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Issue Brief

Bioenergy with Carbon Capture and Storage as a Tool for Climate Change Mitigation

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1. Introduction

Bioenergy with carbon capture and storage (BECCS) combines processes for converting biomass resources or *feedstocks*[1] to usable forms of energy with technologies for capturing and permanently storing carbon dioxide (CO_2) emissions. Properly designed, such systems offer the potential to extract CO_2 from the atmosphere - in effect, transferring carbon atoms captured via photosynthesis to geologic storage - while also supplying zero- or lower-carbon energy. This issue brief describes the main components of BECCS systems and highlights key questions for designing BECCS systems to maximize climate and other benefits.

Proponents of BECCS emphasize the unique opportunity to combine energy production with CDR and point to modeling analyses that project a substantial role for BECCS in achieving future climate mitigation goals.[2] To its critics, however, these theoretical advantages are offset by the practical difficulties - and risks - BECCS presents, particularly if large-scale deployment accelerates the loss of natural forests and grasslands or competes with food production. These concerns are exacerbated by the difficulty of accurately accounting for lifecycle greenhouse gas emissions across the BECCS supply chain (which crosses multiple sectors), the potential for unintended direct and indirect impacts (including to ecosystems and air and water quality), and methodological uncertainties pertaining to the measurement of biogenic carbon fluxes.

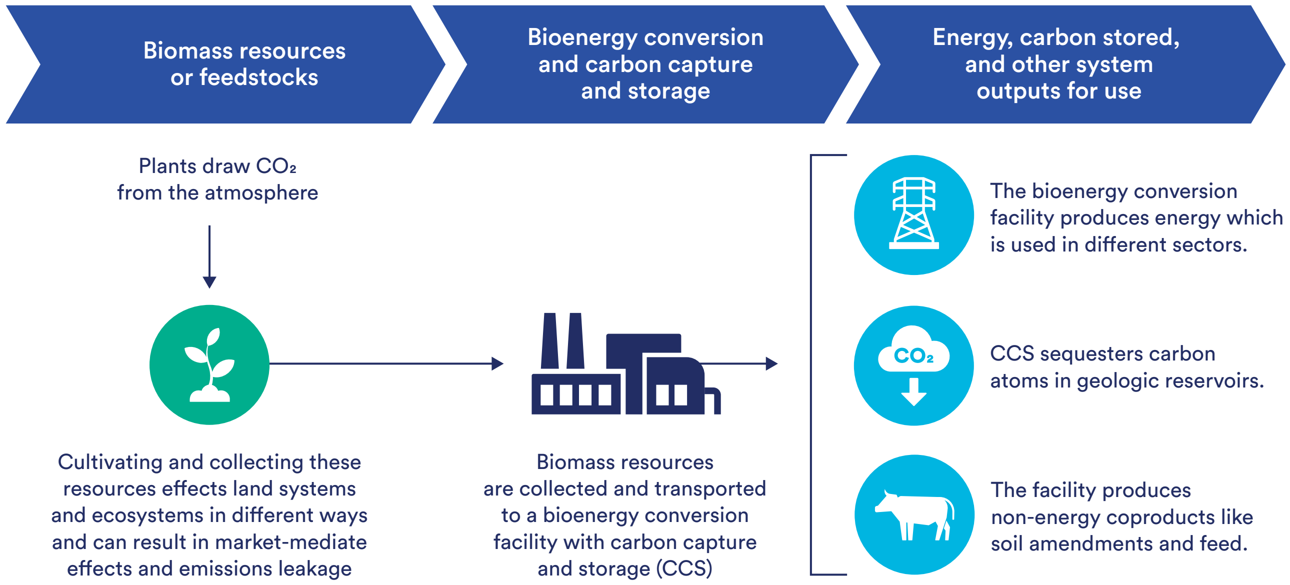
Unfortunately, recent debates over the role of BECCS have tended to become polarized along these contrasting points of view, too often precluding the more nuanced discussion BECCS demands. The range of biomass feedstocks and bioenergy conversion processes that could be deployed with carbon capture and storage is wide. Whether and to what extent a given BECCS system produces net climate benefits relative to other energy and CDR options depends on the specific biomass feedstock and conversion technologies used and on the details of system design. Different components and configurations for both the bioenergy and carbon capture and storage portions of the BECCS supply chain[3] are at varying stages of technological readiness.[4]

CATF's conclusion, based on recent research and emerging models, is that the technologies needed to implement climate-beneficial BECCS systems are within reach.[5] However, additional considerations related to local economic and environmental impact and equity concerns will be essential for determining whether and how to deploy individual BECCS projects. Importantly, a BECCS system can be climate-beneficial yet *still* have other detrimental social and environmental consequences.

