Wood Innovations Grants Program, dedicated to creating new wood-product and wood-energy applications and markets.[335] USFS also has a unique role within USDA as the administrator of the National Forest System, which includes nearly one-third of all federal lands.[336] National Forests are both a potential source of BECCS feedstocks—though current law restricts their ability to qualify under programs like the Renewable Fuel Standard (RFS) (see discussion of the RFS in the EPA section below)—and a laboratory for forest management and forest products innovation.

Other USDA agencies could play smaller roles as BECCS technologies scale up. The Foreign Agricultural Service, for example, which promotes exports of U.S. agricultural products, could have a role in the growing biomass export market.

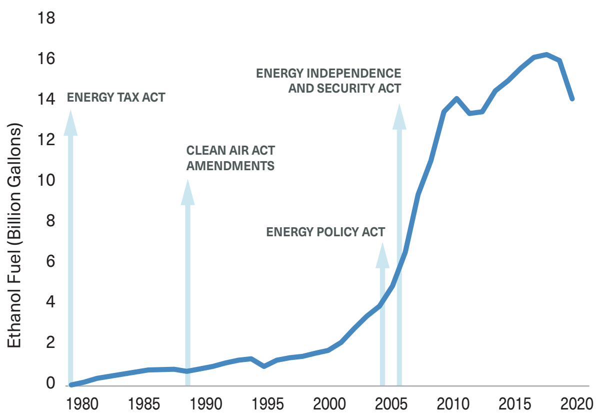
The Environmental Protection Agency

The EPA has important regulatory roles that could influence BECCS deployment (Figure 26). The EPA oversees the permitting of Class VI wells (for geologic storage) and Class II wells (for EOR) under its Safe Drinking Water Act authority, though it can delegate "primacy" over permitting to individual states and tribes.[337] Through the EPA's Greenhouse Gas Report Program (GHGRP), the agency gathers data concerning CO_2 capture and storage and requires regular monitoring of geologic storage wells. Subpart RR of the GHGRP requires all facilities using geologic storage to submit a monitoring, reporting, and verification (MRV) plan for the EPA's review and establishes a mechanism that requires facilities to report the quantity of CO_2 received for injection, the amount of CO_2 sequestered, and annual monitoring activities.[338] Those facilities using geologic storage wells for EOR can also opt to report under Subpart UU of the GHGRP, which only requires facilities to report the quantity of CO_2 received for injection.[339]

The EPA also administers the RFS, which requires producers and importers of petroleum fuels to blend a minimum volume of biofuels into the fuel that they sell.[340] Producers can also trade credits (known as Renewable Identification Numbers, or RINs) to meet RFS obligations. The RFS requires specific volumes of different types of biofuels and each type has a life cycle GHG reduction threshold (compared to fossil fuels) that it must meet to qualify for the Standard.

The RFS is part of a long history of regulatory programs that have helped create the modern biofuel industry (Figure 27). The Energy Tax Act of 1978—which included the first tax exemption for ethanol—was part of a wave of federal legislation in the wake of the 1973 oil crisis, which also included the creation of DOE and the modern federal energy policy apparatus.[341] Ethanol received another boost from the Clean Air Act Amendments of 1990, which created mandates for oxygenates in gasoline. The next major milestones were the Energy Policy Act of 2005, which created the RFS, and the Energy Independence and Security Act (EISA) of 2007, which expanded the mandated quantity of biofuels and diversified the eligible feedstocks. However, the EISA excludes any renewable biomass grown on federal lands—such as National Forests—from qualifying for RINs.[342] These regulations reflected a variety of policy objectives: biofuels have often been championed as a strategy for promoting energy conservation, energy independence and security, air quality, or rural development, rather than for any climate benefit.[343,344]

Figure 27: Timeline of U.S. Federal Legislation Related to Biofuels and Annual Ethanol Production from 1981 to 2020[345,346]



The U.S. biofuel industry, particularly ethanol, has received increased federal support through legislation since the late 1970s. A combination of mandates, tax incentives, and regulations in this legislation have supported much of the production growth seen in the U.S. ethanol industry through the present day. More recent legislation has also attempted to encourage the growth of domestic industries for new types of biofuels. Source: EIA, 2021.

Interagency Collaboration

There is an established history of interagency collaboration on bioenergy through the Biomass Research and Development Board. Established in 2000, the Board coordinates bioenergy and bioproducts policy throughout the federal government.[347] It oversees the BRDI, a collaboration between USDA's NIFA and DOE's EERE that awards grants in areas such as cellulosic fuels, bioproduct diversification, energy and environmental life cycle analysis (LCA), and assessment of feedstock potential on federal land.[348] Though the BRDI was reauthorized in 2018, it has not received funding since fiscal year 2017.[349,350] Revitalization of BRDI could be a part of federal BECCS efforts going forward, as could new interagency collaborations.

The Energy Act of 2020 directs DOE to issue a report on CDR and establish a task force, which could include representatives from other agencies.[351] An explicit interagency CDR RD&D initiative—outlined in EFI's report *Clearing the Air: A Federal RD&D and Management Plan for Carbon Dioxide Removal Technologies*—has also been proposed in Congress (Box 4).[352,353]

Figure 28: Federal Participants in an Interagency CDR RD&D Initiative

There are currently 10 agencies and the Executive Office of the President (EOP) that are participating in the CDR RD&D Initiative at the federal level. Source: EFI, 2019.

The three agencies highlighted in this section are not the only ones with existing programs that could impact BECCS (Figure 28).[354,355] Others include:

- the Department of the Interior's U.S. Geologic Survey (geologic carbon storage) and Bureau of Land Management (feedstocks on federal lands)
- the Department of Commerce's National Oceanic and Atmospheric Administration (aquatic feedstocks)
- the Departments of Defense and Transportation (transportation fuels RD&D)
- the National Science Foundation (early-stage, environmental impacts, and social science research)
- the Executive Office of the President's (EOP) Office of Science and Technology Policy, Office of Management and Budget, and Council on Environmental Quality (policy and interagency coordination)

Box 4: BECCS Policy Proposals in the 117th Congress

This section covers some of the notable legislative activity related to BECCS through October 2021. Several of these proposals have subsequently been incorporated into the Infrastructure Investment and Jobs Act and budget reconciliation bills (Build Back Better Act). Few of these proposals address BECCS directly; their focus is often on CDR, bioenergy, or CCUS more broadly.

CO_2 transport and storage.[356] There are several bipartisan proposals for reforming the Section 45Q tax credit, including direct pay, higher credit values, and a longer eligibility window.[357,358,359,360,361,362] The CCUS Tax Credit Amendments Act of 2021 includes some of these elements, and would also increase the value of the credit for CO_2 from DAC—an idea that could be adapted to BECCS.[363] Another bipartisan effort, the SCALE Act, would provide financing, grants, and faster permitting for CO_2 infrastructure.[364] The Republican-sponsored CCUS Innovation Act would make CDR and CCUS technologies eligible for support from DOE's Title XVII Loan Guarantee Program.[365]

Other tax credits. Other clean energy tax credit proposals include reviving the Section 48C advanced energy manufacturing tax credit—which would include eligibility for CDR, CCUS, and renewable fuels—and extending and expanding existing credits like the PTC.[366,367] The Clean Energy for America Act, from Senate Democrats, would instead replace existing incentives with credits for clean electricity and fuels production.[368] Notably, this proposal uses a life cycle emissions approach to determining credit eligibility, which could advantage BECCS.

Forestry and soil carbon solutions. Another area with bipartisan interest is natural climate solutions, including forestry, biochar, and soil CDR—though these bills generally do not focus on bioenergy applications.[369,370,371,372,373,374,375,376,377,378] These proposals include policies such as expansion of existing USDA programs, new RD&D programs, financial assistance and incentives, job programs, deployment on federal lands, and international cooperation. One notable bill, the Growing Climate Solutions Act of 2021, passed the Senate in June 2021. It would provide technical assistance through USDA to help farmers, ranchers, foresters, and third-party verifiers participate in voluntary carbon markets.[379]

RD&D. The bipartisan CREATE Act of 2021 would create an interagency Carbon Removal Initiative for RD&D on a range of CDR pathways, including BECCS.[380,381] The Bioeconomy Research and Development Act of 2021 would create a similar interagency effort on next-generation biotechnology.[382]

Clean energy standards and carbon pricing. BECCS has been discussed for inclusion in Clean Energy Standard (CES) bills backed by Democrats, in part because negative-emissions power could provide utilities with more flexibility for meeting targets.[383] The Clean Energy Standard Act of 2019, proposed in the last Congress, provided a possible avenue for inclusion of BECCS, tasking DOE and the National Academies of Sciences, Engineering, and Medicine (NASEM) to study proper crediting procedures for biomass based on its life cycle emissions.[384]

A major CES and economywide decarbonization proposal from the 117th Congress, the CLEAN Future Act, does not include this provision; it does, however, allow DAC to generate credits.[385] This bill also includes CDR (including BECCS) in other sections, such as mandatory national and state climate plans, a workforce development grant program, and a manufacturing grant program.

BECCS is also mentioned in two carbon tax bills: the bipartisan MARKET CHOICE Act, which would use a portion of carbon tax proceeds for CDR RD&D, and the Democratic America's Clean Future Fund Act, which would use proceeds to fund a Green Bank to finance decarbonization projects, including DAC and BECCS.[386,387]

Biden administration budget and legislative proposals. The Biden administration's first budget proposal reflected an emphasis on tackling climate change throughout, including at DOE and USDA.[388] The budget proposed a 33 percent increase for BETO, 63 percent for FECM's CCUS programs, and 58 percent for CDR.[389] At USDA, the administration proposed a 15 percent increase for Forest and Rangeland Research at the Forest Service, nearly $200 million at the Agricultural Research Service set aside for climate science and bioenergy, and first-time dedicated funding for the USDA Climate Hubs.[390,391] The administration's proposed infrastructure package, the American Jobs Plan, also included relevant policies such as demonstration projects for industrial carbon capture and the incorporation of the SCALE Act and 45Q tax credit reform.[392]

Sources: Icons from the Noun Project.

Key Issues Identified in the Literature

As noted, BECCS is not defined as a single technology—it is a set of pathways involving a variety of feedstocks, conversion processes, and end-use sectors. The BECCS supply chain involves multiple sectors such as forestry, agriculture, and energy, and could potentially impact climate mitigation, food security, rural livelihood, forest resilience, and biodiversity conservation. Existing GHG accounting methods are limited in their ability to capture the full impact of BECCS projects. The complex nature of BECCS lends itself to wide-ranging and varied discussion on its potential contributions to carbon removal as well as its environmental, economic, and social impacts.

GHG ACCOUNTING METHODS FOR BECCS

GHG accounting quantifies the net emissions of a process or project. It is commonly used by public and private entities to estimate their emissions and track progress toward emission reduction goals. Various organizations establish accounting methodologies to provide consistent approaches to be used across a range of circumstances; for example, the UN Framework Convention on Climate Change (UNFCCC) provides GHG accounting guidelines for nations reporting their emissions to the United Nations, and the Greenhouse Gas Protocol is working with World Resources Institute and the World Business Council for Sustainable Development to issue guidance on corporate accounting guidance for bioenergy, land use, and related inventory areas.[393] For the purposes of public policy, politicians and government employees may identify a preferred third-party system of accounting (such as UNFCCC's), establish an accounting method in legislative text, or develop an accounting approach for specific uses.[394]

Standardized and accurate GHG accounting rules are important because they provide the basis upon which policies and markets can reward the climate benefits of BECCS and other clean energy projects. Accounting rules that provide robust, accurate, and trustworthy emissions estimates could promote investment in BECCS by reducing risks and uncertainty for project developers seeking to secure carbon credits or other incentives for BECCS projects. Developing such rules, however, can be technically and organizationally complex.

Identifying the relevant emissions impact of any process or product is enormously complicated and requires making decisions on scope and methodology that can be subject to debate or contest. Yet simplicity, credibility, and broad acceptance are critical to promote investment in, and ensure proper rewards for, BECCS.[395] Reconciling the necessity of tractable emissions accounting frameworks with the complexity of the real world leaves many open questions regarding the accuracy, completeness, and applicability of GHG accounting protocols for BECCS.

Authors have raised concern about several specific aspects of GHG accounting for BECCS projects:

- GHG accounting rules are inconsistent as to whether and how specific sources of emissions are included when estimating the overall emissions impact of BECCS.
- A typical GHG accounting simplification—counting all bioenergy-related emissions in the land-use sector and assuming zero emissions at point of combustion—shifts the most important emissions measurement burden from the energy sector to the land-use sector where measurement, recording, and verification is far more complex and requires numerous contestable assumptions. The focus on land-use emissions is further complicated by the difficulty in determining the counterfactual use of that land.
- System boundaries are typically drawn narrowly on the feedstock supply chain and disposition though some authors recommend including induced effects in the broader economy.
- Whether the temporal distribution of emissions and removals is an important consideration when accounting for BECCS emissions remains in dispute.

Inconsistent Emissions Categories

An IEA review of several current national and international GHG accounting frameworks found major inconsistencies in whether and how specific sources of emissions were included when estimating the overall emissions impact of BECCS.[396,a] Some, like the LCFS, include comprehensive GHG accounting rules for upstream emissions from biomass growth, transport, processing, and some land-use effects. Many others, however, do not incorporate upstream GHG emissions. The GHGRP, for example, requires facilities to report CO_2 emissions from the combustion of biomass fuels, but not from upstream direct and indirect land-use change.[397] The European Union's Emissions Trading System (EU ETS) only allows sequestered "fossil carbon" to be deducted from a project's total emissions; negative emissions from BECCS are not considered a source of negative emissions under this framework.[398]

a IEA's study reviewed GHG accounting guidelines from UNFCCC, international project-based schemes such as Clean Development Mechanism, the EU ETS, EPA's GHGRP, and the LCFS.

