Geospatial analysis of near-term potential for carbon-negative bioenergy in the United States

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Bioenergy with carbon capture and storage (BECCS) is a negative-emissions technology that may play a crucial role in climate change mitigation. BECCS relies on the capture and sequestration of carbon dioxide (CO_2) following bioenergy production to remove and reliably sequester atmospheric CO_2. Previous BECCS deployment assessments have largely overlooked the potential lack of spatial colocation of suitable storage basins and biomass availability, in the absence of long-distance biomass and CO_2 transport. These conditions could constrain the near-term technical deployment potential of BECCS due to social and economic barriers that exist for biomass and CO_2 transport. This study leverages biomass production data and site-specific injection and storage capacity estimates at high spatial resolution to assess the near-term deployment opportunities for BECCS in the United States. If the total biomass resource available in the United States was mobilized for BECCS, an estimated 370 Mt $CO_2 \cdot y^{-1}$ of negative emissions could be supplied in 2020. However, the absence of long-distance biomass and CO_2 transport, as well as limitations imposed by unsuitable regional storage and injection capacities, collectively decrease the technical potential of negative emissions to 100 Mt $CO_2 \cdot y^{-1}$. Meeting this technical potential may require large-scale deployment of BECCS technology in more than 1,000 counties, as well as widespread deployment of dedicated energy crops. Specifically, the Illinois basin, Gulf region, and western North Dakota have the greatest potential for near-term BECCS deployment. High-resolution spatial assessment as conducted in this study can inform near-term opportunities that minimize social and economic barriers to BECCS deployment.

carbon dioxide removal | negative emissions | carbon capture | carbon sequestration | bioenergy

As of 2016, the global carbon budget indicates only 760 Gt of cumulative global carbon dioxide (CO_2) emissions remain for there to be a 66% chance of holding global temperature increase to 2 °C above preindustrial levels (1). Given that annual CO_2 emissions in 2016 were ∼40 Gt CO_2 (1), the aforementioned budget could be exhausted with ∼20 y at current emissions levels. As such, many studies have highlighted the need for negative-emissions technologies (NETs) to achieve ambitious mitigation goals (2–5). Bioenergy with carbon capture and storage (BECCS) is a widely considered NET due to its perceived near-term feasibility, scalability, and ability to produce energy. Integrated assessment models (IAMs) with scenarios that are likely to meet the 2 °C goal have a median estimate of annual CO_2 removal from BECCS by the year 2100 of 12 Gt CO_2 (5, 6), with deployment beginning as early as 2020 (7). In the United States alone, annual BECCS deployment estimates are as high as 1 Gt $CO_2 \cdot y^{-1}$ in 2050, and between 1 Gt $CO_2 \cdot y^{-1}$ and 3 Gt $CO_2 \cdot y^{-1}$ in 2100 (8). The deployment potential of BECCS depends on not only the availability of biomass but also the presence of suitable geologic storage sites and the existence of transportation methods of biomass or CO_2 between the two resources.

To date, much of the academic discussion surrounding the feasibility of large-scale deployment of BECCS has focused on biomass potential (9–13) but has often neglected to consider the availability and characteristics of suitable storage sites for sequestration. Studies that have considered storage and injection rate capacity in the context of BECCS (6, 14, 15) have considered only aggregated global or national storage and injection rate capacities. While global aggregated storage capacity is generally not considered a limiting factor for BECCS or CCS deployment (16, 17), capacity of specific storage sites varies widely and may lead to regional storage constraints. Injection rate capacity, a function of the porosity, permeability, and thickness of the porous storage basin, is the annual CO_2 injection rate achievable in a single well in a storage site (18). Injection rates that exceed the injectivity of a particular storage reservoir increase subsurface pressures to unacceptably high levels and may create fractures in the cap rock, induce seismicity, or activate faults, making the project more prone to leakage and costlier to monitor. Although additional injection wells could, in principle, achieve similar injection rate capacities while minimizing such risks, drilling and subsequently monitoring more wells will drive up costs. As a result, storage sites with large injection rate capacity are most attractive for BECCS because they can sustain high CO_2 sequestration rates. Consideration of the storage and injection rate capacity of storage formations at a fine spatial scale is crucial in determining potential storage sites suitable for near-term BECCS deployment.