2. BECCS: An overview

Research shows that biomass-based carbon dioxide removal (CDR) generally has higher carbon removal efficiency[6] than other engineered forms of CDR, but that efficiency varies depending on the biomass feedstocks, bioconversion processes, and products.[7] BECCS systems can be broken down into these three system components, including useable energy, stored carbon atoms, and other coproducts, as relevant.
Figure 1 provides a schematic illustration of the three main components of a BECCS system.

Figure 1: Schematic depicting three main components of a BECCS system



Biomass Feedstocks

The choice of biomass feedstock - the first component of any BECCS system - and the beneficial or detrimental land-use implications that flow from this choice will generally be one of the most important factors in assessing the lifecycle climate impact of a given BECCS system. Biomass feedstocks include a wide variety of organic (carbon-based) materials derived from living or recently living plants.[8] What all these materials have in common is that they contain carbon captured from the atmosphere via photosynthesis. BECCS systems may utilize plants that were intentionally cultivated for use in energy systems, such as corn, triticale (a hybrid of wheat and rye), switchgrass, or poplar. These and other bioenergy crops can be grown on a variety of lands, including existing cropland, seasonally fallow land, or newly cleared forests and grasslands; these choices can have positive or negative land and climate effects. As an alternative to dedicated bioenergy crops, BECCS systems can also use feedstocks removed from managed lands (e.g., forest thinnings) or a variety of biogenic coproducts, residues, or wastes from existing agrifood systems or industrial processes, including crop residues, animal manure, sawmill residues, food processing waste, municipal solid waste, and nonrecyclable paper. The choice of biomass feedstock and related land-use and market-mediated effects are also key drivers of non-climate concerns commonly raised about large-scale bioenergy systems, including air and water quality, food security, and biodiversity.[9]

Bioconversion and Carbon Capture Systems

Multiple pathways exist for (1) converting the chemical energy stored in biogenic materials to the usable forms of energy demanded by modern economies and (2) capturing resulting emissions for permanent geologic storage. The specific biomass feedstock used in a BECCS system and the desired system outputs often dictate the choice of bioconversion process, which in turn may dictate available technology options for carbon capture. Bioenergy conversion pathways in use today include (1) thermochemical processes that rely on high heat, pressure, and/or catalysts, including direct combustion to produce heat and electricity and gasification or pyrolysis to produce solid, gaseous, and liquid fuels or products, and (2) biological processes that extract energy using enzymes and microorganisms, including fermentation and anaerobic digestion.[10] Carbon capture may be relatively straightforward in biological facilities where the microbial processes used to produce bioenergy and other outputs generate highly concentrated streams of CO_2. Around the world, the most widely deployed bioenergy conversion processes involve the combustion of woody biomass harvested from plantations or natural forests and the biological conversion of food crops and crop residues to liquid fuels like ethanol or gaseous fuels like biogas.

Thermochemical and biological conversion pathways have different advantages and disadvantages, with implications for lifecycle carbon reduction potential and other impacts. For example, thermochemical pathways have the advantage that they can be utilized with a wider variety of biomass feedstock, including those high in lignin, and generally do not require pretreatment of biomass, which can be both cost- and carbon-intensive. On the other hand, thermochemical conversion systems can require harsh operating conditions.[11] Biological pathways present different tradeoffs: suitable biomass feedstock options may be limited and may require energy-intensive pretreatment to access energy in cellulosic biomass, but some conversion processes can operate at lower temperatures, produce nearly pure streams of CO_2, and deliver high-value biofuels and biochemicals. The energy efficiency of the processes and the energy source powering the conversion process often drive the estimated climate mitigation potential associated with different bioenergy conversion and carbon capture and storage systems. In general, the technologies for bioenergy conversion and carbon capture and storage have different efficiencies in capitalizing on the different molecular components of biomass feedstocks, and lifecycle climate impacts.[12]

System Outputs

BECCS systems always produce energy in addition to isolating carbon atoms for geologic storage. Energy products have different emissions profiles and various applications, such as fueling airplanes and powering industries like cement production. Some BECCS systems also output non-energy and non-CO_2 coproducts such as livestock feed, biochar, and liquid digestate fertilizer. Like energy products, these outputs have different emissions profiles and applications, including the potential to displace more greenhouse gas-intensive products.