A Focus on the Land-Use Sector

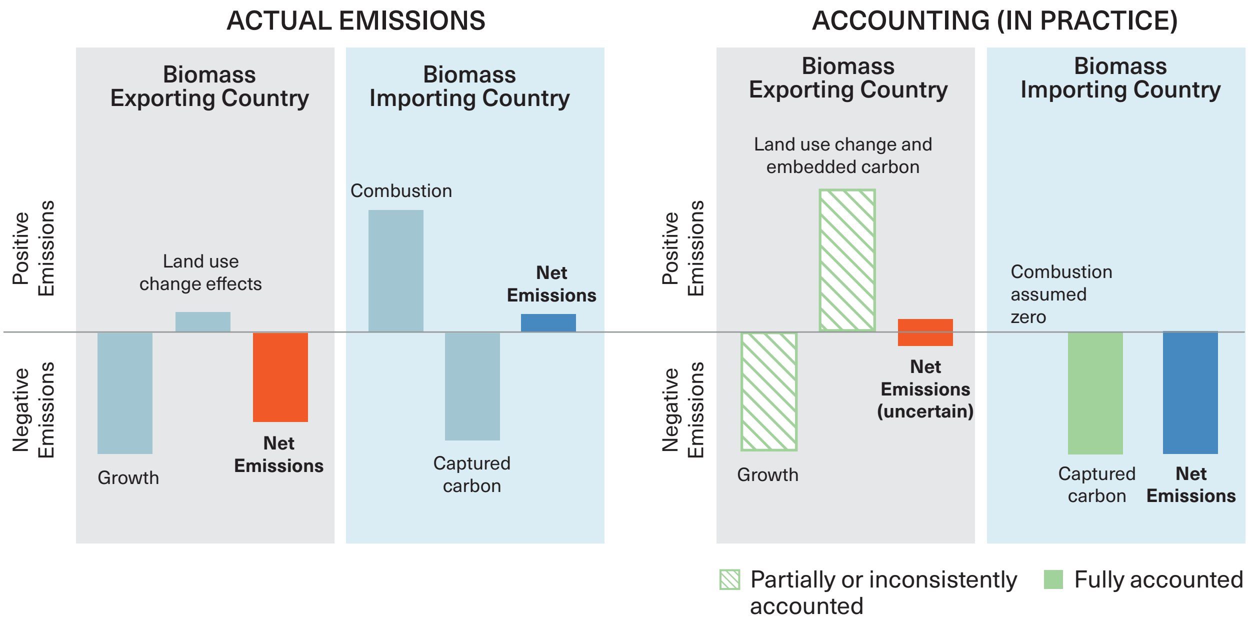
GHG accounting frameworks tend to count most bioenergy emissions in the land-use sector rather than the energy sector. Though this approach would theoretically include all emissions from BECCS, narrowing in on the land-use sector adds uncertainty to emissions estimates because monitoring, reporting, and verification in the land-use sector is less robust than in the energy sector.[399] In addition, some GHG accounting frameworks do not require including emissions from direct biomass combustion or land-use change altogether.

The UNFCCC GHG reporting guidelines—those used by nations submitting official national emissions inventories to the United Nations—requires that CO_2 emissions from biomass combustion be counted in the land-use sector at the time of harvest and reported as zero in the energy sector to avoid double counting.[400] The EU ETS and the Renewable Energy Directive have similar requirements.[401] Reporting guidelines for the Kyoto Protocol—the first global framework for mutual national emissions reductions commitments—excludes biogenic emissions altogether and leaves to the discretion of each country the method for including emissions from harvested wood products.

Estimating the net emissions impact of land-use change is complicated by an additional factor: the counterfactual use of the land absent the purposeful planting and/or harvesting of biomass.[402] Diverting purpose-grown tree plantations no longer needed in the pulp and paper industry for the purposes of biomass, for example, is likely to have marginal net emissions consequences. Alternatively, denuding a mature forest and later using the land for purpose-grown crops could have a less beneficial net emissions impact.

Issues of incomplete or inconsistent coverage of GHG emissions become particularly problematic for cross-border trade. If a country exporting biomass fails to completely account for emissions in the land-use sector, global accounting of emission will be inaccurate no matter the accuracy and completeness of the importing country's reporting (Figure 29). An assessment of Nationally Determined Contributions identified that only 11 of 167 countries provided a land use, land-use change, and forestry (LULUCF) target that can be fully quantified.[403] In addition, the capabilities for implementing MRV for LULUCF vary across countries, and the MRV tends to be poorly implemented, especially in developing countries.[404,405] One proposed approach to sidestep this accounting error is to use only wastes, residues, and by-products for biomass.[406]

Figure 29: GHG Accounting for Bioenergy in Practice[407]



Current GHG accounting methods do not account for when and where GHG emissions or removals occur. This leads to incentives to use imported biomass since the user of biomass secures the benefits of the emissions reduction without having to account for emissions from land-use change. Source: Adapted from IEA Greenhouse Gas R&D Programme, 2014.

Timing Mismatch for Carbon Emissions and Removals

The temporal distribution of emissions and removals—and whether these details are important for understanding the net emissions impact of BECCS—is another GHG accounting issue raised in the literature. According to some authors, emissions from feedstock-related land-use changes plus supply chain emissions create a “carbon debt” that is paid off over time as a particular forest regrows and absorbs CO_2.[408] Under this accounting framework, the “carbon payback period” or “carbon breakeven time” can approach several decades, depending on the growth characteristics of the feedstock.[409] Authors have proposed incorporating this temporal dynamic into accounting frameworks through approaches such as counting emissions and removals when they actually occur.[410]

Alternatively, other authors suggest evaluating bioenergy options based on a holistic and long-term assessment of their contributions to climate and the environment, rather than focusing on the timing of GHG emissions and removals.[411] Robust and comparable payback time estimates are difficult to make, they claim, given the wide variations of ecological systems and accounting methodology choices.[412] More importantly, these authors highlight that mitigation options should be evaluated at the systems-level to incorporate the long-term implications of induced changes in land management practices across large geographies, particularly in the forestry sector.[413,414,415]

CAN BECCS DELIVER NET-NEGATIVE EMISSIONS?

Emissions from BECCS pathways can be net-positive or net-negative.[416,417] In the near-term, the primary emissions benefits from BECCS derive from its displacement of fuels with higher life cycle emissions. These benefits do not require that BECCS pathways deliver net-negative life cycle emissions, so even projects where emissions from production, transportation, and conversion of feedstocks and energy products exceed the captured CO_2 can support beneficial emissions reductions.

As nations around the world aim for net-zero emissions by midcentury or so, incremental emissions gains from displacement of higher-emitting fuels will be insufficient. Negative-emissions pathways will be a necessity, and the promise of net-negative BECCS pathways is a primary motivation for their policy support. This section discusses the life cycle emissions impacts of BECCS feedstocks, conversion processes, and end uses.

Potential for Net-Negative Emissions by Feedstock

Each feedstock has a different potential for net-negative emissions depending on a range of factors such as biomass yield, fertilizer application, fuels used for conversion, and direct and indirect land-use change.[418] For example, some feedstocks—such as sugarcane, perennial grasses, and waste cooking oil—generally have lower life cycle emissions than other feedstocks.[419] The net-negative emissions potential of feedstocks, however, tend to be site- and case-specific and highly dependent on local factors. Table 4 shows estimates for biomass potential and equivalent amounts of CO_2 that would be removed from the global system (also known as CO_2 flux) for BECCS across various feedstocks in the United States.

Table 4: Estimated U.S. Biomass Potential and Equivalent CO_2 Fluxes (2040, Mt/yr)[420,421,422]

	Technical Potential		Economically Feasible	
Feedstock	Biomass	CO_2 Flux	Biomass	CO_2 Flux
Harvested wood and wood wastes	474	841	241	418
Purpose-grown non-wood crops	415	724	308	537
Agricultural wastes	219	382	195	339
Other organic wastes	254	205	254	205
Algae	73	?	?	?
Total	**1,435**	**2,152**	**998**	**1,499**

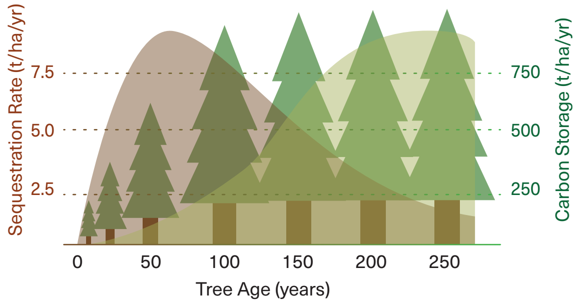
BECCS could contribute to 1.5 to 2 Gt/yr of CDR in 2040, equivalent to 25 to 36 percent of 2018 U.S. net GHG emissions of 5.9 GtCO_2 (which includes both emissions and removals from Land Use, Land-Use Change, and Forestry). Source: Data from NASEM, 2018 and NASEM, 2019.

Harvested Wood and Wood Wastes

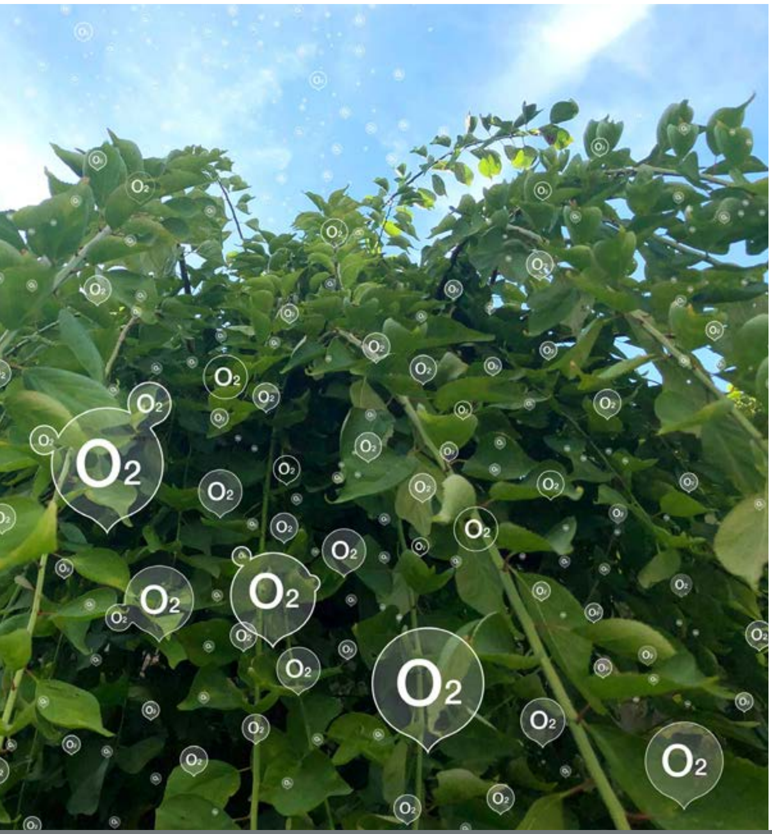
Using forestry feedstocks for BECCS can result in losses or gains in forest carbon stocks depending on the dynamics of management operations and natural biotic and abiotic forces.[423] The potential for net-negative emissions of wood products are highly dependent on species, local climate variables, and time horizons.[424] The scale of assessment is also influential; the net emissions impacts measured by stand-level assessments could be different from the results by landscape-scale assessments that incorporate economic factors and forest management practices.[425] At the stand level, using forestry wastes could reduce emissions more quickly than using purpose-harvested wood because the carbon payback periods of forestry wastes could be shorter than those of harvested wood.[426] At the forest level, forest growth, combined with sustainable management, can enable biomass production that delivers cumulative net GHG savings even when using purpose-harvested wood.[427]

Studies have shown a large variance in the estimated life cycle emissions of forestry products. For example, one review of life cycle emissions from different feedstocks for electricity generation found that emissions from forestry byproducts tend to be lower than the emissions from other biomass sources such as agriculture residue, purpose-grown wood and non-wood energy crops, and organic waste.[428] Another study, however, found that forestry products could have greater life cycle emissions than other feedstocks depending on factors such as end-use or region.[429,430] Fast-growing forests with short rotations tend to have less emissions reduction potential than slow growing forests with longer rotations given the change in carbon sequestration rates over the life of the trees (Figure 30).[431]

Figure 30: Sequestration Rate and Carbon Storage Over the Age of Forests[432]



Old forests store more carbon than young forests, but young forests sequester carbon at a faster rate than old forests. Sequestration rates increase rapidly as trees grow and then decline gradually over time. Source: NCASI, 2021.



Purpose-Grown Crops

Despite the significant potential of energy crops as BECCS feedstock supply, the actual use of purpose-grown crops for BECCS is uncertain due to concerns about land-use impacts (see discussion of "Land-Use Impacts of Feedstock Production" on page 74). As shown in Table 4, purpose-grown non-wood crops account for 36 percent of the CO_2 removal from economically feasible U.S. biomass for BECCS in 2040.[433] NASEM's 2019 report, *Negative Emissions Technologies and Reliable Sequestration: A Research Agenda*, however, excluded energy crops—both wood and non-wood—from the lower bound of estimate of carbon flux because of environmental and food security concerns.[434]

The context-dependent impact of purpose-grown crops on land-use change may lead to net-positive life cycle emissions of certain BECCS pathways. For example, a comparative analysis of three feedstocks using pyrolysis with biochar showed that the biochar-pyrolysis system with switchgrass would be a net-positive GHG emitter if the indirect land-use change is included, while the GHG emissions from the other two feedstocks—crop residues and yard waste—would be net-negative.[435]

Agricultural Wastes

Agricultural wastes have significant potential for net-negative emissions through BECCS pathways, but their specific potential varies depending on how they are collected, processed, and transported. A review of GHG emissions from electricity generation using different biomass feedstocks found that the mode and distance of transportation was a major contributor to GHG emissions for agricultural residues.[436] In addition, agricultural residues need to be processed into pellets or other forms to be used for power generation, which may generate additional emissions.[437] Several studies also found that gasification of agricultural residue had high potential for emissions reduction.[438,439]

Other Organic Wastes

Many regions of the world combust waste for energy, and the technology to capture CO_2 from this process is similar to the capture technology used for fossil fuel-fired power plants.[440] A global scenario analysis found that, if all available 4 Gt/yr of MSW worldwide was used as feedstock, BECCS using MSW could potentially reduce CO_2 emissions by 2.8 $GtCO_2$/yr by 2100, while landfill gas combustion with CCS could reduce CO_2 emissions by 1.16 $GtCO_2$/yr worldwide.[441] The dispersed nature of waste, however, is one of the technical challenges to expanding waste-based BECCS deployment. In this context, an analysis of potential urban waste-based BECCS in China showed that the regions with higher densities of population and economic activity would have high emissions reduction potential through waste-based BECCS projects.[442]