In addition to the availability of biomass and suitable storage sites, the ability to transport CO_2 or biomass between the two resources can be an important factor that constrains the potential of BECCS. Transporting biomass is comparatively more

Significance

Bioenergy with carbon capture and storage (BECCS) is widely utilized in ambitious climate mitigation scenarios as a negative-emissions technology. However, the future technical potential of BECCS remains uncertain. Two significant deployment barriers that have largely been overlooked by previous studies are the suitability of existing storage sites and the availability of transportation of biomass and/or CO_2. This study assesses the near-term deployment potential of BECCS in the United States in the absence of long-distance transportation networks. Considering these constraints, 30% of the projected available 2020 biomass resources can be utilized for BECCS, yielding a negative-emissions potential of 100 Mt $CO_2 \cdot y^{-1}$. The analysis further pinpoints areas with colocated resources that could be prioritized for near-term deployment of BECCS.

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expensive than fossil fuels due to its lower energy density. Even woody biomass, which has a higher energy content relative to other lignocellulosic biomass, is expensive to transport distances of 50 miles or less (19), while transportation of other lignocellulosic biomass, like corn stover or miscanthus, are prohibitively expensive to justify transport beyond 12 miles in some instances (20). Similarly, studies assessing the complexities and cost of CO_2 transport have concluded that building new CO_2 pipelines is a time consuming process that faces potential public opposition, and that economies of scale strongly favor building large pipelines compared with many smaller ones (21, 22).

Complex permitting required for building CO_2 transport pipelines is a time-consuming process (23). For example, the 808-km Cortez CO_2 pipeline in the United States took 8 y to complete because of regulatory hurdles, despite construction lasting only 2 y (21). The existing 3,700 km of CO_2 pipelines in the United States are largely used for enhanced oil recovery (EOR). Expanding the system to use the maximum amount of biomass available for BECCS will likely require large-scale CO_2 or biomass transportation infrastructure. Until these advances occur, early deployment of BECCS will need to target sites with colocated biomass potential and suitable storage sites. Strategically siting BECCS plants using high-resolution spatial data can help inform near-term opportunities that minimize social and economic barriers to BECCS deployment that arise from transportation constraints.

As of 2017, only one demonstration-scale BECCS project has been deployed globally, with a removal capacity of 1 Mt $CO_2 \cdot y^{-1}$ (24). This is far less than the gigatonne-scale deployment needed by the end of the century to meet the 2 °C goal. Near-term deployment opportunities can reduce costs and constrain the sustainable scale of BECCS (25). Deploying BECCS in countries or regions best suited for the technology can also enhance global near-term deployment efforts by encouraging the development of related technologies and informing future projects (26). The United States, in particular, is a nation of interest for large-scale BECCS deployment due to its relatively high biomass productivity, as well as abundant and well-mapped geologic CO_2 storage sites. The United States also has an advanced bioenergy industry and multiple pilot-scale CO_2 injection projects, making it well positioned to commercialize the BECCS industry (26).

This study leverages continental US (CONUS)-wide, spatially explicit estimates of biomass production potential and geological CO_2 storage formations, including site-specific estimates of storage and injection rate capacity, to assess the near-term deployment potential of BECCS in the United States in the absence of long-distance CO_2 pipelines and biomass transportation networks. County-level biomass availability data from the US Department of Energy (DOE) Billion-Ton Report (27) alongside potential CO_2 geologic storage sites as provided by the US Geological Survey (USGS) Assessment of Geological Carbon Dioxide Storage Resources (28) are used in the analysis. The near-term BECCS deployment potential in the United States, both with and without a suitable storage site, as well as areas most relevant for near-term BECCS deployment are determined. The analysis further discusses the deployment potential nearly at the middle of the century, and its sensitivity to energy crop adoption.

Results and Discussion

The US DOE's 2016 Billion-Ton Study (BT16) quantifies the amount of biomass resource that would be available economically in the future, and includes estimated potential from agricultural residue, woody biomass and residuals, and dedicated energy crops. BT16 estimates that, by 2020, a total of 210 Mt to 230 Mt of lignocellulosic biomass will be available annually in the CONUS for BECCS, depending on the rates of yield increase of dedicated energy crops (*Methods*). Of the total potential biomass, 50% is agricultural residue, 40% is harvested and residual woody biomass, and 10% is dedicated energy crop. BT16 provides biomass availability data at the county level (Fig. 1). Per county biomass availability in the United States is generally below 0.1 Mt of biomass per year, emphasizing the importance of high-yielding regions like the midwestern Corn Belt and the Southeast United States. In 2020, 37% of all biomass is located in the midwestern Corn Belt, where the majority of the biomass (89%) is agricultural residue. Energy crops are highly concentrated in the Southern Plains region, and woody biomass production is concentrated in the Southeast, Pacific West, and Appalachian regions. The total biomass availability of 210 Mt to 230 Mt in 2020 can produce as much as 370 Mt $CO_2 \cdot y^{-1}$ to 400 Mt $CO_2 \cdot y^{-1}$ for sequestration (*Methods*).