BECCS Systems' Complexity is a Challenge and Opportunity

In simple terms, whether a given BECCS system has the net effect of adding carbon to the atmosphere, *avoiding new additions* of carbon, or *removing* carbon depends on the difference between the total direct and indirect greenhouse gas emissions[13] across the entire supply chain and the gross amount of biomass carbon geologically sequestered over its lifecycle. A system that achieves net CDR[14] has a distinctly different impact on atmospheric CO_2 concentrations than a system that only reduces or avoids new emissions.[15]

While the gross amount of carbon captured and placed into geological storage is relatively easy to measure, a comprehensive accounting of lifecycle emissions across the complete supply chain is far more difficult as direct and indirect effects can vary across time, space, and sectors. The time needed to grow the biomass; the distance between the biomass feedstock, the bioconversion facility, and the geological CO_2 storage site, and the end uses for BECCS system outputs are all variables that influence net lifecycle greenhouse gas impacts, in addition to biomass type and source, choice of bioenergy conversion and carbon capture technology, and energy input requirements and sources. All these variables matter when designing finance, policy, and incentive structures to achieve climate goals. Further complicating this picture, policies and accounting methodologies that prioritize the use of biomass feedstocks for energy may miss opportunities to reduce land sector emissions and enhance removals and land systems.

The following sections address key questions related to each of the three main components of BECCS systems: biomass feedstocks and land interactions, bioenergy conversion and carbon capture and storage (CCS), as well as system outputs.

3. Biomass feedstocks and land interactions - key questions

Can a BECCS system reduce greenhouse gas emissions from biomass feedstocks associated with residues and wastes or land management activities?

Agriculture, forestry, and other land uses are estimated to account for almost one-quarter of net global anthropogenic greenhouse gas (GHG) emissions.[16] This contribution includes emissions from plant respiration and decomposition, as well as emissions from the burning of crop residues and trees, and emissions from manure and agrifood waste.[17]

BECCS systems that interrupt the transfer of carbon from biogenic material back to the atmosphere could mitigate global warming by reducing CO_2 concentrations in the atmosphere while also delivering air quality benefits. For example, selective thinning of forests at risk of severe fire in the western United States could reduce wildfire risk and related wildfire smoke, particulate matter, and carbon emissions;[18] if these materials are then used in BECCS systems that capture CO_2 and particulate matter, adverse air quality impacts from wildfires and from the pile burning[19] of forest thinnings might also be mitigated.[20] At present, forest fires are estimated to cause approximately 267 million metric tons (Mt) of CO_2-equivalent GHG emissions globally each year - including 2 Mt CO_2eq in the U.S. alone[21] and contribute 6% of global particulate matter ($PM_{2.5}$) pollution.[22]

The agriculture sector presents further emission reduction opportunities. Every year, an estimated 5 billion metric tons of crop residues are left on fields globally.[23] Annual emissions from the decomposition and burning of these residues are estimated to total 234 Mt CO_2eq, mainly in the form of nitrous oxide.[24] Beyond crop residues, 14% of food produced on farms never reaches the point of retail sale.[25] These large-scale losses in the form of crop residues and food waste also represent a significant loss of embodied inputs, including synthetic fertilizers (responsible for an estimated 600 Mt CO_2eq of nitrous oxide emissions from soils annually and an additional 466 Mt CO_2eq emissions from fertilizer production), and on-farm energy use (responsible for an estimated 928 Mt of annual CO_2eq emissions globally).[26] Globally, manure applied to soils and left in pastures is estimated to emit approximately 941 Mt CO_2eq annually as nitrous oxide. In this context, the use of forest thinnings and agrifood residues and wastes in modern BECCS facilities might deliver large climate benefits - researchers have estimated that quantities of these biomass feedstocks in the U.S. alone could support as much as 700 Mt of CO_2 capture per year, mostly via BECCS systems optimized for carbon removal.[27]