Algae

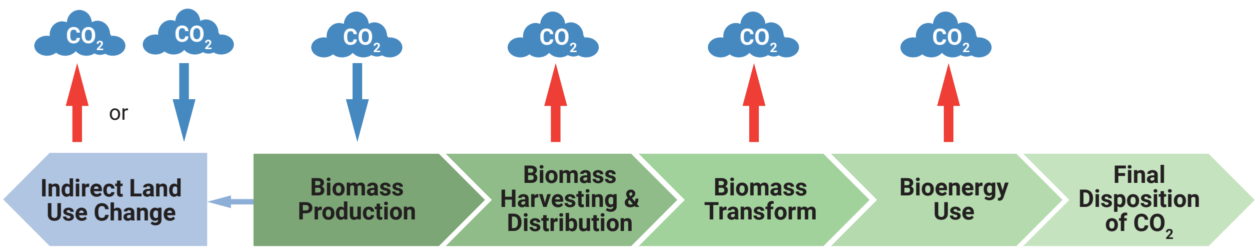
Many studies have found significant emissions reduction or negative emissions potential from using algae for energy production. Algae absorbs higher levels of CO_2 with less land use than terrestrial plants.[443] Previous studies on GHG impacts of using algae compared to using other biomass feedstocks, however, find mixed results. An LCA of biodiesel production from microalgae showed that the emissions from algae were significantly lower than the emissions from canola and ultra-low sulfur diesel.[444] Another study found that the emissions from algae use were greater than those from conventional crop use due to greater upstream emissions impacts from using algae (e.g., demand for CO_2 and fertilizer).[445] An LCA using commercial data found that the emissions from using algae for biodiesel production were much higher than the emissions from soy diesel.[446]

Potential for Net-Negative Emissions by Conversion and End Use of Biomass

Studies on the GHG emissions impacts of BECCS pathways can come to different conclusions as to whether a pathway can achieve negative emissions. Overall, use of BECCS in the power sector has greater potential for negative emissions than BECCS use in biofuel production because more CO_2 can be captured. The life cycle emissions from the supply chain of BECCS, however, depend on many factors related to biomass production, harvesting and distribution, conversion, use, and even indirect land-use change (Figure 31). Therefore, a “cradle-to-grave” approach, including both upstream and downstream emissions, is often used for measuring the net impact of a BECCS pathway.[447] In addition, the boundary often includes indirect land-use change, whose effects could be more significant than those of direct land-use changes.[448]

Many studies have found significant potential for negative emissions when BECCS is used in the power sector. Applying CCUS to biomass combustion can significantly improve the carbon intensity of biomass power plants, which have higher emission factors (at the point of combustion, not over the life cycle) than natural gas plants without CCS.[449] One analysis showed that all waste-based BECCS scenarios led to net-negative GHG emissions in the Australian power sector.[450] Simulations of different technologies in the U.K. showed that adding a CO_2 capture plant drastically reduces emissions in biomass power plants.[451] Co-firing biomass with CCS enables negative life cycle CO_2 emissions in a coal-fired power plant, depending on co-firing ratios.[452,453] An integrated gasification system of coal and biomass with CCS could produce electricity with net-zero life cycle GHG emissions depending on the share of biomass used in the system.[454]

Figure 31: BECCS Supply Chain and Emissions[455]



GHG emissions are generated throughout the BECCS supply chain; emissions can be greater or lesser than the amount of carbon captured. Indirect land-use change emissions could be significant depending on the conditions of biomass production; they could also be negative in the case that the economic value for biomass production induced more intensive cultivation than would have been otherwise. Source: Adapted from Jones and Albanito, 2020.

Reaching net-negative pathways of biofuel production is more challenging than in the power sector because less CO_2 can be captured in the conversion process compared to the pathways to generate electricity and heat. An LCA of ethanol production with CCS shows that ethanol-gasoline blends above 85 percent could potentially deliver net-negative emissions—up to -5.05 kgCO_2 per 100 kilometers travelled in a passenger vehicle—if a low-carbon electricity source (e.g., wind power) powered the production process.[456] This study also found that the potential amount of CO_2 removed was highly dependent on the carbon intensity of the electricity and heat generation unit used; to maximize CO_2 removal, the project should be located near low-carbon energy sources. A case study by Lawrence Livermore National Laboratory showed that emissions capture from both fermentation and steam-generation processes in the production of ethanol could not achieve life cycle negative CO_2 emissions, though it could reduce emissions by 43 percent.[457]

BECCS SUPPLY CHAIN CHALLENGES

A key challenge for BECCS development in the United States is that biomass supply, feedstock pre-processing facilities, bioenergy conversion facilities, and CO_2 storage locations are rarely co-located, requiring additional and distinct infrastructure. Skilled labor and equipment, such as felling machines to harvest and chippers to pre-process, is required to convert the feedstock from the field or forest into a useable form at the conversion facility. CO_2 infrastructure (e.g., pipelines) to transport the captured CO_2 from the conversion facility to a CO_2 storage site is necessary unless the conversion site is co-located with suitable geologic storage.

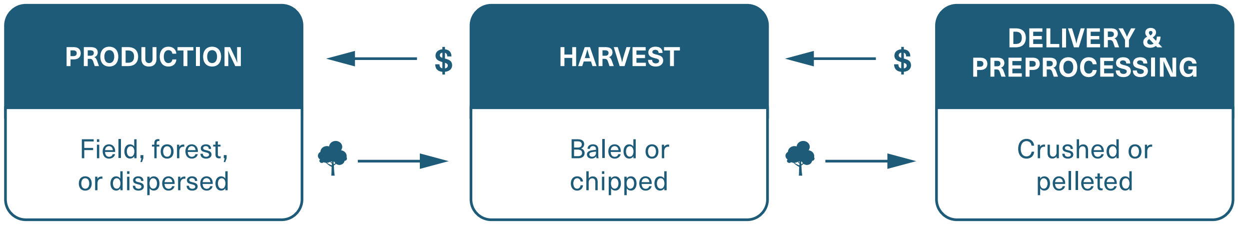
Feedstock Supply Chains

Different biomass feedstocks have distinct supply chains, costs, and total emissions impacts. These factors should be considered when assessing the BECCS potential of a region. DOE broadly divides the biomass feedstock supply chain into three parts—production, harvest, and delivery and processing—as shown in Figure 32.[458] Various types of equipment, trucks, and trained workers are needed at each stage. Timber harvesting requires felling tools like chainsaws and extraction gear like cables; energy crop harvesting requires mowing and baling machines. Wood pre-processing requires chippers and pelleting machines.

The nascent biomass supply chain today depends on agricultural supply chains. The supply of biomass is vulnerable to a multitude of factors—geographic variability, damage due to weather and pests, and degradation in storage.[459] Agricultural and forestry feedstock supply relies on trucks transporting a single feedstock type to a plant that processes only that feedstock, increasing costs.[460] Production, harvest, pre-processing and chemical conversion may be located far away from one another due to differences in ideal growth locations and demand centers. The low density of these crops forces underutilization of truck capacity. Baling and chipping machines designed for conventional agricultural crops break down easily when used for stiff and thick lignocellulosic crops or harvested wood. DOE has been funding RD&D projects that address supply issues, such as development of intermediary regional processing facilities that could accept all kinds of feedstocks in a particular region and convert them to bioenergy or bioproducts.

Unlike agricultural or forestry feedstocks, municipal wastes like food waste and sewage already have centralized supply chains managed by municipalities that gather such wastes and take them to landfills and treatment plants, respectively, making it relatively easier to divert such wastes to BECCS plants.

Figure 32: Typical Biomass Supply Chain[461]



In a simplified biomass supply chain, the producer sells raw feedstock to the harvester; and the harvester sells the baled or chipped feedstock to the pre-processor. Source: DOE, 2016.

CO_2 Transportation Infrastructure

Captured carbon that is not co-located with suitable geologic storage must be transported to a permanent storage location via pipeline, truck, rail, or ship. There are 4,500 miles of CO_2 pipelines, largely confined to a few specific regions: the Texas and Louisiana Gulf Coast, West Texas, the southern Midwestern states, and Wyoming.[462] Existing CO_2 infrastructure geographically overlays many oil and gas reservoirs because it can provide additional revenue through EOR, where CO_2 is injected into wells to release additional crude oil and is then permanently stored in those underground reservoirs. The majority of operational CCUS projects to date are also found in these regions.

In part due to its limited geographic reach, CO_2 infrastructure at present is insufficient to support a gigaton-scale CO_2 management network.[463] There are about 1,500 CO_2-generating facilities that could be eligible for the Section 45Q Carbon Oxide Sequestration tax credit today (i.e., industrial facilities emitting at least 100,000 metric tons of CO_2 emissions each year and power generators emitting at least 500,000 metric tons each year), but only a small percentage of them are close to the existing CO_2 pipeline infrastructure that would be required to sequester their captured CO_2.[464]

Despite the need for a gigaton-scale CO_2 management network, there are legal, financial, and public support barriers to further U.S. CO_2 transportation infrastructure development. Currently, the permitting environment for CO_2 infrastructure is complex because of the numerous entities involved in the process, and the uncertainties surrounding permitting landscapes and timelines, which vary across states.[465] Additionally, without clear public policy support mechanisms for CO_2 transportation, there is essentially no financial incentive to inject CO_2 for long-term geological storage aside from the revenue that comes from EOR.[466] There are also varying public opinions on CO_2 pipeline development and storage projects, including hesitancy about technical risks like leakage, investment tradeoffs compared to other carbon abatement technologies, historic inequities, and concerns that CO_2 transportation and storage does not decrease the use of fossil fuels.[467] These components of the current CO_2 infrastructure landscape exemplify why CO_2 pipeline construction has been expensive and publicly unpopular to date.

RESEARCH, DEVELOPMENT, AND DEMONSTRATION GAPS

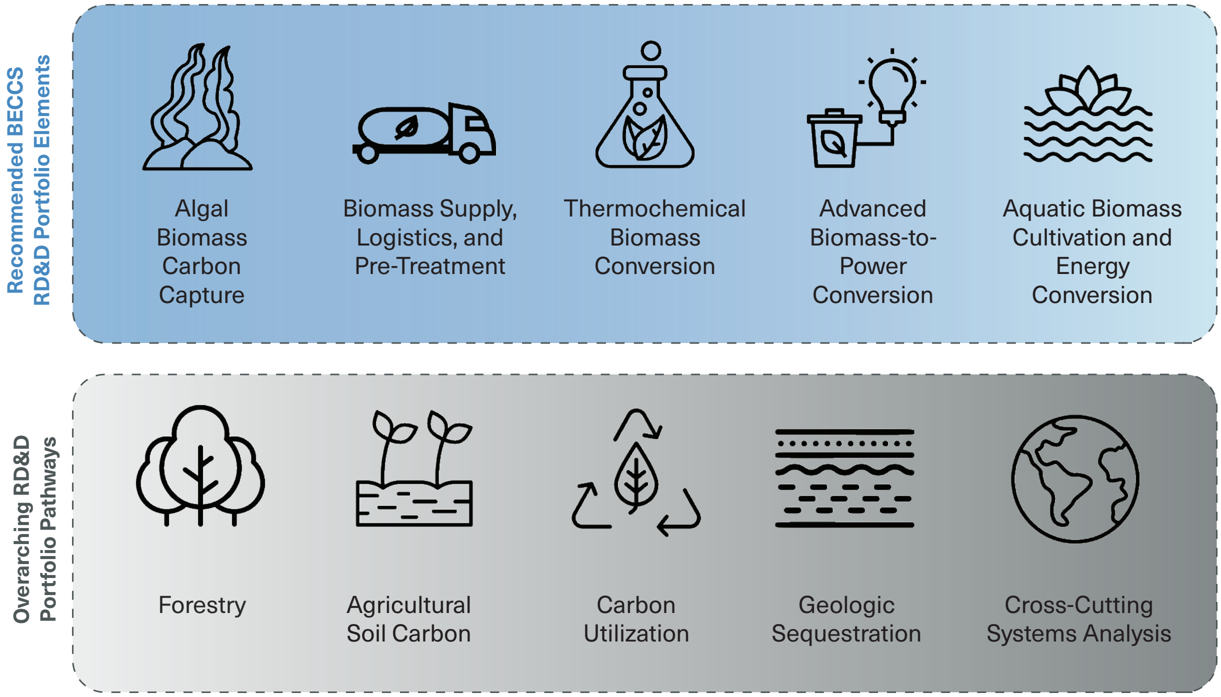
RD&D is necessary to increase the technological and economic viability of BECCS and encourage its large-scale deployment alongside other CDR solutions. In addition to lowering the cost of BECCS, RD&D can also address other goals such as increasing efficiency and decreasing resource needs, identifying new use cases and geographies for deployment, and providing greater certainty of negative life cycle emissions. There are RD&D needs across the supply chain for BECCS from feedstocks to CO_2 storage, as well as crosscutting issues. This section gives a non-exhaustive overview of some major areas for further RD&D across the BECCS supply chain.

EFI's previous CDR report, *Clearing the Air: A Federal RD&D Initiative and Management Plan for Carbon Dioxide Removal Technologies*, identified five priority areas for BECCS RD&D that build on the NASEM's *Negative Emissions Technologies* report:

- Feasibility and optimization research on algal biomass carbon capture;
- Biomass supply, logistics, and pre-treatment;
- Biomass conversion to fuels with biochar, including RD&D of thermochemical conversion pathways, maximizing biochar and bio-oil production, and distributed biomass processing;
- Advanced biomass-to-power conversion, including advanced boiler technology, conversion of existing coal-fired plants, and LCA; and
- Aquatic biomass cultivation and energy conversion pathways.[468]

The EFI report also outlined RD&D needs for related areas such as forestry, agricultural soil carbon, carbon utilization, geologic sequestration, and crosscutting systems analysis (Figure 33).[469]

Figure 33: Recommended RD&D Portfolio Elements and Pathways for BECCS[470]



The elements and pathways visualized in this figure draw upon EFI's previous CDR report, Clearing the Air: A Federal RD&D Initiative and Management Plan for Carbon Dioxide Removal Technologies*, which proposes a ten-year, $11-billion RD&D portfolio for CDR technologies. The recommended RD&D portfolio elements in the first row would specifically support BECCS technologies, while the overarching RD&D portfolio pathways in the second row would support BECCS RD&D in addition to other CDR technologies. Source: EFI, 2019. Icons from the Noun Project.*

Feedstock RD&D

Innovation will be crucial to lowering the cost and emissions intensity of biomass feedstocks. Federally-funded RD&D on logistics—harvest and collection methods, storage technologies, transportation and handlings, and advanced pre-processing—has led to increased biomass availability, lower costs, and lower emissions intensity.[471] BECCS can also benefit from RD&D related to other CDR methods, such as improved monitoring and modeling of forest and soil carbon, and high-carbon input bioengineered crops.[472] Finally, RD&D is needed to commercialize new feedstocks that could have benefits for BECCS but are not yet widely cultivated, namely algae.