Potential storage sites are located under 44% of the CONUS counties. The counties overlaying potential storage sites produce 31 to 32% (110 Mt $CO_2 \cdot y^{-1}$ to 120 Mt $CO_2 \cdot y^{-1}$) of the total biomass potential in the United States in 2020. Of the biomass colocated with storage sites, 41% is agricultural residue, 44% is woody biomass, and 16% is energy crop. The relatively small fraction of colocated biomass validates the need for transportation systems for either biomass or CO_2 for deployment of BECCS at the scale of several hundred megatonnes of CO_2 per year in the United States.

However, storage site characteristics vary widely, and analysis of individual storage basins provides insight into those that are suitable for CO_2 injection. The storage sites used in this analysis have been identified and characterized by the USGS Assessment of Geologic Carbon Dioxide Storage Resources in the United States. The USGS assessment considers sedimentary formations of siliciclastic and carbonate rocks that exist in forms of saline aquifers or oil and gas reservoirs that have sufficient porosity and permeability to store CO_2. USGS further screens the storage sites for adequate depth for CO_2 injection (>900 m) and presence of a seal formation to trap the injected CO_2 (28). USGS's detailed analysis provides information on the storage capacity as well as the porosity, permeability, and depth of the geological formations. The information provided can be used to calculate whether suitable injectivity is available to accommodate the CO_2 produced from biomass combustion.

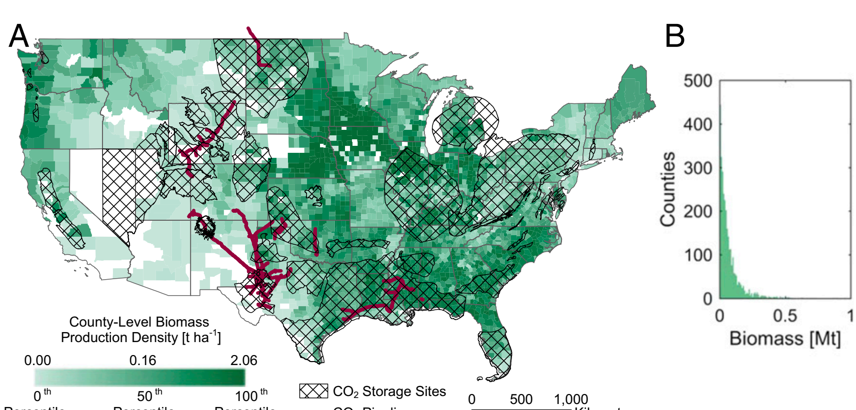

Fig. 1. Distribution of biomass production. (*A*) County-level biomass production density (tonnes per hectare) in 2020 for the basecase scenario in BT16, potential geologic storage sites for CO_2, and currently existing pipelines for CO_2. The highest producing counties are located in the midwestern Corn Belt and the Southeast United States. (*B*) Distribution of annual biomass production per county (megatonnes). The production of biomass is skewed heavily to low values, typically below 0.1 Mt biomass.

Calculated injection rate capacities for a single well in a county overlaying a distinct storage-formation range from 0.001 Mt $CO_2 \cdot y^{-1}$ per well to 60 Mt $CO_2 \cdot y^{-1}$ per well (Fig. 2). The calculated injection rates do not indicate that injection would occur at such rates, but rather serve as proxies for a storage site's maximum injectivity. Only 13 counties out of the total 1,256 colocated counties produce more biomass-sourced CO_2 than is possible to inject into a single well in the underlying storage reservoir. The Gulf region features an extremely high injection rate capacity of >5 Mt $CO_2 \cdot y^{-1}$ per well, while low injection rate capacity formations (<0.25 Mt $CO_2 \cdot y^{-1}$ per well) are found in Nevada, Utah, and Colorado. For comparison, injection rates for pilot-scale CCS projects are usually on the order of 0.01 Mt $CO_2 \cdot y^{-1}$ to 0.3 Mt $CO_2 \cdot y^{-1}$, while demonstration and commercial-scale projects are on the order of 1 Mt $CO_2 \cdot y^{-1}$ or greater (29). This analysis uses a cutoff of injectivity less than 0.25 Mt $CO_2 \cdot y^{-1}$, below which BECCS projects are not considered feasible due to risks associated with demonstration-scale injection of CO_2 into low-injectivity reservoirs.