Many future scenarios for expanding BECCS focus on wastes and residues, which constitute only 20% of overall bioenergy biomass feedstocks today.[28] For example, in a net-zero scenario developed by the International Energy Agency (IEA), global deployment of BECCS using biomass feedstocks that consist of 60% residues or wastes removes 190 Mt of CO_2 and delivers 100 Exajoules of bioenergy annually by 2030.[29]

Expanding the use of waste and residue biomass feedstocks in bioenergy production, however, will also present its own challenges. One risk is that reduced or avoided emissions could be over-credited in GHG accounting systems; if these inflated credits are then used to offset fossil fuel emissions, emission reduction efforts in other sectors could be hampered.[30] Another risk is that a growing market for bioenergy biomass feedstocks could inadvertently incentivize *increased* residue or waste generation or inappropriate expansion of waste categories to biomass with an alternative market value. If not thoughtfully managed, the collection and utilization of crop and forest residues can also have adverse unintended impacts on agricultural productivity, forest ecosystems, land carbon sinks, and soil carbon and nutrient pools. For example, excessive removal of branches and wood chips from forests or corn stover from agricultural fields could deplete soil carbon reservoirs.[31]

Can biomass feedstock use be managed to avoid adverse impacts on land carbon sinks and support ecosystems?

Globally, forests and grasslands are estimated to absorb around 500 billion metric tons or gigatonnes (Gt) of CO_2 annually. Most of this CO_2 is released back to the atmosphere through plant respiration and decomposition. Still, these land carbon sinks play a crucial role in counterbalancing the roughly 40 Gt of CO_2 emitted annually from fossil fuel use and net land use change, thereby buying time for the deployment of zero-emitting energy technologies. Scientists estimate that approximately 12 Gt (net) is stored each year in terrestrial reservoirs, including forests and soils.[32]

Indiscriminate use of biomass feedstocks for BECCS in ways that compromise crucial land carbon sinks must, therefore, be avoided. Negative climate- and ecosystem- impacts from deforestation or the accelerated conversion of natural forests or grasslands - either to support biomass production or to replace land diverted from food crop production elsewhere in the agricultural sector - could offset any benefits from expanded BECCS deployment.

Instead, the removal and use of biomass feedstocks from ecosystems should be the byproduct of land management plans that aim to improve the carbon sink and ecosystem health. For example, removing plants that have invaded and altered ecosystems and whose removal is considered an urgent land management objective in many locations might improve the ecosystem's capacity to serve as a land carbon sink. Improved systems for tracking and tracing the source of biomass materials in BECCS systems are needed to verify biomass provenance.

Do opportunities exist to *enhance* the health and carbon storage capacity of land systems through the intentional production of biomass feedstocks for BECCS?

The intentional production of feedstocks for bioenergy can undermine the health and carbon storage capacity of land systems (for example, the conversion of native prairies to corn for ethanol). However, strategic development of biomass feedstocks for BECCS might mitigate climate change impacts by promoting beneficial land system improvements on socially marginal,[33] degraded, or seasonally fallow land. Plant species that could be suitable in these settings include herbaceous perennials like switchgrass (*Panicum virgatum*) and Big Bluestem

(*Andropogon gerardii*), woody perennials like hybrid poplar (*Populus nigra*) and willow (*Salix* sp.), and winter crops,[34] like winter rye (*Secale cereale* L.), which can be a good candidate for bioenergy conversion if it is harvested before the grain matures and is cultivated in a manner that does not require high levels of nitrogen fertilizer.[35] One study estimates up to 46% of the land used for annual crop production in the European Union could be prioritized for *beneficial* land-use changes while maintaining or increasing overall productivity - such as planting perennials for bioenergy - that could also help reduce nitrogen leaching to lakes and rivers, as well as prevent soil erosion.[36] These types of land-use and management changes can improve biodiversity,[37] increase soil carbon storage, reduce fertilizer use and impacts,[38] and increase carbon capture by plants via photosynthesis.[39]

The potential to achieve these beneficial outcomes depends on the types of crops being cultivated, the biophysical characteristics of the land, and existing land management practices.[40] Synergistic food–fuel systems that satisfy multiple needs in climate-beneficial ways can be achieved by integrating the production of food crops (for human and animal consumption) and nonfood crops (for energy) on multifunctional land and farms.[41] However, care must be taken to ensure that beneficial land-use changes in some locations do not cause detrimental land-use changes elsewhere or jeopardize biodiversity.