Energy Conversion RD&D

RD&D on the conversion component of BECCS is crucial to both biopower and biofuels pathways. RD&D could help determine pathways for integration of BECCS-generated power onto an electricity grid that may have a growing proportion of intermittent renewable resources, which could pose challenges around load following, ramping, and system flexibility.[473] Additionally, long-term research into plant network configuration, capital cost reduction, impacts on CO_2 transport and storage equipment, and competition for biomass supply may be necessary.[474]

A key part of biofuels RD&D is commercializing technologies to develop biofuels from new types of feedstocks, especially lignocellulosic biomass. Lignocellulosic biofuels have long been a research objective for DOE, but the technology has yet to be widely deployed. Biofuel RD&D also encompasses the production of new types of fuels, such as hydrogen and drop-in liquid biofuels, which could serve new use cases. Further research is also needed on less conventional conversion processes that could provide benefits to BECCS, such as modular systems, pyrolysis, and supercritical water extraction.[475]

CCUS RD&D

There are RD&D gaps specific to CCUS that will also need to be addressed in advance of BECCS deployment, particularly in terms of engineering distributed bioenergy production systems. Further research is needed into the co-location of BECCS facilities with CO_2 storage, including the potential for on-site storage sites and the collection of CO_2 into long-distance pipeline networks.[476] The quality and variability of CO_2 produced from different biomass feedstocks will also require exploration to understand the long-term impacts of these factors on pipeline and subsurface equipment.[477]

More generally, CCUS RD&D may also help reduce the capital costs of CCUS and inform general CO_2 transportation and network configuration.[478] This type of research could explore sequestration techniques that reduce seismic risks and monitor injection sites over the long-term.[479] Additional portfolios could focus on utilization technologies—including geochemical, chemical, and biological conversion—examining system and process integration, the development of new materials, and the development of the enabling technologies and infrastructure required for a CO_2 utilization market.[480] A particular area of interest is carbon “recycling” into fuels, using CO_2 combined with low-carbon hydrogen as the basis for low-emissions fuels, including drop-in replacements for fossil fuels.[481]

RD&D is also needed into non-CO_2 forms of carbon capture and storage, such as biochar. Better monitoring, modeling, and demonstrations of biochar use in soils can help with understanding of its stability and its impact on soil carbon.[482,483] Biochar production engineering and market development will also be important.

Crosscutting RD&D

Interdisciplinary social science research could contribute to a more holistic understanding of the indirect impacts of large-scale BECCS deployment. Most social science research to date on BECCS has focused on the technology adoption barriers and public acceptance, rather than on the social processes and the understanding of community dynamics along the BECCS value chain.[484] Existing research has identified a set of indicators—including employment status, trade volume, and public opinion, among others—that could help quantify the socioeconomic sustainability of bioenergy applications. These indicators embody broader socioeconomic issues related to BECCS like social well-being, energy security, trade, profitability, resource conservation, and social acceptability.[485] Further research could also explore comparisons between past and present energy transitions, the subsequent investment gap, and how that would relate to scaling up the bioeconomy. This social science research could provide useful information to policymakers and other key stakeholders, such as landscape-level analyses of CDR technologies and assessment of technological diffusion across different socioeconomic contexts.[486]

Given the interconnectedness between technological and social science research on BECCS, techno-economic assessments could be used to address simultaneously current RD&D gaps in both research areas. GHG LCAs also require insights from both technological and social science research because of their model input complexity, the required long-distance transport methods involved in the BECCS industry, and second-order impacts of BECCS projects. These more cumulative assessments and analyses are necessary to determine whether BECCS projects are contributing to a net removal of CO_2 from the atmosphere.[487]

Further research can also address crosscutting issues associated with BECCS. Academic researchers and federal laboratories could coordinate regional LCAs and integrated assessment modeling. Studying BECCS alongside other CDR technologies could inform project developers on how these potential solutions would impact different economic and social contexts. Such modeling—reinforced by empirical studies to validate both concerns and opportunities—could also explore the indirect impacts of BECCS deployment on ecosystem services, biodiversity, radiative impacts from albedo changes, food security, and water resource depletion.[488]

A final crosscutting RD&D objective is the exploration of engineered biomass carbon removal (i.e., BiCRS) pathways that do not involve conversion to energy. Examples include engineered wood products, subsurface bioliquid injection, creation of durable bioproducts (e.g., bioplastics, biofiber cement), and ocean-based pathways.[489,490] These systems could be integrated with BECCS; shared innovation could also benefit both energy and non-energy pathways. Figure 34 summarizes these crosscutting RD&D gaps in addition to those dealing with BECCS feedstocks, energy conversion, and CCUS.

Figure 34: Summary of RD&D Gaps for BECCS

FEEDSTOCK RD&D

Feedstock logistics

Forest/soil carbon modeling and monitoring

Algae feedstock commercialization

High-carbon input bioengineered crops

ENERGY CONVERSION RD&D

Systems integration

Lignocellulosic conversion commercialization

Algae conversion commercialization

Hydrogen

Drop-in liquid biofuels

Emerging conversion processes

CCUS RD&D

CCUS system design

Geologic storage capital costs

Modeling/monitoring of geologic and biochar storage

Enabling technologies and infrastructure for CO_2U

New CO_2U product development

Biochar production and market development

CROSSCUTTING RD&D

Social science research

Techno-economic and life cycle analysis

Modeling and regional assessments

Non-energy biomass carbon removal and storage

Increased RD&D efforts into BECCS feedstocks, energy conversion, and CCUS applications could address many of the current RD&D gaps for BECCS. Additional RD&D into crosscutting issue areas using techno-economic analyses, integrated assessment modeling, and LCAs could also provide a better understanding of the full impact of gigaton-scale BECCS deployment.

ENVIRONMENTAL IMPACTS AND RESOURCE REQUIREMENTS OF BECCS

BECCS projects are of consequence to their environments—impacting water, air, and natural ecosystems—and require resources such as land, water, and fertilizer to grow biomass and convert it to energy. The literature identifies several key environmental and resource considerations, including potential benefits and detriments.

Local Air Quality Impacts

Current bioenergy supply chains have varying effects on local air pollutants, such as particulate matter (PM), CO, sulfur oxides (SO_x), nitrogen oxides (NO_x), ammonia (NH_3), and volatile organic compounds (VOC).[491] Feedstock production can have both positive and negative air quality effects, while transportation, pre-processing, conversion, and combustion can all produce pollution, as seen in Figure 35.

Negative Impacts

The production, transport, and pre-processing of biomass feedstocks could generate local air pollutants; these pollutants will vary by feedstock type and region. For example, DOE found that emissions of many air pollutants were lower per unit biomass for lignocellulosic feedstocks than for corn grain.[492] Fertilizers, pesticides, and fossil fuel use for transportation and pre-processing are all sources of air pollution. These emissions can be mitigated by process changes such as more efficient machinery, local production of biomass, and rail transport.

Figure 35: Local Air Quality Impacts of the BECCS Supply Chain[493]

	Fertilizers	Pesticides	Harvesting	Preprocessing	Transport	Combustion	CO_2 Capture
NO_x	▲		▲		▲	▲	▼
NH_3	▲		▲				
VOC		▲		▲			
PM			▲ ▽		▲	▲	▼
SO_x				▲	▲	▲	▼
CO				▲	▲		

▲ Possible Pollutant Source ▽ Indirect Mitigation Opportunity ▲ Direct Mitigation Opportunity

Harmful air pollutants, including nitrogen oxides (NO_x), ammonia (NH_3), volatile organic compounds (VOC), particulate matter (PM), sulfur oxide (SO_x), and CO are released during various stages of the feedstock supply chain—production, pre-processing, transport, and combustion. Harvesting could potentially be an indirect way to mitigate pollutants if it leads to the prevention of wildfires or agricultural residue burning. CO_2 capture technologies reduce the amounts of NO_x, PM, and SO_x before the gas stream reaches the inlet of the capture system. Source: Data from DOE, 2017.

Conversion of biomass to energy can also have negative impacts on local air quality. Combustion of most biomass or biofuels produces some air pollution.[494,495] Certain waste management systems that could be harnessed for BECCS—such as biogas combustion and waste incinerators—have been found to have negative air quality impacts. At the same time, these systems sometimes replace infrastructures with their own pollution problems, such as manure lagoons and landfills.[496,497]

Another potential negative consequence of BECCS projects is the loss of passive air quality benefits provided by living biomass. Trees and forests provide health benefits by improving air quality and lowering temperatures in the surrounding area. If BECCS feedstock production leads to deforestation, air quality in surrounding communities could degrade.[498] On the other hand, BECCS could have a beneficial impact if trees are planted, or forestland is restored, due to a market for wood.

Positive Impacts

Using various waste feedstocks for BECCS could potentially have positive impacts on air quality. Agricultural and forest residues are often disposed of by burning, releasing PM and hampering local air quality.[499] These negative side effects can be avoided by diverting these wastes to BECCS pre-processing plants. Collecting forestry residues can also help prevent wildfires, which have serious negative impacts on air quality at the local level and beyond.[500]

BECCS could also benefit air quality through the application of carbon capture to conversion and combustion facilities. Carbon-capture retrofits of fossil fuel facilities have the potential to reduce SO_x, NO_x, and PM from those facilities—a benefit that can also be achieved through bioenergy plant retrofits.[501]

Water Requirements and Impacts

BECCS projects need water at various stages, especially during feedstock growth and thermal power generation. One study, projecting that 12 $GtCO_2$/yr of BECCS be deployed globally by 2100 to reach 2 degree compliance, found that nearly 60 km^3 of water (1.5 percent of global freshwater withdrawal[b]) would be needed for each gigaton of CO_2 captured and sequestered via BECCS.[502,503] The U.S. agricultural sector, for reference, consumed 163 km^3 of freshwater for irrigation in 2015, which is slightly more than one-third of total U.S. water withdrawals.[504]

Tapping groundwater and diverting water from ecosystems for BECCS projects could put pressure on resources in water-constrained regions.[505] A recent modeling study found that gigaton-scale BECCS relying on irrigation—without the implementation of sustainable water management practices—could increase water stress[c] globally at levels that rival the water stress imposed by climate change.[506]

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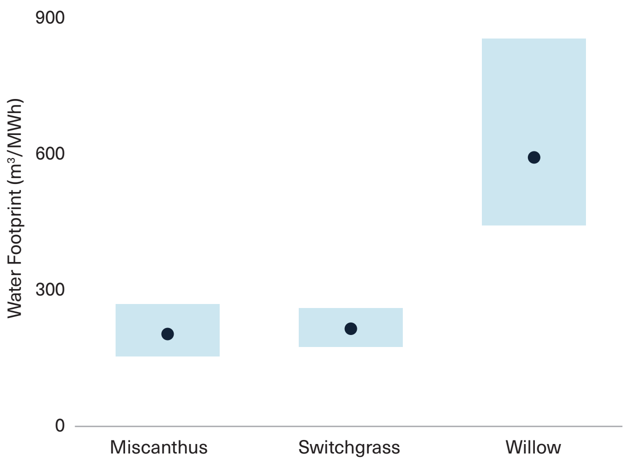
b Water withdrawal is different from water consumption: withdrawal refers to water that is extracted from sources, whereas consumption refers to water that is evaporated, removed, converted, or used by living organisms.

c Water stress is the ratio of total water withdrawals to available discharge.

Feedstock Production

The volume of water needed for BECCS projects will vary by region, feedstock, and conversion method.[507] For example, *BT16* modeled the water-consumption footprint of producing various feedstocks across scenarios.[508] Biomass grown over a large area in the Corn Belt will need substantially more water than biomass grown densely in the Southeast. Feedstocks like corn grain and soybeans will need irrigation; deep-rooted perennial grasses absorb more rainwater and need little to no irrigation. Figure 36 compares the water requirements of three agricultural feedstocks.

Figure 36: Water Footprints of Agricultural Feedstocks[509]



Wood and non-wood lignocellulosic crops need a large volume of water to be produced, transported, pre-processed, and converted to electricity in a power plant with carbon capture. Woody feedstocks like willow need more water than non-wood feedstocks like miscanthus and switchgrass. Source: Data from Fajardy and MacDowell, 2017.

Water contamination is also an issue associated with feedstock production, especially fertilizer runoff.[510] *BT16* studied the impact of feedstock growth on the water quality of the Mississippi River, and consequently advised that the impact of forest biomass removal on water quality and supply be empirically investigated.[511] The study identified numerous conservation practices and perennial feedstocks that could help reduce nutrient leakage into bodies of water and improve water quality.[512]

Thermal Power Generation with Carbon Capture and Storage

Thermal power generation needs water to run steam turbines and to cool down systems. The total volume of water used for thermal power generation in 2015 was 184 km^3/yr, 41 percent of all water withdrawn in the United States.[513] The majority of this water is not consumed and is returned to nearby bodies of water; however, the high temperature of wastewater harms aquatic life.[514] Carbon-capture technologies like BECCS systems for thermoelectric power generation require additional water to operate, depending on the type of technology used.[515] The amount of water consumed by a BECCS power plant is a small fraction of the total water footprint of the purpose-grown crops in Figure 36.[516]

Land-Use Impacts of Feedstock Production

Like many other aspects of BECCS, the land-use impact of increased demand for feedstocks is highly circumstantial; the volume, location, and type of feedstock requirements are important determinants. Policy guardrails will be critical to ensure sustainable use of land and to prevent unintended consequences from the growth of the BECCS industry.

Waste-based feedstocks, while finite, may have very little direct land-use impact. However, even a small increase in the economic value of those feedstocks can increase the overall harvest value and change land-use patterns. Larger-scale deployments are guaranteed to have major land-use implications: BECCS deployment to achieve carbon removal of 10 $GtCO_2$/yr to 15 $GtCO_2$/yr globally could require 380 million to 700 million hectares (Mha) of land area; gigaton-scale BECCS in the United States alone could require around 80 Mha of land, 20 percent larger than the land area of Texas.[517,518]

Many countervailing factors determine the land-use impacts of biofuels feedstocks production. First, consider the case of woody biomass. Most woody biomass in the United States today derives from low-value trees and harvest residues that are incidental to the higher-value primary forest product and would either be left in the field to decompose, burned on-site, or sold to the wood pulp industry.[519] Where these lower-value products would have been left at the harvest site, their use as a bioenergy feedstock would have only marginal land-use impacts by increasing the aggregate value of the harvest and providing a financial incentive to maintain or increase the total acreage under active management. The higher the demand for woody feedstocks, the less incidental these feedstocks would be to the harvest and the greater the financial incentive to maintain more land under management. DOE estimates that there is roughly 40 Mt of forestry and other wood wastes available as bioenergy feedstock, roughly four times the amount of U.S. pellet production today; exceeding this amount of annual woody biomass demand would require dedicated forests.[520] Agricultural wastes face similar economics: roughly 50 million dry metric tons are available annually at or below $30/dry metric ton, increasing to 150 million dry metric tons for prices above $50/dry metric ton. Above these volumes, dedicated crops or harvests would be required.