USGS estimates total storage capacity of 3,000 Gt CO_2 in the United States. Assuming 100% capture and sequestration of all CO_2 from biomass dedicated to BECCS in the United States, 75 Gt to 121 Gt CO_2 is available cumulatively from 2020 to 2100, indicating that absolute storage will not to be a limitation for BECCS deployment. This conclusion is consistent with several previous assessments that have considered storage capacity as a factor of consideration for BECCS deployment (4, 17). Across the total 26 storage basins evaluated, 15 basins fill less than 5% of their capacity throughout the century, while the remaining nine basins are filled by less than 40% (Fig. 3). Assuming on-site sequestration of the total BECCS CO_2 potential from counties overlaying storage sites, two basins, the Kansas Basin (central Kansas) and Black Warrior Basin (northern Mississippi), reach full capacity by the end of the century. Both basins have a total storage capacity less than 400 Mt CO_2. If the United States were to achieve annual gigatonne-scale BECCS deployment, storage sites with less than 400 Mt CO_2 capacity may require early termination of projects. Given this risk, storage sites with less than 400 Mt CO_2 capacity would most likely not be used for injection, and they are thus considered not suitable for injection in this study. High-spatial resolution studies can identify and assess these potential barriers in advance of deployment.

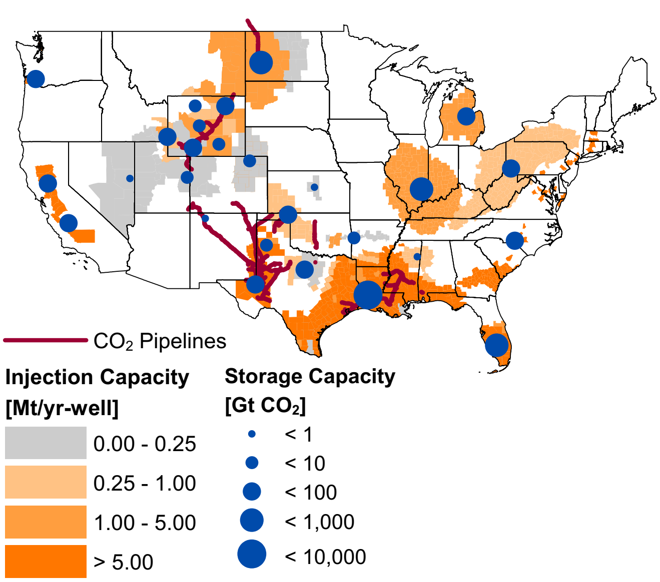

Fig. 2. Site-specific achievable injection rates (megatonnes per year per well) and aggregated storage capacity by basin (gigatonnes). Injection rates are calculated using site-specific data, while the storage capacity data are provided by USGS. Both injection rates and storage capacities show a wide range of values, but areas with high injection rates tend to also have large storage capacities, such as the Gulf region, the Illinois basin, and western North Dakota.

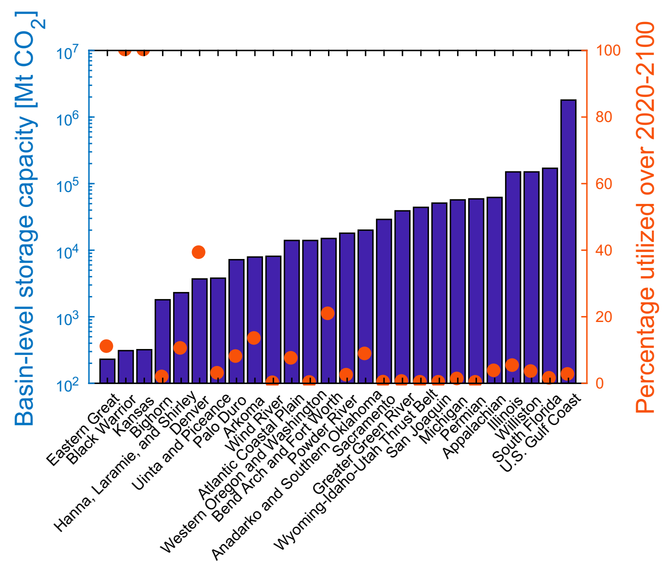

Fig. 3. Distribution of basin storage capacities on a logarithmic scale, and the percentage of the storage basin filled from the cumulative biomass overlaying the storage basin by the year 2100. The storage capacities span orders of magnitude, ranging from 400 Mt CO_2 to more than 100 Gt CO_2. Two of the basins, Black Warrior Basin and Kansas Basin, reach capacity by the end of the century.