4. Bioenergy conversion technologies - key questions

How flexible and resilient will the BECCS system be to a diverse biomass feedstock supply?

Scaling up bioenergy conversion facilities to process large amounts of wastes and residues (on the scale implied by the IEA's net-zero scenario, for example) will require significant supply chain build-out and technological advances in biomass processing and bioconversion. The spatial distribution of these biomass feedstocks poses collection- and transport-related emissions and supply chain challenges. Mobile processing or conversion units or depots to pre-process material before transport to a centralized BECCS facility may be needed to scale BECCS efficiently. Waste and residue biomass composition can be highly variable, with large seasonal changes in the material - this poses a challenge for bioenergy conversion systems that generally thrive on consistent biomass feedstock supplies and rely on a single conversion process.[42]

Attracting investment into expensive processing facilities without a guaranteed supply of appropriate biomass is a critical challenge. Optimizing conversion processes and developing both centralized and modular processing and conversion facilities could help maximize BECCS energy yields and carbon removal and help address concerns about the reliability of biomass supplies. Conversion facilities that can accept and process a wide variety of biomass feedstocks and be resilient to changes in moisture content, pH, etc., will likely be at lower risk of disruptions. Greater flexibility may also be helpful to biomass suppliers, particularly if they are not required to meet strict specifications for biomass composition.

Which conversion processes and technologies can most efficiently use the chemical components of biomass feedstocks to deliver energy and other valuable outputs, and what is their technological readiness?

Different bioenergy systems and processes are at varying stages of technological readiness and require different kinds of support to become commercially viable. Many novel bioconversion technologies that can efficiently utilize biomass wastes and residues and valorize important biomass components like lignin are still under research and development.[43] Resources like biomass grown for energy on seasonally fallow land are not yet produced at scale in many regions and without a guaranteed feedstock supply, conversion facilities may not be able to secure capital investments needed to build a facility or supply chain. Pre-processing depots and flexible biomass supply chains are not yet in place to support large-scale processing of biomass feedstocks driven by circular economies, sustainable landscape design, and land management plans.

What factors influence the greenhouse gas emissions implications of different bioenergy conversion and carbon-capture processes and technologies?

Challenges still exist related to developing and commercializing technologies and processes that can efficiently extract the chemical energy stored in biomass, convert it to usable energy outputs such as electricity and liquid or gaseous fuels, and effectively capture and store associated CO_2 emissions. Specific technology and process choices will have important implications for lifecycle greenhouse gas emissions and other environmental, economic, and social impacts of BECCS systems. For example, powering or heating bioconversion with the system's own waste energy or with other renewable or carbon-free sources might reduce lifecycle emissions and increase system outputs of carbon removal.[44] Ethanol refining requires natural gas and electricity (together, they are responsible for approximately 80% of a facility's biorefining emissions), and combined heat and power systems can improve energy efficiency.[45] Biogenic emissions produced and emitted in the energy sector currently go unaccounted for, but should not be presumptively zero, which adds to differences in BECCS lifecycle assessments.

5. System outputs - key questions

The types of outputs generated by a BECCS system also have emissions implications, particularly if these outputs may be responsible for increased downstream emissions or, conversely, if they have the potential to displace higher-emitting alternatives.

Does the BECCS system achieve net CO_2 removal (CDR) or avoid/reduce greenhouse gas emissions?

All BECCS systems transfer some quantity of carbon captured by plants via photosynthesis from the atmosphere to permanent geologic storage. At a minimum, adding CCS to existing bioenergy systems usually reduces emissions relative to conventional bioenergy conversion processes; at best, it can achieve CDR and help permanently lower CO_2 concentrations in the atmosphere (negative emissions). Both outcomes can be helpful to climate change mitigation, but it is important to design accounting standards, policies, and financial incentives to differentiate between systems that avoid emissions versus those that achieve actual carbon removal, especially as energy systems transition toward zero-carbon energy resources.

Can the energy output from a BECCS system replace emissions-intensive energy in hard-to-decarbonize sectors?