In the case where land is required for dedicated feedstock production or induced through increased value of incidental waste feedstock production, the land's past and future alternative uses are a large determinant of the environmental and economic consequences of feedstock production. Replacing non-native grazing land with managed forests, for example, would very likely increase that land's ability to store carbon and improve local ecology. Maintaining existing forests in lieu of urban development—the leading driver of deforestation in the United States—would also very likely improve carbon sequestration and ecological outcomes for that plot of land.[521,522]

Another area of study regarding land use for BECCS is the potential impact of feedstock production on food security—in particular, the question of whether devoting agricultural land to purpose-grown crops or forestation would increase land demand and food prices.[523,524,525] There is disagreement in the literature over how much risk food security issues present to BECCS deployment. One study estimates that half of biomass demand from BECCS could be met by agricultural wastes, residues and other forest resources, with the remainder coming from purpose-grown energy crops cultivated on just 8 percent of U.S. cropland.[526] At least one study argues that bioenergy production improves food security.[527] Another study notes that any rise in food prices could be expected to occur when BECCS is implemented at large scale (in 2040 or later), suggesting that it may not be a concern in the near term.[528]

There are several ways to reduce the land-use impacts of purpose-grown crops. These crops could be grown on land unfit for the growth of food crops, such as previously developed land (brownfields) and marginal agricultural land.[529] Crop yields, however, tend to be lower when grown on marginal lands and require more land for a similar volume of feedstock.[530] Use of more energy-dense feedstocks also decreases land requirements; miscanthus, for example, has been found to produce more energy per unit area harvested when compared to other crops such as corn, switchgrass, and poplar.[531]

Indirect land-use change is an extremely difficult-to-quantify driver of environmental and economic outcomes related to bioenergy production. Land used for energy feedstocks displaces other productive uses (e.g., urbanization, food crop production, wildlife management). These displaced uses may turn up in other locations, which can have variable environmental consequences.[532] For example, if continued forest management is more economic for a particular plot of land than urbanization, that urbanization may occur on natural forest lands or a desiccated brownfield, each with very different environmental impact. At today's level of bioenergy production from Southeast forests, however, there is little evidence that indirect land-use change is having a material impact.[533]

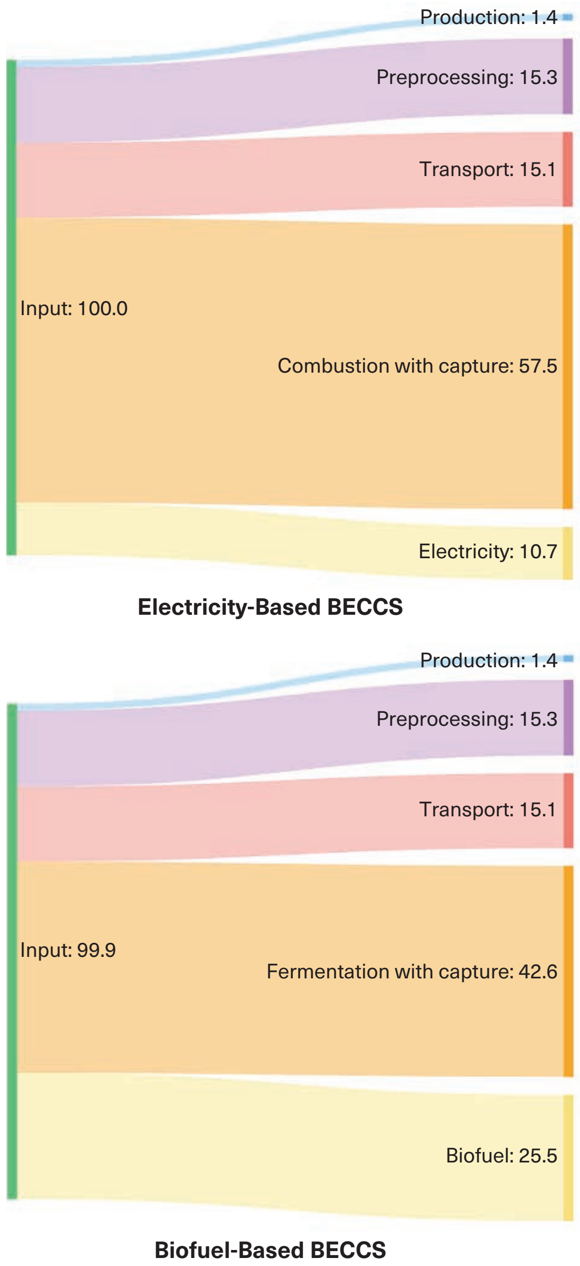
Energy Requirements

Energy is needed throughout the BECCS supply chain to produce, harvest, process, and transport feedstocks, build infrastructure like pre-processing plants and CO_2 pipelines, and for conversion and carbon capture processes. Energy requirements vary depending on the feedstock, conversion method, carbon capture technology, and purity and volume of captured CO_2.[534,535]

Feedstocks impact the energy consumption of a BECCS pathway because each feedstock has different fertilizer requirements, moisture content, ideal growing locations, distance from harvest to pre-processing sites, pre-processing energy requirements, and combustion efficiencies.[536] Considering the factors leading to higher energy requirements for woody crops like willow relative to herbaceous grasses like miscanthus or switchgrass provides a useful example.[537] First, willow needs more fertilizer to achieve the same yield as these grasses; chemicals, which include fertilizers, can contribute up to 10 percent of the energy requirements of a feedstock.[538,539] Additionally, woody feedstocks have a higher moisture content than herbaceous grasses; more energy needs to be spent on drying the former before they can be pelletized.[540] Lastly, 70 percent of energy consumed while pre-processing biomass into pellet form is used to dry wood.[541]

The BECCS conversion plant—where emissions are captured while biomass is converted to a useful form of energy—is the most energy-intensive component of the supply chain (Figure 37).[542] Conversion efficiencies of biofuel-based BECCS can be more than twice as energy efficient as electricity-based BECCS.[543]

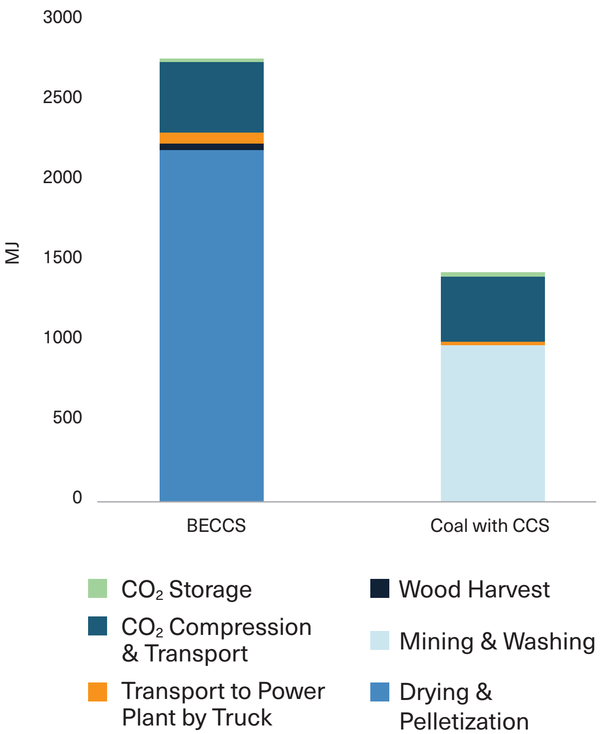
Figure 37: Energy Flow Diagram for 100 MJ of Energy Input for Electricity- and Biofuel-Based BECCS Using Miscanthus[544]



Biofuel-based BECCS pathways can produce more than twice the amount of usable energy when compared to electricity-based BECCS pathways (see "Electricity" in the electricity-based BECCS diagram versus "Biofuel" in the biofuel-based BECCS diagram). Source: Adapted from Fajardy et al., 2019.

BECCS can be much more energy-intensive than fossil fuel combustion. Producing electricity via BECCS requires nearly twice as much energy as producing electricity via coal with CCS, mostly due to the energy required to pre-process the biomass (Figure 38).[545] Wood and wood pellets also have a lower combustion efficiency than coal, requiring more fuel per unit of generated electricity.[546,547]

Figure 38: Energy Consumed to Produce 1 MWh of Low Carbon Electricity via BECCS and Coal with CCS[548]



Nearly twice as much energy is needed to produce electricity via BECCS than via coal with CCS. Eighty percent of this energy is consumed during the drying and pelleting stage. Source: Data from Qun Yi et al., 2018.

Biodiversity Impacts of Forestry Feedstock Production

Accounts of the effects of bioenergy systems on biodiversity vary. In some cases, biodiversity loss may occur where natural ecosystems are replaced by intensively-managed forests that, in part, support bioenergy markets.[549,550] A change in plant species may hurt critical wildlife that depend on specific trees (e.g., certain types of pine or hardwood). On the other hand, harvesting low-grade wood for bioenergy reduces tree density (forest thinning) and lowers the risk of damage from pests, diseases, or fires, providing biodiversity benefits.[551] Potential negative impacts on ecosystems can also be mitigated by introducing incentives for forest carbon sequestration.[552]

Reforestation or forest preservation for bioenergy purposes can also benefit natural ecosystems. Historically, parts of the Southeastern United States have consisted of pine grasslands[d] that sustained many bird species; conversion of these pine grasslands to other uses (as well as changes in forest composition from fire suppression) led to a decline in the bird populations.[553] Pine plantations grown by private foresters have assisted in the recovery of the biodiversity that was lost in past forest conversions.[554] BECCS creates a market for low-grade wood that adds to the incentives that private forest landowners have to maintain their woodlands, preventing forests from being converted to other land uses like pastureland; it also incentivizes more active forest management that could likewise have beneficial ecosystem impacts.[555] Although trees are harvested and used

d Pine grasslands are open forest ecosystems that consist of a pine forest overstory and a grassland understory.

for bioenergy (and other products), more new trees are grown, leading to a net increase in trees and creating new homes for wildlife. Some plantations, however, have fewer standing dead trees per hectare, which may have a detrimental long-term effect on species that live in such trees.

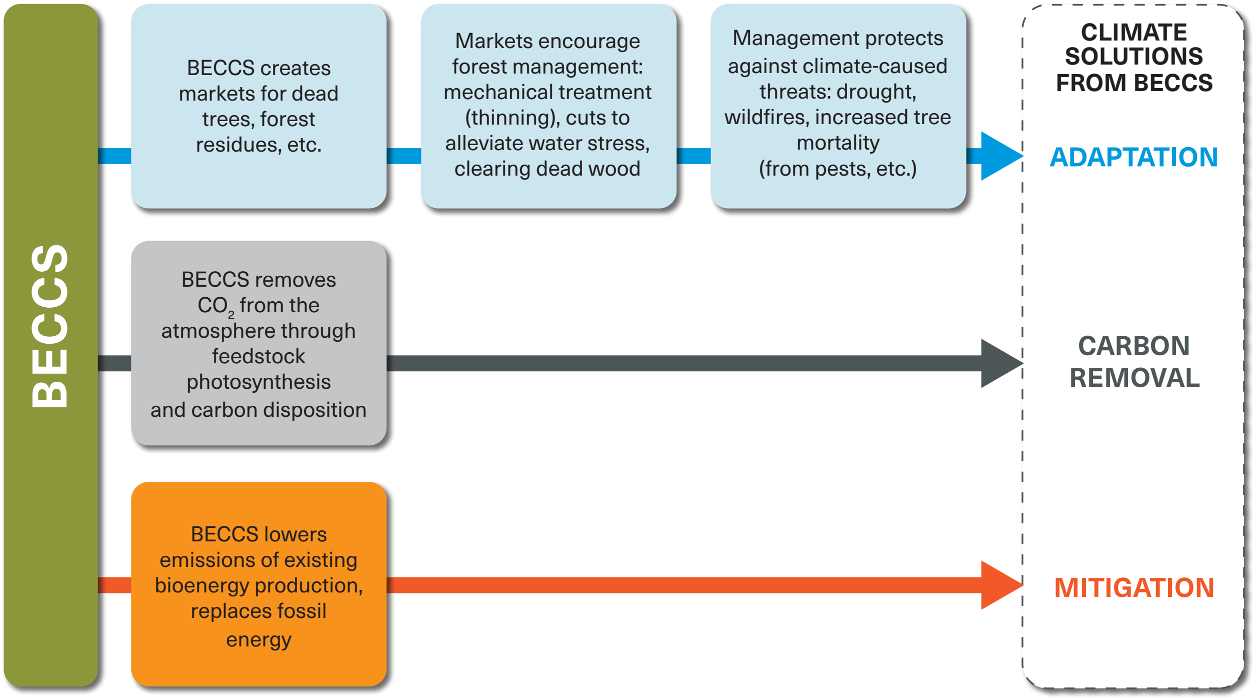
Opportunities for BECCS to Enhance Forest Resilience

Forest resilience is receiving growing attention as disturbances to ecosystems have become more severe in recent years, in large part due to climate change.[556] Warmer temperatures increase the intensity and frequency of drought, which leads to higher tree mortality.[557] The Western forests in the United States have already shown significant forest transformations caused by the interactions between warming temperature, droughts, insect attacks, and wildfires.[558] A severe drought in the early 1990s brought a widespread infestation of pine bark beetles to Arizona and New Mexico, killing millions of trees. Dead combustible trees, higher temperatures, dry winds, and the lack of natural burns have led to a growing number of intense wildfires in Western forests.[559]

Active forest management can make forests more resilient to stressors driven by climate change. Changing the structural and functional components of forest vegetation and enhancing water supply are options for drought resilience and adaptation.[560] Changing the structural components of vegetation includes thinning or managing the density of planted forests that results in less water demand, less vulnerability to water stress and insect outbreaks, and reduction of wildfire risks.[561] Changing functional components include planting more drought- and disturbance-adapted species. Water supply could be enhanced by cutting forests, a practice that potentially increases streamflow; however, there are mixed findings in the literature regarding the relationship between forest cover and water supply.[562]

BECCS could support active forest management by increasing the economic value of woody biomass made available through strategic tree cuttings. The abovementioned forest management measures are expected to generate significant amount of woody biomass that can be used as a BECCS feedstock (Figure 39). Currently, dead trees and trees cut to purposefully thin forests are not widely used for BECCS projects due to their high cost and low market value.[563] This waste biomass must be collected, chipped or ground, and transported to end users—all costly steps—and would still have a lower market value than other sources of biomass, making it difficult for this process to be profitable.[564] BECCS technologies could increase the profitability of biomass from forest management by increasing demand for woody biomass.[565] BECCS could also provide incentives to project developers if its carbon removal is rewarded by the government or private carbon markets. Increasing the economic value and demand of woody biomass would promote investment in thinning, harvesting, and replanting trees, all of which contribute to forest resilience.[566]

Figure 39: BECCS: A Strategy for Carbon Removal, Climate Mitigation, and Adaptation



In addition to the value it provides by reducing emissions and removing carbon from the atmosphere, BECCS can also be a strategy for climate adaptation by encouraging forest resilience practices. Forest management helps increase resilience against stressors driven by climate change, such as more intense and frequent drought, more intense and frequent wildfires, and increased insect attacks. BECCS can help encourage management strategies, such as clearing dead trees and mechanical treatments, by creating monetizable uses for this otherwise low-value wood. Other forest resilience strategies to complement these are also crucial, such as prescribed burning and planting disturbance-adapted species.