Given the limitations created by the requirement for sufficient storage and injection rate capacity, the CO_2 potential overlaying a suitable storage site decreases to 100 Mt $CO_2 \cdot y^{-1}$ to 110 Mt $CO_2 \cdot y^{-1}$ in 2020. Approximately half of the 10 Mt $CO_2 \cdot y^{-1}$ decrease comes from storage capacity-limited counties, while the other half comes from injection capacity-limited counties. The northern Illinois basin, the US Gulf region, and western North Dakota are shown to be the most promising areas for near-term BECCS deployment (Fig. 4). Indeed, currently existing bioethanol CCS projects such as the Decatur plant in Illinois (30) and planned projects such as the Red Trail Energy's project in North Dakota (31) inject CO_2 from biomass into these basins and take advantage of colocated biomass and storage. In these regions, future biomass resource consists heavily of agricultural residues. In contrast, the Gulf region consists mostly of energy crops and woody biomass. The Gulf region, in particular, would be a strategic location to deploy BECCS, in large part due to its existing infrastructure of pipelines, experience with CO_2 injection, and high-resolution basin characterizations from oil and gas explorations. Existing CO_2 injection projects in the Gulf region include the Port Arthur Project and Petra Nova Project, which capture CO_2 from fossil fuel power plants and inject it for EOR purposes (24).

While BECCS deployment is projected to begin as early as 2020, deployment is expected to increase throughout the century. Using the same method as the analysis conducted for 2020, the BECCS deployment potential of 2040 is assessed. The results indicate that the total economically available biomass in the United States in 2040 could be as high as 610 $Mt \cdot y^{-1}$ to 1,040 $Mt \cdot y^{-1}$. Notably, the fraction of biomass attributable to energy crops increases to 61 to 75%. Economically available biomass in 2040 translates to a technical CO_2 removal potential of 1,040 Mt $CO_2 \cdot y^{-1}$ to 1,780 Mt $CO_2 \cdot y^{-1}$, and, of this, 38% (400 Mt $CO_2 \cdot y^{-1}$ to 680 Mt $CO_2 \cdot y^{-1}$) is colocated with a storage basin. The increase in the overlapping biomass ratio from 31 to 32% in 2020 to 38 to 39% in 2040 is attributed to areas with suitable storage sites such as the Gulf region undergoing widespread land-use conversion to bioenergy crops in the BT16 scenarios. In 2040, the three regions previously pointed out to be promising locations for BECCS deployment, the northern Illinois basin, the Gulf region, and western North Dakota, still have relatively large CO_2

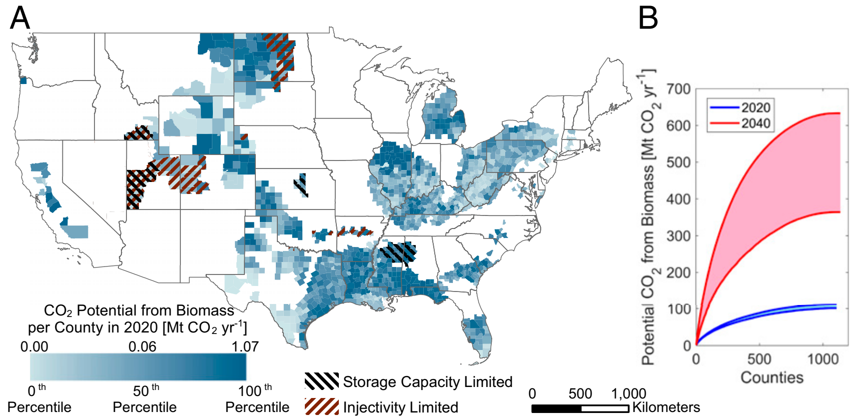

Fig. 4. Distribution of technical potential of BECCS. (*A*) Map of technical potential of CO_2 that would be available from biomass in 2020, under the BT16 basecase scenario. Regions with highest CO_2 potential and colocated storage sites are northern Illinois basin, the Gulf region, and western North Dakota. The CO_2 potential in each county translates to a power capacity of 0.1, 12, and 29 MW for the 5th, 50th, and 95th percentiles, respectively. (*B*) Cumulative sum of the potential CO_2 in counties with a suitable storage site for 2020 and 2040. The lower bound of the range indicates the base case scenario, while the higher bound indicates the 4% yield increase scenario. The range of uncertainty is much larger for 2040 than for 2020.

storage potential from biomass. The western Gulf region sees a particular rise in potential CO_2 availability from expected energy crops. While the majority of counties have an increase in biomass production, areas that had relatively lower potential in 2020, such as the Appalachian basin, California, Central Plains region, and Michigan, remain less productive relative to other regions. Table 1 summarizes the total CO_2 potential from all biomass, biomass colocated with a storage site, and biomass colocated with a storage site with suitable storage and injection rate capacity.