BECCS systems, by definition, produce energy while also capturing carbon atoms for permanent geologic storage. These energy outputs can take the form of liquid or gaseous fuels, heat, and electricity. Recent BECCS project announcements are diverse across power (combined heat and power plants), industry (cement, pulp and paper applications, hydrogen), and transport (hydrogen) sectors.[46] BECCS systems that deliver electricity, hydrogen, or process heat can be designed to capture nearly all the carbon present in the biomass feedstocks used to operate the system. In the case of BECCS systems that deliver hydrocarbon fuel products - e.g., biofuels or biogas - the use of these products will generate downstream CO_2 emissions absent carbon capture at the point of use. In these cases, lifecycle climate benefits will also depend on whether downstream emissions from BECCS system outputs are lower per unit of energy delivered than the current or most likely alternative energy source.

An example would be the use of biomass-based sustainable aviation fuels (bio-SAFs) to help decarbonize the aviation sector. Biomass-based SAFs, particularly if they are refined using hydrogen that is also sourced from BECCS or other low- or zero-carbon suppliers, could reduce GHG emissions relative to the use of conventional kerosene jet fuel. But bio-SAFs would still release some CO_2 back to the atmosphere.[47]

Another example involves the use of heat produced at BECCS facilities to meet thermal needs in the industrial sector, including to operate carbon capture processes - thereby reducing external energy needs and emissions. For example, existing pulp mills are large sources of biogenic carbon emissions and produce heat that could be supplied to facilities for biogenic CO_2 capture and storage. Heat produced via BECCS systems could also be directed to iron, steel, and chemical manufacturing processes that are difficult to electrify and require a high-temperature heat source. A related consideration is that the climate impacts of BECCS outputs will vary across regions: benefits are likely to be maximized, for example, where BECCS facilities can take advantage of proximity to both reliable biogenic waste streams and energy users or off-takers that have few other decarbonization alternatives.

Where biomass supplies are constrained, and other low- or zero-carbon energy resources are available, it may make sense to reserve BECCS energy outputs for hard-to-decarbonize sectors like industry that require a high-temperature heat source, or for sectors like power that need dispatchable renewable energy. These use cases may be especially relevant where alternative sources of clean firm power (such as nuclear or geothermal) are not available. In regions with abundant, economically recoverable waste or residue biomass feedstocks that would otherwise be at risk of causing emissions, BECCS may deliver climate benefits regardless of the specific downstream application of resulting energy outputs, assuming the system does not encourage more waste production. Such regions could include parts of the western U.S. where forest thinning is needed to reduce wildfire risk and densely populated urban areas in the Northeast that generate large waste streams.[48]

Can BECCS systems produce outputs that return value to the land used to grow biomass feedstocks?

BECCS systems can be designed to deliver additional, non-energy and non-CO_2 coproducts such as livestock feed, biochar, and liquid digestate fertilizer. These coproducts, like the energy outputs from a BECCS facility, will have different emissions profiles and potential applications, in some cases including applications that displace more GHG-intensive products.

Prominent examples of outputs that might return value to land include soil amendments. For example, processes that convert crop residues into liquid biofuels and return a carbon- or nitrogen-rich byproduct back to the land that the crop residues were taken from may avoid concerns related to decreased soil carbon and soil fertility when harvesting residues.[49] As another example, processes that produce liquid digestate, a nitrogen-rich residue that can be used as a nitrogen fertilizer may displace the need for GHG-intensive synthetic nitrogen fertilizers.[50] BECCS coproducts cannot, however, be assumed to automatically reduce climate impacts compared to the conventional alternative, and full lifecycle assessments will be needed to understand their advantages, if any. Many potential BECCS coproducts, like digestate, would be expected to decompose and release their carbon content back to the atmosphere within much less than 100 years. Carbon in other coproducts, like biochar, could be expected to remain in terrestrial storage for longer.[51]

Similarly, some BECCS coproducts could generate additional emissions when used, whereas others could deliver long-term climate benefits by, for example, increasing the organic carbon content of soils, an important form of terrestrial carbon storage. In some cases, the way a coproduct is used can also make a difference. For example, applying liquid digestate fertilizer to cropland via simple surface broadcasting could lead to increased ammonia emissions and nitrate leaching. This would not only harm air and water quality; it might make future applications of fertilizer less effective at increasing crop yields. If digestate is instead injected into soils at the optimum time for crop growth, the result might be lower ammonia emissions, increased nitrogen availability to plants, and higher yields.[52]

Impacts from BECCS coproducts have a regional dimension insofar as demand for, and likely uses of, these coproducts are likely to vary across different locations. Farms with ample cropland, for example, may be well-positioned to use the digestate coproduct from anaerobic digesters as a fertilizer and apply it in beneficial ways. By contrast, operations with less land, like some confined animal feeding operations, may not be able to use this material without incurring reactive nitrogen losses. A BECCS facility located near such operations may need to transport digestate coproducts elsewhere, which will incur additional transport emissions.