The role of BECCS is more important when forest management practices increase GHG emissions, which could happen under certain regional conditions. An analysis of Western forests found that fire prevention measures and large-scale biomass harvest led to emissions reduction in only three of 19 forest regions. In total, these measures led to higher emissions compared to current forest management practices.[567] In Oregon, one study showed that using forest residues for bioenergy production increased emissions compared to leaving the residues in forests.[568] Adding CCUS to the bioenergy production using residues from forest management can contribute to reducing the potential additional emissions from active forest management. In this context, BECCS can encourage forest management practices that mitigate the risk of increasing GHG emissions.

SOCIOECONOMIC AND ENVIRONMENTAL JUSTICE CONSIDERATIONS FOR BECCS

BECCS technologies present both opportunities and challenges for society. BECCS deployment can create economic opportunities all along its supply chain, especially in rural areas; at the same time, thorough assessment and engagement are required to address EJ and public acceptance concerns in the communities where these supply chains will be located.

Rural Economic Development Opportunities

Bioenergy feedstock production for BECCS can create numerous economic opportunities, especially in rural areas. Increased demand for biomass may stimulate the agricultural and forestry economy, creating new markets for farmers and foresters.[569] In a survey, U.S. farmers strongly favored BECCS over other CDR because of a perceived economic benefit from perennial biomass feedstocks that could serve as a revenue source.[570] Greater utilization of purpose-grown energy crops and agricultural residues can create new jobs and revenue sources as well.[571] Leftovers from harvesting, such as husks, could be burned for energy as biomass instead of being thrown away, used as compost, or burned en masse in residue fields.[572] Residues will increase as more crops are grown.[573]

Feedstock production is not the only part of the BECCS supply chain that could bring economic opportunities. Bioenergy production facilities could also be a source of job preservation at existing infrastructure, such as coal power plants, that are retrofitted for BECCS processes.[574] New facilities could also be a source of jobs and rural economic development, since bioenergy facilities are often co-located with feedstock production. Carbon capture systems and CO_2 transport, utilization, and storage infrastructure also present job opportunities, especially for (1) workers transitioning out of fossil fuel industries; (2) workers in other industries that have suffered from changes to the global economy; and/or (3) workers in rural areas.[575] The BECCS projects at the ADM ethanol plant in Illinois, for example, have involved the collaboration of oilfield services company Schlumberger to develop the plant's carbon storage system.[576] Additional economic development value could come from hubs that integrate BECCS into shared infrastructures for CCUS, clean fuels, etc.[577] Within such hubs, BECCS projects could also harness ancillary revenue streams such as the creation of durable products from biomass feedstocks or CO_2 utilization.

Components of the bioeconomy tend to intersect with other industries, making it challenging to compute economic indicators like directly created jobs and revenues.[578] One study that analyzed the economic impacts of the *BT16* report found that producing and converting a billion tons of biomass to energy, fuels, and products by 2030 could generate $259 billion of revenue and 1.1 million jobs. [579] This future economy could expand beyond current products to include a variety of biofuels and non-energy bioproducts. The economic impacts of BECCS on communities should be quantified on a regional basis to identify ideal clusters for such economic development.

Developing BECCS facilities in regions that have experienced economic decline, such as former paper and pulp production hubs, could have unique benefits such as forest preservation, economic growth, and new jobs.[580] Similar benefits might also be possible in communities formerly dependent on fossil fuel jobs and industries. Bioenergy industries could also help local areas become more resilient to national economic downturns, as evidenced by the pellet industry's performance during the coronavirus pandemic, when the Southeast's pellet industry was designated as an "essential" industry due to established safety protocols.[581] Production, exports, and employment in this industry increased in 2020, in contrast to other sectors, supporting local economies and contributing to regional economic recovery.[582]

Agricultural Impacts of BECCS Deployment

One risk factor with large-scale BECCS deployment is the possibility of BECCS feedstocks increasing demand for land and food prices (see discussion of "Land-Use Impacts of Feedstock Production" on page 74). Higher food prices could erode some of the potential economic benefits of BECCS deployment.

On the other hand, BECCS deployment could also provide incentives to implement agricultural practices that have economic and environmental/climate benefits. For example, several practices that could be implemented as part of feedstock production or carbon sequestration for BECCS—such as alley cropping,[e] planting perennial grasses, genetic modification of crops, and biochar burial—also could replenish soil organic carbon (SOC) and improve crop productivity.[583] SOC is crucial to the health of agricultural systems, contributing to soil fertility, water retention, and structure; plant health and nutrient supplies; and erosion resilience. Human activity has led to a huge loss of SOC, possibly as much as 50 to 70 percent since the dawn of modern industrialized agriculture. Much of this SOC has been oxidized to CO_2, contributing to climate change. Implementing these beneficial practices could increase yields (and therefore revenue) and sequester more carbon through both the plant growth phase and the BECCS process. These practices are not adequately incentivized at present, but BECCS could provide a new incentive by creating a market that values maximization of life cycle carbon removal.[584]

Public Acceptance and Environmental Justice

CCUS, CDR, and bioenergy technologies face categorical opposition from some stakeholders, often being seen as "false solutions" that will hinder the progress of decarbonization and environmental remediation.[585,586,587,588,589] Criticism of CDR solutions includes the "moral hazard" argument: that the possibility of future CCUS or CDR will diminish the urgency and pace of decarbonization today, and possibly delay the transformational changes necessary to combat the climate crisis. A related concern is that these strategies facilitate the preservation of fossil fuel and other environmentally damaging infrastructure, allowing polluters to use the promise of offsets or future retrofits to gain license to continue emitting GHGs and harming the local environment.

e Alley cropping is the practice of comingling trees with other crops on agricultural land.

Another objection to CDR and bioenergy technologies is that they do not remove or avoid as much carbon as they claim. Recent news coverage has highlighted cases of forestry offsets that are lower quality than advertised and questioned whether international biomass supply chains allow undercounting of life cycle emissions.[590,591] These examples have reaffirmed some stakeholders' objections to these technologies.

BECCS-specific literature in some cases addresses these objections head-on, but also emphasizes the need for additional strategies and efforts to address these concerns and increase stakeholder buy-in around these technologies. For BECCS to garner public support, local communities should be consulted in all stages of project development and throughout the BECCS supply chain, from feedstock production to CO_2 storage.[592] Engagement strategies that focus on effective communication, transparency and trust, monitoring, iterative assessment, and local goal setting are critical to creating sustainable BECCS supply chains.[593]

CDR Environmental Justice Considerations

Part of the mistrust of BECCS technologies comes from a long history of polluting infrastructure that disproportionately burdens vulnerable groups, especially low-income and minority communities. BECCS projects need to be carefully sited and designed so as not to add to the litany of energy, waste, and industrial facilities that have caused harm in these communities.

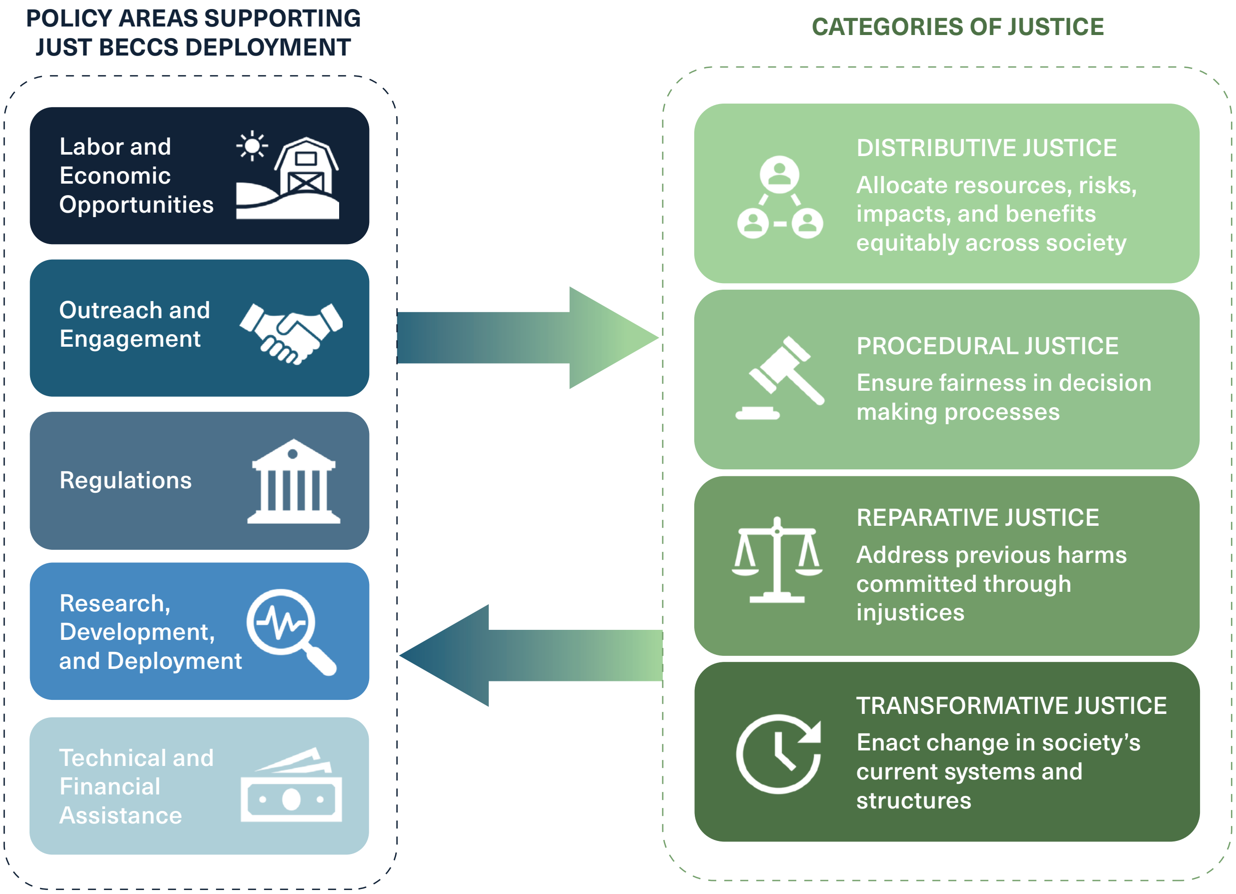
Some researchers have started to examine CDR broadly in an EJ context. Interest in CDR has been driven in large part by IAMs, which do not examine the nuances of impacts at a local level.[594] Grappling with these nuances is crucial to BECCS's success. Carbon180's recent report, *Removing Forward: Centering Equity and Justice in a Carbon-Removing Future*, identifies four categories of justice related to carbon removal (Figure 40):

- Procedural justice: fairness in decision-making processes;
- Distributive justice: equitable allocations of benefits and mitigation of risks;
- Reparative justice: repairing of previous harms; and
- Transformative justice: changes to current systems and structure to make them more equitable and just.[595]

Energy and other resource requirements, land use, emissions leakage, and pollutant production associated with BECCS and other CDR pathways all have the potential to create distributional justice issues by disproportionately impacting disadvantaged groups.[596] These same disadvantaged communities often the lack the resources—or are denied the opportunity—to fully participate in discussions around CDR projects, creating a procedural justice issues.[597] Carbon180 cites the previous example of a coal CCS project where developers and political officials announced the project before consulting local stakeholders.[598] In addition to community-level distributional concerns, CDR deployment will also have to reckon with global and intergenerational distributional issues, such as allocating responsibility for CDR and considering how balancing CDR and mitigation can impact future generations.[599]

Experience from other new infrastructure associated with decarbonization (such as renewable energy) has shown that the spatial dimension of justice is a key distributional and procedural issue.[600] Solar installations in California, for example, have often been built in rural communities to provide power to urban population centers, with the host communities typically having little say in the decision-making process but suffering negative consequences such as wilderness destruction. CDR, like many (if not all) other energy infrastructures and climate solutions, presents potential spatial justice problems because it fundamentally involves tackling a global problem with localized infrastructure. Some studies have already articulated spatial justice concerns with bioenergy infrastructure, such as pellet plants, that could be a part of future BECCS supply chains (see below, under "Bioenergy Environmental Justice Considerations").

Figure 40: Policy Pathways to Address Environmental Justice Considerations in BECCS Deployment[601]



There are a handful of pathways through which public policy can promote BECCS deployment while also promoting justice, particularly for disadvantaged communities. Policies that address the four categories of justice are better positioned to create just outcomes when deploying CDR technologies across society. Adapted from Carbon180, 2021.