Of particular importance in BT16 is the assumption that large portions of the southern United States, where land is comparatively less productive than the Midwest, will produce dedicated energy crops. However, there are still many uncertainties on the yield of energy crops and the amount of land that would need to be dedicated to energy crops. BT16 assumes 1% annual yield increase for energy crops as the base case scenario. For comparison, corn and soybean yields in the United States grew annually by 1.8% and 1.4%, respectively, over the past 40 y (32). The implications of energy crop projections not materializing can be illustrated through considering near-term technical potential for BECCS based on agricultural residue and woody biomass alone. Under this scenario, the CO_2 potential overlaying a storage site decreases by 16 to 20% in 2020, and 71 to 82% in 2040, which translates to a negative-emissions potential of 85 Mt $CO_2{\cdot}y^{-1}$ to 88 Mt $CO_2{\cdot}y^{-1}$ in 2020 and 104 Mt $CO_2{\cdot}y^{-1}$ to 111 Mt $CO_2{\cdot}y^{-1}$ in 2040. The large proportion of energy crops in the 2040 biomass availability assessment has significant implications for the CO_2 removal potential of BECCS, and further emphasizes the importance of biomass availability in BECCS deployment assessment analysis.

The technical potential of BECCS is also sensitive to the injection rate capacity of a suitable storage site. The injection rate capacity calculation is conducted assuming single-phase flow of water, instead of two-phase flow of water and CO_2, which provides a conservative estimate for the achievable injection rate of a storage site (33). The current injection capacity calculation assumes a 50% allowable pressure increase at the well bore. Note that the pressure would increase to 50% only at the borehole and diffuse exponentially radially in the reservoir. The Environmental Protection Agency regulates CO_2 injection wells as Class VI wells, limiting the injection pressure to 90% of the fracture pressure of the subsurface storage reservoir. Typical fracture pressures range from 14 $MPa{\cdot}km^{-1}$ to 23 $MPa{\cdot}km^{-1}$ (34), and the allowable 50% pressure increase used in this study corresponds to a fracture gradient of 15.5 $MPa{\cdot}km^{-1}$, which falls in the low end of the range (*Methods*). Assuming two-phase flow or using higher or lower allowable pressure increase assumptions may influence the injection rate capacity estimates, and consequently the technical potential of BECCS as determined in this study.

BECCS is unique among the NETs because it has a positive energy value. The results from this analyses indicate that the total energy potential of the biomass overlaying suitable storage sites in 2020 is ~0.3 exajoules $(EJ){\cdot}y^{-1}$, and increases to 1 $EJ{\cdot}y^{-1}$ to 2 $EJ{\cdot}y^{-1}$ in 2040 in large part because of anticipated deployment of energy crops. In 2016, the United States generated a total of 15 EJ of electricity, 1.5% (0.2 EJ) of which was from bioenergy (35). The results from this analysis imply that the United States has the potential to nearly triple its bioenergy generation by 2020 and increase almost 10-fold by 2040, while achieving negative emissions. Given that studies have emphasized that BECCS will have a higher carbon mitigation value than energy value in the future (4, 36), BECCS power plants will likely operate at baseload. Energy from BECCS may provide a reliable source of baseload capacity of renewable generation for states with high renewable portfolio standards, such as California and New York (37).

Based on this analysis, the United States has a negative-emissions potential in 2040 that is consistent with median IAM BECCS deployment projections by the middle of the century that stabilize greenhouse gas concentrations at 450 ppm CO_2e. Assuming globally harmonized energy policies starting as early as 2010, BECCS deployment estimates in the United States across four different IAMs range from 0 Mt $CO_2{\cdot}y^{-1}$ to 1,000 Mt $CO_2{\cdot}y^{-1}$, in 2050, with a median of ~500 Mt $CO_2{\cdot}y^{-1}$ (8, 38). The analysis conducted in this study estimates a near-term deployment potential of 360 Mt $CO_2{\cdot}y^{-1}$ to 630 Mt $CO_2{\cdot}y^{-1}$ in 2040, indicating that the United States has a negative-emissions potential that is consistent with median IAM projections for the middle of the century, assuming that the entire potential for BECCS where the biomass resources and storage reservoirs are colocated is realized. However, capturing all of the potential may provide other significant challenges and opportunities.