6. Conclusion

The variety and complexity of considerations discussed in this issue brief underscore our central point: BECCS represents many systems and technologies; the potential to scale climate-beneficial BECCS systems exists, but they cannot be categorically labeled as climate-beneficial or detrimental. Rather, any assessment of the climate merits of a given BECCS system requires an understanding of how different choices influence overall emissions. These considerations are also important from a deployment perspective since different biomass feedstocks, supply chains, and technologies will present different scaling challenges.

At present, BECCS deployment remains limited - current CO_2 capture by such systems globally is estimated to be on the order of just 2 Mt per year.[53] For climate-beneficial BECCS to play a larger role in mitigation, significant socio-economic concerns and environmental challenges would have to be overcome. Financial and labor requirements to rapidly scale BECCS will be formidable; in addition, the carbon credits that projects may generate (for carbon atoms geologically stored) are likely to confront concerns about the potential to delay or deter emission reduction investments in other industries depending on how carbon credits are or can be used,[54] and skepticism based on the public health and environmental impacts of past conventional bioenergy development, and supply chain barriers (particularly for cellulosic biomass feedstocks) will need to be addressed.

A nuanced understanding of BECCS systems and an appreciation of the tradeoffs inherent in different system design choices is a critical starting point for identifying promising deployment opportunities and for developing policies and incentives that will help ensure beneficial outcomes. The best opportunities for BECCS deployment offer a unique opportunity to advance multiple goals, including emissions reductions, carbon dioxide removal, economic development, and improved ecosystem health and resilience. A strategic approach to expanding the role of modern BECCS offers the best hope of realizing these opportunities and will help position the agriculture and energy sectors - along with the communities and industries that depend on them - to continue thriving in an era of mounting climate threats and other challenges.

Acknowledgments

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Endnotes

[1] Biomass resources are commonly called biorenewable resources, or biomass feedstocks. These materials can include living or recently living plants such as crops, crop residues, or forest residues; they can also include other biogenic resources such as human and animal wastes.

[2] M. Pathak, R. Slade, P.R. Shukla, J. Skea, R. Pichs-Madruga, D. Ürge-Vorsatz,2022: Technical Summary. In: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [P.R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, J. Malley, (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA. doi: 10.1017/9781009157926.002. Across the scenarios limiting warming to 2°C (>67%) or below, cumulative volumes of BECCS reach 328 (168–763) GtCO_2, CO_2 removal from AFOLU (mainly A/R) reaches 252 (20–418) GtCO_2, and DACCS reaches 29 (0–339) GtCO_2, for the 2020–2100 period. Annual volumes in 2050 are 2.75 (0.52–9.45) GtCO_2 yr^{-1} for BECCS, 2.98 (0.23–6.38) GtCO_2 yr^{-1} for the CO_2 removal from AFOLU (mainly A/R), and 0.02 (0–1.74) GtCO_2 yr^{-1} for DACCS. (Box TS.10) {12.3, Cross-Chapter Box 8 in Chapter 12}; IEA (2021), Net Zero by 2050, IEA, Paris https://www.iea.org/reports/net-zero-by-2050, Licence: CC BY 4.0.

[3] Most geologically sequestered carbon to date has been stored as carbon dioxide, but other approaches to storing carbon, such as in mineral form or bio-oil, are emerging.

[4] https://www.iea.org/energy-system/carbon-capture-utilisation-and-storage/bioenergy-with-carbon-capture-and-storage; https://demoplants.best-research.eu/