BECCS also provides opportunities to achieve reparative and transformative justice. CDR can provide opportunities to remake current paradigms, such as current technology-sharing practices that lock developing nations out of owning and operating newer low-carbon technologies.[602] A key dimension is labor and economic justice: BECCS provides opportunities to repair previous harms by providing jobs in disadvantaged communities, transitioning workers from fossil fuel and legacy forest-product industries, and empowering historically disenfranchised workers in agriculture and forestry.[603] Some marginalized groups, such as Tribal communities, have chosen to build green infrastructure as an opportunity for economic development.[604]

Building new low-carbon infrastructure does not automatically create reparative or transformative justice; not all jobs are of equal quality, nor are all projects equally valued by a community. Ultimately, BECCS provides both opportunities and potential pitfalls in the pursuit of EJ; policies, guidelines, and stakeholder engagement are necessary to achieve just outcomes. Carbon180's *Removing Forward* report recommends policies (Figure 40)—including many relevant to BECCS—that map to the four categories of justice, such as:

- Distributive: extending and strengthening enforcement of EPA regulations that apply to CDR methods that involve combustion, such as BECCS;
- Procedural: establishing minimum public engagement standards for projects receiving federal funding;
- Reparative: increasing assistance through USDA conservation programs to Black and Indigenous farmers and foresters, who have historically been discriminated against by federal programs;
- Transformative: introducing greater worker protections into visa programs used to hire temporary agricultural and forestry workers.[605,606]

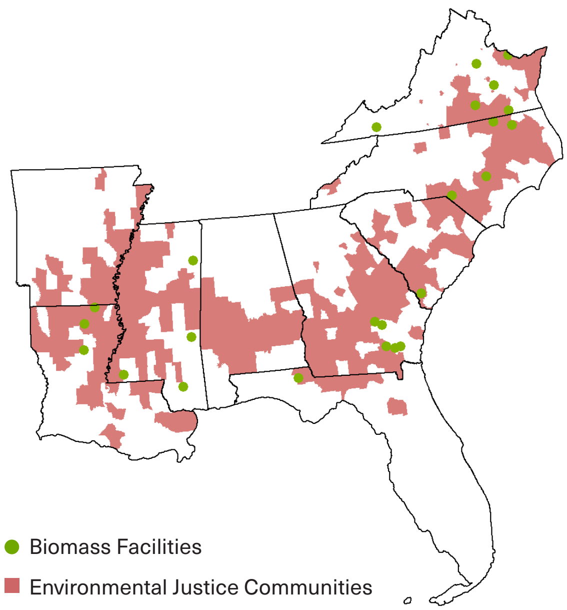
Bioenergy Environmental Justice Considerations

In addition to general justice and equity concerns about CDR, BECCS must also contend with issues that relate to the use of bioenergy technologies. Gigaton-scale BECCS deployment would require a massive buildout of bioenergy facilities, as well as a potential transformation of forest and agricultural land to supply feedstocks.

EJ concerns around increased demand for biomass feedstocks for BECCS include the direct and indirect impacts of land-use change, including impacts on emissions "leakage," food security, biodiversity, water, and nutrients (see discussion of "Land-Use Impacts of Feedstock Production" on page 74).[607] Use of resources, such as water and fertilizer, can also have environmental and economic spillover effects. Greater feedstock demand could also result in the displacement of small landholders; case studies show that, on a local level, already disadvantaged populations are most likely to suffer the drawbacks of bioenergy deployment.[608]

Bioenergy supply chains may, in some cases, already be causing disproportionate harm to the health of vulnerable communities in the United States. One area of concern is wood pellet production facilities. These facilities are predominantly sited in the South, where one study found that such facilities are 50 percent more likely than not to be located in EJ communities—defined in the study as those where the county poverty level is above the state median and at least 25 percent of the population is nonwhite (Figure 41).[609] This study did not attempt to establish causality, nor did it examine whether rural areas with plentiful biomass resources are more likely to be EJ communities in the first place. Nevertheless, these facilities could still be compounding the problem that these communities have historically borne a disproportionate amount of harm from polluting industries.

Figure 41: Pellet Mills and Environmental Justice Communities in Southeastern United States[610]



Most pellet mills in the Southeast currently are in EJ communities—counties where at least 25 percent of the population is nonwhite and where the poverty level is above the state median. Further research is warranted on why this overlap exists in the Southeast, as well as on the impacts of BECCS on EJ communities in the United States generally. Source: Davis, 2020.

Although numerous grassroots organizations and news reports have highlighted the noise and air pollution impacts of U.S. pellet production, few scientific studies have done so. According to the study mentioned above on pellet plants in EJ communities, these facilities have loud machinery and increase road and rail traffic, all of which contribute to noise pollution.[611]

The nonprofit organization Environment Integrity Project studied the wood biomass industry and claims that pellet production facilities consistently violate Clean Air Act regulations.[612] The Clean Air Act requires new polluting plants to use the best control technologies to keep emissions within the permitted level. The authors claim that states charged with implementing clean air requirements failed to require adequate emissions reductions, causing unnecessary emissions harmful to human health.

Other aspects of BECCS systems have also created or worsened EJ issues. Waste facilities are often located in marginalized communities, and incinerators in particular have caused health issues for local residents.[613] In addition to stationary polluting infrastructure, BECCS—if not carefully scaled up with EJ in mind—could contribute to detrimental, inequitable impacts including freight transportation pollution, deforestation, and economic consequences for farmers and foresters.

While local communities located around BECCS infrastructure are the most at risk from negative environmental impacts, they are also the most likely to enjoy benefits to economic development and jobs (see discussion of "Rural Economic Development Opportunities" on page 80). In particular, these facilities and their supply chains have the potential to provide economic boons to regions facing economic distress. The planning, siting, and operation of BECCS projects must balance these factors when attempting to maximize benefits and minimize harms to vulnerable populations.

Geologic CO_2 Storage Safety Concerns

The risk associated with CO_2 storage also impacts its public acceptance and the socioeconomic considerations for BECCS deployment. One of the major concerns impacting public trust of storage projects is the potential risk of leakage.[614] Some literature also suggests that injecting CO_2 into geologic reservoirs can induce minor seismic activity, affecting nearby communities.[615]

There are a variety of factors at CO_2 storage sites that must be assessed before the sites are determined to be suitable, including an absence of permeable faults, low seismicity, adequate geomechanical conditions, and general compatibility with existing aboveground land use. Accounting for these issues, the potential for CO_2 leakage is minimal and its immediate environmental risk is significantly lower than an uncontrolled oil or gas release.[616] An IPCC analysis found it very likely that 99 percent of the CO_2 injected in underground storage would remain secure for 100 years, and likely that it could be safely stored for 1,000 years.[617] This is further supported by two decades of CCUS projects that have safely stored CO_2 underground.[618] Additional RD&D to improve storage safety is ongoing, including DOE's Advanced Storage R&D technology program, which has specifically focused on reducing the risk of seismic disruptions.[619]

Additionally, geologic storage projects must obtain permits to inject CO_2 underground. Projects injecting CO_2 in deep geologic reservoirs must receive Underground Injection Control (UIC) Class VI permits which are governed by the EPA or a qualified state agency.[620] These permits require that certain environmental quality standards are met, such as requirements that the storage site will not threaten underground sources of drinking water.[621] Class VI permitholders must also provide information on seismic history in their application, and not exceed injection pressures that could induce seismicity.[622] The EPA and qualified state agencies also regulate EOR facilities as Class II wells, requiring that all new wells obtain a Class II permit and that well owners adhere to permitting standards for construction, operation, financial responsibility, mechanical integrity, and corrective action.[623]

A robust regulatory environment and MRV of CO_2 storage is necessary to provide environmental and safety assurances to developers, investors, and local communities. A constellation of regulations—including EPA's UIC permitting and GHGRP programs, the Internal Revenue Service's (IRS) requirements for claiming the 45Q tax credit, and state regulations such as North Dakota's Class VI permitting regulations and the California LCFS's CCS Protocol—have started to establish such a regulatory environment in the United States.[624,625] Gaps still remain, however, such as:

- EPA regulations for EOR are generally less stringent than for geologic storage; Class II permits do not require provision of seismic history information, and EOR projects do not require a long-term MRV plans under the GHGRP. IRS requirements for EOR, however, are somewhat more strict.[626,627]
- No comprehensive regulatory regime—including monitoring requirements—currently exists for offshore geologic storage.[628]
- No federal framework exists for managing long-term liability for geologic storage, which may require monitoring beyond the lifespan of the individual company that originally injected the CO_2.[629,630] States such as North Dakota and California have begun developing policies (such as a state-run trust fund) for managing long-term liability, but the federal government will likely need to play a role.[631,632]

Appendix

TECHNOLOGICAL READINESS OF DIFFERENT PATHWAYS

There are multiple pathways that help convert biomass to energy or other useful products. For example, lignocellulosic biomass can be combusted for steam or heat as well as gasified or pyrolyzed to generate hydrogen; starch crops can be fermented for ethanol; organic wastes and oil crops can be anaerobically digested to produce renewable natural gas; algae can be hydrolyzed and the processed to produce different products. Each pathway is at a different stage of technological readiness, partially measured by technology readiness level (TRL).[a,633]

To show the technological readiness of each BECCS pathway, all existing or developed BECCS pathways were classified into four categories: *commercial, pre-commercial, pilot & demonstration, and uncertain.* A pathway was classified as *commercial* if its biomass conversion technology was at commercial phase according to the NASEM's 2019 *Negative Emissions Technologies* report and its CO_2 capture, separation, and sequestration technology was currently in operation or commercially proven. A pathway was classified as *pre-commercial* if its biomass conversion technology was at pre-commercial phase according to NASEM and its CO_2 capture, separation, and sequestration technology was proven by academic research. A pathway was classified as *pilot & demonstration* if its biomass conversion technology was at pilot & demonstration phase according to NASEM and its CO_2 capture, separation, and sequestration technology was proven or under development by academic research. Lastly, a pathway was classified as *uncertain* if significant academic research on its CO_2 capture, separation, and sequestration technology was not found.

Commercial BECCS Pathways

Commercial pathways are already at the deployment stage, so they are beyond the TRLs defined by DOE (Figure 42). They have a capacity of 1000 dry metric tons per day.[634]

Lignocellulosic biomass like forestry, wood wastes, invasive trees, and agricultural residues can be stationarily combusted to generate steam or heat. Starch crops like sugarcane, sugar beet, sorghum and corn and can biochemically fermented to produce ethanol. Organic wastes like food waste, sewage and manures can be anaerobically digested to manufacture RNG. This RNG can be combusted to generate steam to run turbines to produce electricity or to generate heat; it can also be converted to methanol, a commercially viable product, which can be further converted to dimethyl ether and long-chain biofuels.

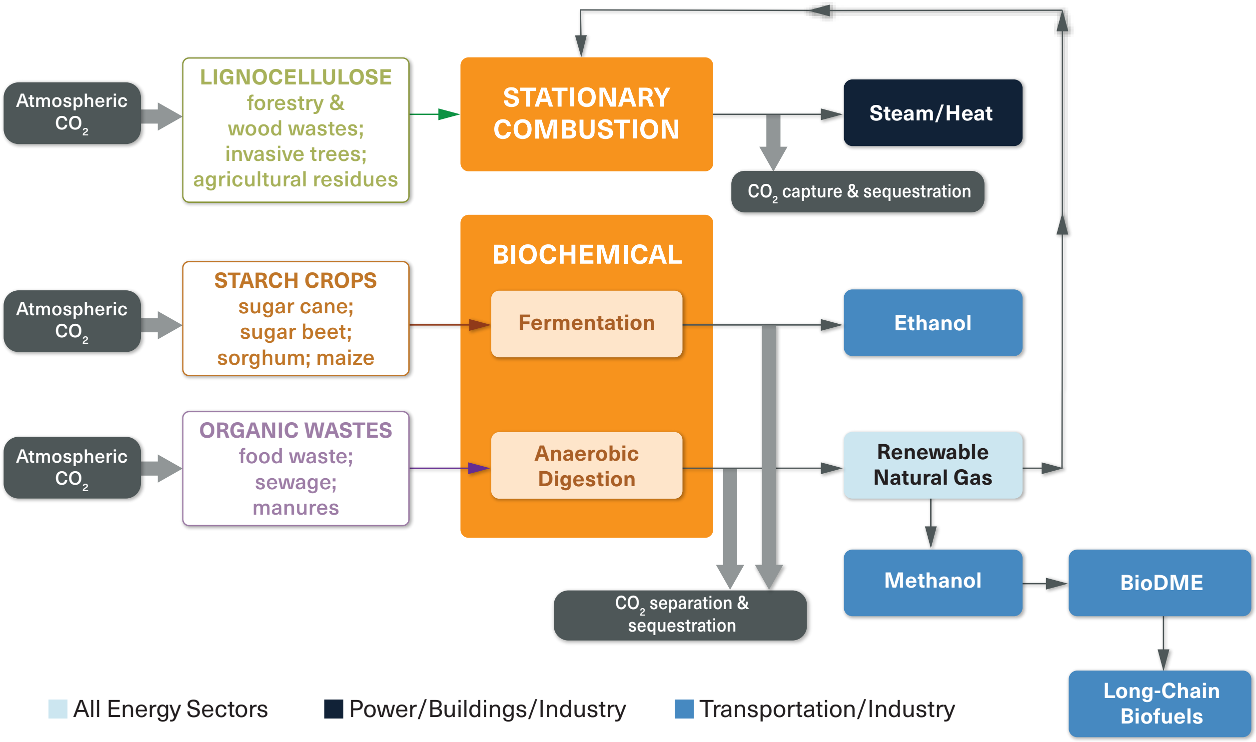
Four of five commercially operating BECCS projects in the United States use corn, other starch crops, or agricultural waste to produce ethanol.

a TRL is a metric developed by U.S. government agencies like the DOE to describe the maturity of a technology. It is measured from 1 (less mature) to 9 (more mature).

Two projects in the Midwest use the captured carbon for EOR whereas the third injects it in a deep saline reservoir. The fourth project, located in California, liquefies the captured carbon for the food and beverage industry.

Chevron, Microsoft, Clean Energy Systems, and Schlumberger New Energy announced a BECCS project in Mendota, California.[635] Using an oxy-combustion technology developed by CES, the plant will convert agricultural waste from California's Central Valley into a renewable synthesis gas that can be used to generate electricity or produce hydrogen. The plant is expected to come online in 2022 and remove 7 $MtCO_2$ over twenty years. Clean Energy Systems also plans to retrofit three to five more existing biomass facilities that could remove 3 $MtCO_2$ to 14 $MtCO_2$ over their lifetimes.[636]

Figure 42: Commercial Pathways for BECCS[637]



These pathways harness biomass conversion methods that are well understood and widely deployed. Some projects that combine these conversion methods with CCUS have already been deployed at pilot or full scale; others are in development. Source: EFI analysis; adapted from NASEM, 2019.