The biomass-sourced CO_2 colocated with a storage site is distributed widely around the country. Meeting the potential of 100 Mt $CO_2{\cdot}y^{-1}$ can range from establishing more than

Table 1. Negative-emissions potential in 2020 and 2040 in total and with constraints

Negative-emissions potential, Mt $CO_2{\cdot}y^{-1}$	2020	2040
Total	370 to 400	1,040 to 1,780
With colocated storage	110 to 120	400 to 680
With colocated storage with sufficient storage and injectivity	100 to 110	360 to 630

Table 2. Parameters used for injection capacity estimation and pressure calculation

Parameter	Description	Nominal value	Units
Q	Volumetric injection rate	Site-specific	$m^3 \cdot s^{-1}$
k	Permeability of formation	Site-specific	m
h	Thickness of porous region in formation	Site-specific	m
ΔP_{max}	Pressure buildup at the injection well	Site-specific	Pa
μ	Dynamic viscosity of water	5.8×10^{-4} (at ∼47 °C)	Pa·s
T	Timeframe for injection	30 Y (= 9.5×10^8 s)	s
$\varnothing$	Porosity of formation	Site-specific	—
c	Compressibility of rocks	1×10^{-09}	Pa^{-1}
r_e	Radius of pressure influence	Site-specific	m
ρ	Density of water	1,000	$kg \cdot m^{-3}$
g	Acceleration of gravity	9.81	$m \cdot s^{-2}$
d	Depth to center of formation	—	m
α	Maximum allowable pressure differential	0.5	—

1,000 localized BECCS projects with a colocated power plant and injection site to aggregating BECCS projects by transporting biomass and CO_2 over long distances to centralized facilities. Under the localized BECCS scenario, assuming a 0.85 capacity factor, the power plants in each county would have a range of capacities from 0.1 MW to 29 MW (5th to 95th percentile) with a median of 12 MW. For context, there are currently ∼300 biomass power plants in the United States with a median capacity of 23 MW (39). Under the localized BECCS scenario, the median capacity BECCS power plant in a county would also have a capture and injection rate of ∼0.06 Mt $CO_2 \cdot y^{-1}$. These injection rates are much smaller than for any of the commercial CCS projects, and will likely lack the economies of scale of existing projects. For example, globally, there are currently 21 large-scale CCS projects in operation, sequestering an average of 1.8 Mt $CO_2 \cdot y^{-1}$ (24). Monitoring costs will also need to be amortized over a much smaller quantity of CO_2, thus increasing costs per tonne of CO_2 stored. On the positive side, the small quantities of injection will pose lower environmental risks by causing lower pressure buildup in the storage reservoirs during injection and much smaller CO_2 plume footprints. The small size of these projects may warrant development of special regulations tailored to their unique attributes. Furthermore, the potential for locally generated power from locally sourced biomass from a renewable energy source may provide a supportive environment for small-scale BECCS projects. Other potential factors influencing the ability to deploy BECCS include sufficient policy support, appropriate market conditions, and favorable public perceptions (40). As such, capturing the potential from the distributed BECCS resources presents unique opportunities and challenges that make it difficult to make conclusions about the degree to which the 100 Mt $CO_2 \cdot y^{-1}$ technical potential is feasible.

This analysis estimates the near-term deployment potential of BECCS in the United States, taking into consideration not only biomass availability but also the colocation of storage sites with sufficient storage and injection capacity. Approximately 30% of the biomass potentially available for BECCS in 2020 is colocated with a storage site corresponding to sequestration of about 100 Mt $CO_2 \cdot y^{-1}$ in 2020 and 360 Mt $CO_2 \cdot y^{-1}$ to 630 Mt $CO_2 \cdot y^{-1}$ in 2040. The analysis identifies optimal sites for near-term BECCS deployment and emphasizes the need to consider source–sink matching for future near-term BECCS deployment assessments. The method employed in this study provides a framework for future studies assessing near-term BECCS potential, even on a global scale. Moving forward, detailed analysis of BECCS projects in regions with both high biomass production and a suitable storage site can also help inform near-term opportunities that minimize social and economic barriers to BECCS deployment.