[5] Field, J. L., Richard, T. L., Smithwick, E. A. H., Cai, H., Laser, M. S., LeBauer, D. S., Long, S. P., Paustian, K., Qin, Z., Sheehan, J. J., Smith, P., Wang, M. Q., & Lynd, L. R. (2020). Robust paths to net greenhouse gas mitigation and negative emissions via advanced biofuels. Proceedings of the National Academy of Sciences, 117(36), 21968–21977. https://doi.org/10.1073/pnas.1920877117; Schulte, L. A., Dale, B. E., Bozzetto, S., Liebman, M., Souza, G. M., Haddad, N., Richard, T. L., Basso, B., Brown, R. C., Hilbert, J. A., & Arbuckle, J. G. (2021). Meeting global challenges with regenerative agriculture producing food and energy. Nature Sustainability, 5(5), 384–388. https://doi.org/10.1038/s41893-021-00827-y; SDSN/FEEM 2021. Roadmap to 2050: The Land-Water-Energy Nexus of Biofuels. New York: Sustainable Development Solutions Network (SDSN) and Fondazione Eni Enrico Mattei (FEEM). Section 4.3 The Case of the United States: Reimagining Biofuels as if Carbon Mattered. https://roadmap2050.report/static/files/roadmap-to-2050-biofuels.pdf

[6] The net flux of carbon, defined as the carbon removal efficiency, can be thought of as a measure of process efficiency https://pubs.rsc.org/en/content/articlelanding/2025/su/d4su00552j

[7] Sanchez et al. 2025. Carbon removal efficiency and energy requirement of engineered carbon removal technologies. RSC Sustain. DOI: 10.1039/D4SU00552J.

[8] Biomass resources in this context are generally understood to exclude fossil resources (such as coal) derived from plants that captured carbon millions of years ago. Biorenewable Resources: Engineering New Products from Agriculture, Second Edition. Robert C. Brown and Tristan R. Brown. 2014 John Wiley & Sons, Inc. Published 2014 by John Wiley & Sons, Inc

[9] Adler, P. R., del Grosso, S. J., Inman, D., Jenkins, R. E., Spatari, S., & Zhang, Y. (2012). Mitigation Opportunities for Life-Cycle Greenhouse Gas Emissions during Feedstock Production across Heterogeneous Landscapes. In Managing Agricultural Greenhouse Gases (pp. 203–219). Elsevier. https://doi.org/10.1016/B978-0-12-386897-8.00012-7

[10] Other pathways exist, including physical processes like crushing high-lipid biomass resources to extract oil, and hybrid schemes, such as the use of biological processes to produce intermediates, which are then thermochemically converted to deliver other outputs.

[11] https://roads2removal.org/

[12] Daystar, J. S., Treasure, T., Gonzalez, R., Reeb, C., Venditti, R., & Kelley, S. (2015). The NREL Biochemical and Thermochemical Ethanol Conversion Processes: Financial and Environmental Analysis Comparison. BioResources, 10(3). https://doi.org/10.15376/biores.10.3.5096-5116

[13] Direct BECCS supply chain emissions occur during biomass resource cultivation (including soil carbon emissions from directly cultivated land and fertilizer production emissions), harvest, transportation, processing, conversion to energy, and the transportation and injection of carbon dioxide into geologic storage. Direct supply chain emissions can be measured or calculated with a degree of certainty. Indirect supply chain emissions are not measured; they are estimated using models and will always have some degree of uncertainty. These indirect sources include emissions from land use conversion (e.g. clearing forests to replace food production on lands converted to bioenergy crops) and market effects not directly related to biomass resources.

[14] When BECCS systems achieve and prioritize CDR, do no harm to, and ideally improve, social or environmental systems, they are considered part of the broader umbrella of biomass carbon removal and storage technologies, or BiCRS. BiCRS systems may or may not produce energy as a co-product and include systems such as the pyrolysis of biomass resources to produce bio-oil for subsurface injection and the production of cross-laminated timber from forest biomass for mass timber buildings.

[15] The Science Based Targets Initiative (https://sciencebasedtargets.org/) requires permanent carbon dioxide removal to counterbalance any residual emissions to achieve a true state of net-zero, where emissions are fully neutralized by removals. Avoided and reduced emissions do not result in a net removal of carbon from the atmosphere and, therefore, do not compensate for a residual emission.; Luers, A., Yona, L., Field, C. B., Jackson, R. B., Mach, K. J., Cashore, B. W., Elliott, C., Gifford, L., Honigsberg, C., Klaassen, L., Matthews, H. D., Peng, A., Stoll, C., van Pelt, M., Virginia, R. A., & Joppa, L. (2022). Make greenhouse-gas accounting reliable - build interoperable systems. Nature, 607(7920), 653–656. https://doi.org/10.1038/d41586-022-02033-y; Joerss, W. Challenges for the accounting of carbon removals Challenges

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