Pre-commercial BECCS Pathways

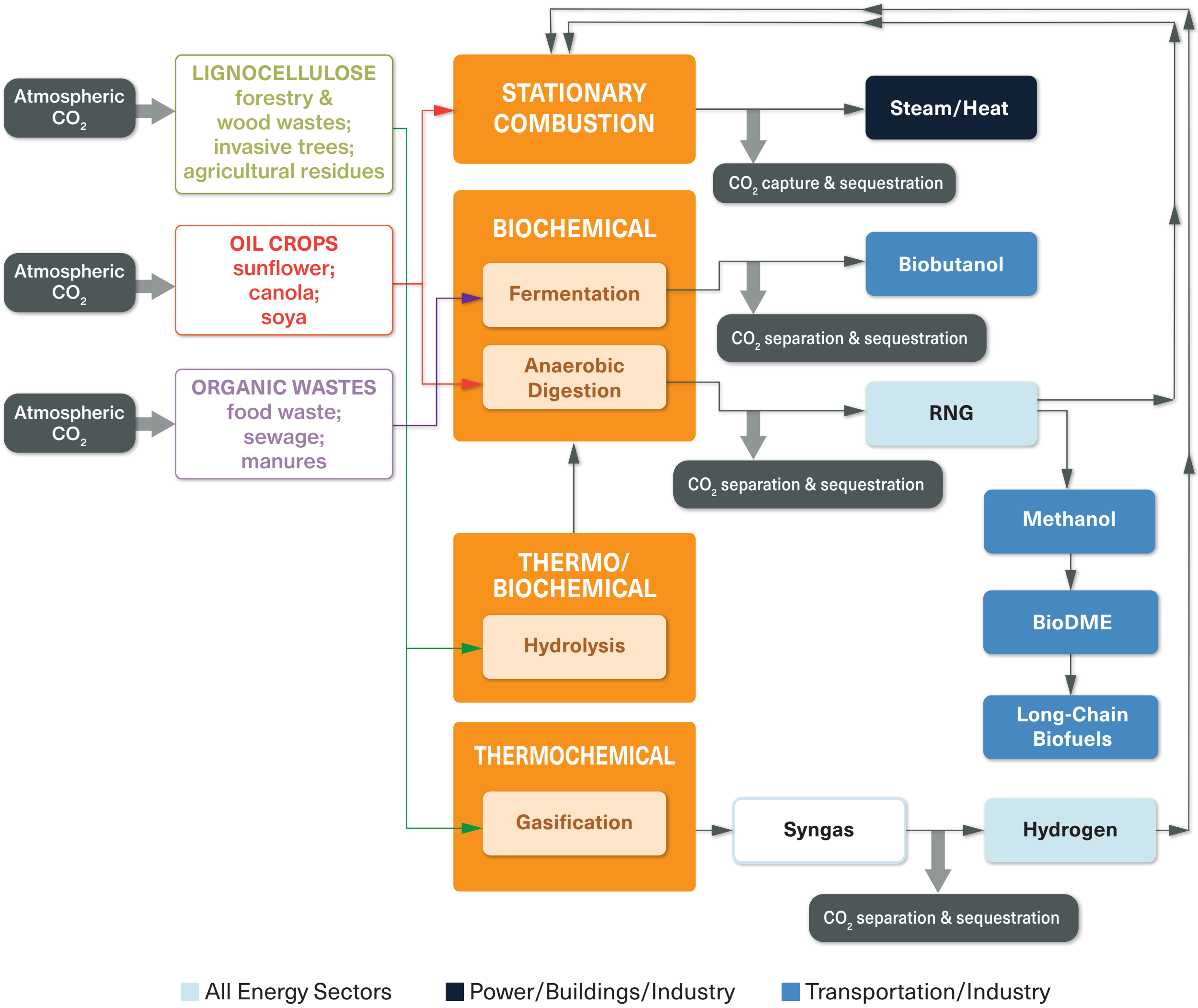
Pre-commercial pathways have a TRL between seven and nine (Table 5) and are at the demonstration stage (Figure 43).

Lignocellulosic biomass can be thermochemically gasified to produce syngas, which can be further reacted to produce hydrogen via the water-gas shift reaction. Lignocelluloses can also undergo thermo-biochemical hydrolysis and then be anaerobically digested like organic wastes. Oil crops such as sunflower, canola, and soybeans can be stationarily combusted to generate steam or heat. They can also be anaerobically digested to produce RNG and related products. Starch crops can be fermented to produce biobutanol, a possible alternative fuel for transportation.[638]

Table 5: TRL Description for Pre-commercial Pathways[639]

TRL	DOE Definition	Application to BECCS
9	"Actual system operated over the full range of expected conditions"	Technology operates under full range of operating conditions Proven for a volume of 50 to 250 dry metric tons per day
8	"Actual system completed and qualified through test and demonstration in a plant environment"	Technology works under expected conditions Testing for a volume of 50 to 250 dry metric tons per day
7	"System prototype demonstrated in a plant environment"	The design is almost complete Prototype is 5 to 25 percent of final scale Development for a volume of 50 to 250 dry metric tons per day

Figure 43: Pre-commercial Pathways for BECCS[640]



These pre-commercial biomass conversion technologies have been deployed less widely and CCUS applications have been proven in academic research. Source: EFI analysis; adapted from NASEM, 2019.

Pilot- and Demonstration-Stage BECCS Pathways

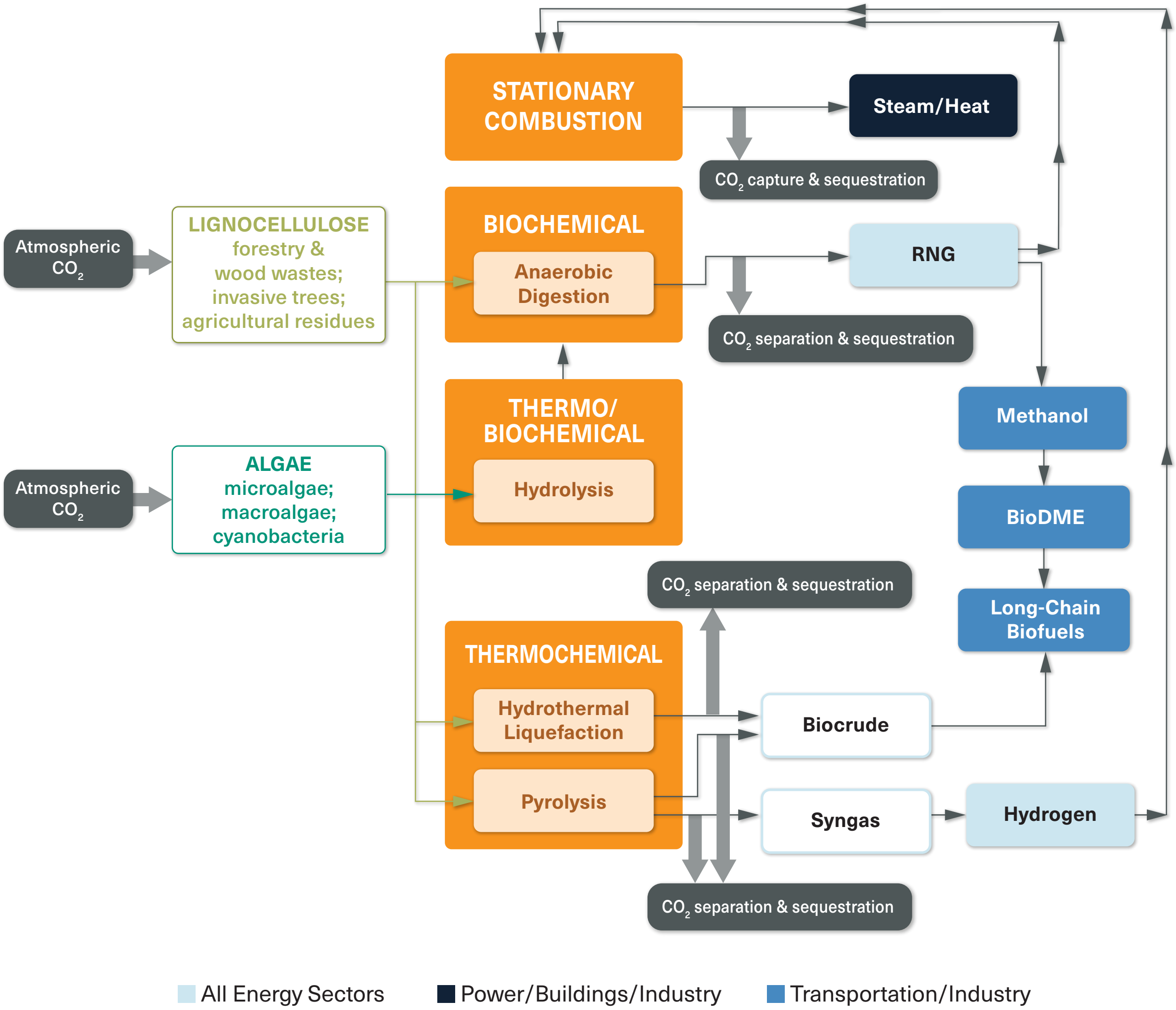
Pilot and demonstration pathways have a TRL between four and six (Table 6) and are in the development stage (Figure 44).

Lignocellulosic biomass can be anaerobically digested to produce RNG and related products. It can be hydrothermally liquefied to produce biocrude, which can be converted to long-chain biofuels. It can also undergo pyrolysis, which can either produce biochar and biocrude, or biochar and syngas for hydrogen. Algae—microalgae, macroalgae, and cyanobacteria—can undergo hydrolysis and then be anaerobically digested, similar to lignocellulosic biomass.

Table 6: TRL Description for Pilot and Demonstration Pathways[641]

TRL	DOE Definition	Application to BECCS
6	"Engineering/pilot-scale prototypical system demonstrated in a relevant environment"	The 'pilot-scale' prototype is 1 to 5 percent of final scale The prototype is tested in a relevant environment
5	"Laboratory-scale similar-system validation in a relevant environment"	Technological integration such that the bench-scale system has a configuration similar to the final design
4	"Component and/or system validation in a laboratory environment"	The 'bench-scale' system is 1 percent of final scale The system is developed and validated in a laboratory environment

Figure 44: Pilot & Demonstration Pathways for BECCS[642]



These pathways use biomass conversion technologies that are currently in the pilot or demonstration phase. CCUS applications have been proven or under development in academic research. Source: EFI analysis; adapted from NASEM, 2019.

Technologically Uncertain BECCS Pathways

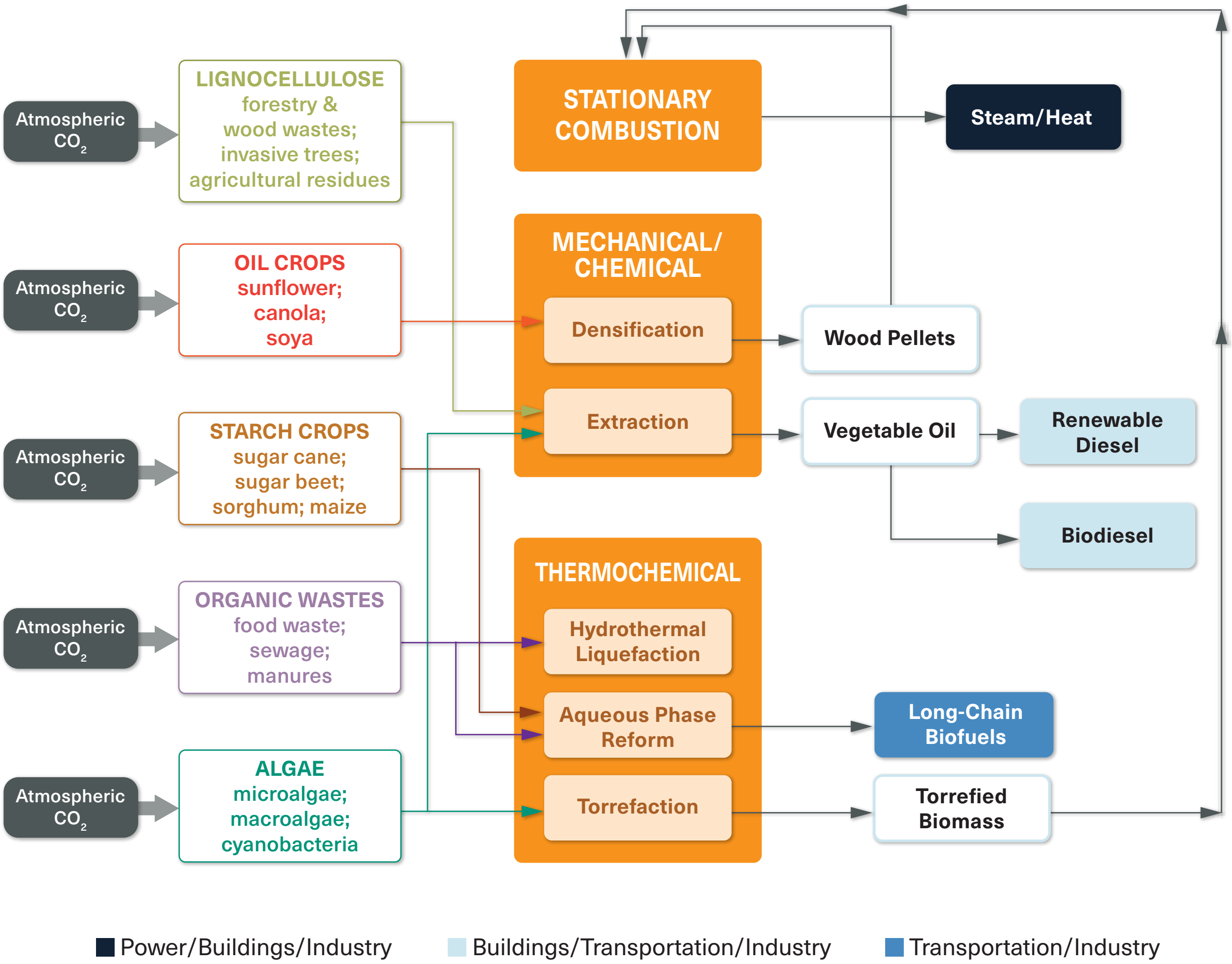
There are various uncertain pathways still in the applied research phase and have a TRL under 4 (Table 7, Figure 45).

It may be possible to extract vegetable oil from lignocelluloses, and then convert this oil to renewable diesel or biodiesel. Oil crops may be densified into wood pellets for combustion. Starch crops may undergo aqueous-phase reforming to produce long-chain biofuels. Organic wastes may undergo hydrothermal liquefaction and aqueous-phase reform. Algae may undergo extraction for oils and diesels or torrefaction for torrefied biomass (biocoal).

Table 7: TRL Description for Uncertain Pathways[643]

TRL	DOE Definition	Application to BECCS
3	"Analytical and experimental critical function and/or characteristic proof of concept"	Analytical and laboratory-scale R&D to validate certain predictions. Individual component testing.
2	"Technology concept and/or application formulated"	Speculative applications are invented. Little proof that the idea works.
1	"Basic principles observed and reported"	The lowest TRL. Research moves from scientific papers to application.

Figure 45: Uncertain Pathways for BECCS[644]



It is unclear whether CCUS technologies could be applied to these biomass conversion methods. Some of the energy products of these pathways (e.g., wood pellets) are used in other BECCS applications, but their production itself may not be compatible with carbon capture. Source: EFI analysis; adapted from NASEM, 2019.

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