Methods

County-level data of biomass availability were obtained from US DOE's BT16. The Billion-Ton Report is a series of national biomass resources assessments conducted to quantify the potential of US biomass resources for the production of renewable energy and bioproducts as well as to inform bioenergy policies, research, and development. The 2016 edition is the third such report, building on the 2005 Billion-Ton Study and 2011 US Billion-Ton Update by adding feedstock and expanding the analysis to take into consideration updated costs. BT16 also includes a second volume that considers the sustainability of the analysis conducted and potential climate change impacts on future supplies. The total biomass available in BT16 is an estimation of the economically available biomass resources given the latest available yield and cost data. In this analysis, only farm gate biomass cost of $60 per dry ton of biomass is analyzed.

In this analysis, BECCS is assumed to be solely for electricity generation, which captures a relatively high proportion of biogenic CO_2 during energy production. Agricultural residue (corn, wheat, barley, oats, rice, cotton, sugarcane, and sorghum stubble), woody biomass and woody residuals (forest thinning and sawmill residue), and dedicated energy crops (biomass sorghum, energy cane, eucalyptus, miscanthus, pine, poplar, switchgrass, and willow) are included in "biomass." Other types of biomass included in BT16, such as municipal solid waste, food waste, and manure, were not included in the analysis, as the heterogeneity and high moisture content of these feedstock may make them unsuitable for large-scale electricity generation.

In BT16, agricultural residue production is taken as a fraction (1:1 to 1:1.57 ratio of residue to grain) of the total conventional crop production, and also limited by sustainability and economic constraints. Energy crop production is determined largely by energy crop yield and available land for energy crop growth, which BT16 constrains to fallow lands and 10% of existing agricultural lands. Woody biomass production is restricted to timberlands and is dependent on conventional timber production as well as sustainability constraints. A further detailed description of the method and assumptions behind BT16 can be found in the report (27).

In 2020, BT16 has four potential scenarios of energy crop and agricultural residue production depending on the yield growth of dedicated energy crops. The four scenarios are 1%, 2%, 3%, and 4% yield growth of energy crops, with the 1% scenario being considered the base case scenario. While included under the same scenarios, agricultural residue production growth is not consistent with and is marginal to the production growth of energy crops. Relative to energy crop growth, woody residue and woody production in the

Table 3. Heat content, CO_2 content, and generation efficiency

Description		Unit
Heat content of biomass (HHV) (42)*	19.2	Gigajoules per dry tonne biomass
CO_2 content of biomass (43)†	1.71	Tonnes CO_2 per dry tonne biomass
Generation efficiency (44)‡	0.266	—

*Assuming average of heat content values of various blended lignocellulosic biomass.

†CO_2 content of dry wood and wood residuals.

‡Generation efficiency of biomass power plant equipped with CCS.

United States remains relatively constant over the four scenarios from 2020 to 2040, and so, only the base case scenario for woody residue (medium housing and low energy demand) is used in the analysis. The analysis was conducted for the CONUS. For aggregated CO_2 potential from biomass from 2020 to 2100, production values in BT16 from 2020 to 2040 were used. Production values beyond 2040 were assumed to be held constant until 2100.

Potential geologic storage sites for CO_2 were obtained from the USGS National Assessment of Geologic Carbon Dioxide Storage Resources. The USGS defines Storage Assessment Units (SAUs) as a "mappable volume of rock that consists of a porous reservoir." The definitions of SAUs are further constrained by their depths, their location relative to potable water, and the presence of a seal formation; 202 SAUs within 36 sedimentary basins were identified by USGS. Only SAUs that provided quantitative data were considered in the analysis (192 SAUs within 33 basins). Quantitative data included permeability, depth, porosity, thickness, and estimated buoyant and residual trapping capacities of an SAU. Methods of calculating the storage capacities are detailed further in the USGS report (28), and storage capacity values used in this study were aggregated by basin.

For each county, the allowable injection rates were calculated assuming one well injecting into a storage formation beneath the county. Note that storage formations may overlap geographically at different depths, and multiple storage formations constitute a basin. If multiple SAUs were located under one county, the maximum injection rate across the SAUs was determined to be the injection capacity of the county. The allowable injection rates per well were approximated based on Darcy's law for single-phase flow using Eq. **1**.

$$Q_{\max}=\frac{2\pi k h\ \Delta P_{\max}}{\mu \log\left(\frac{r_e}{r_w}\right)} \text{ where } r_e=\sqrt{\frac{2\kappa T}{\varnothing \mu c}}. \quad [1]$$

The pressure differential value in Eq. **1** was determined using hydrostatic pressure and a maximum allowable pressure difference of 50% of the hydrostatic pressure ($\alpha=0.5$), and was calculated using Eq. **2**. The parameters used are provided in Table 2.

$$\Delta P_{\max}=\rho g d \alpha. \quad [2]$$

The fracture gradient of 15.5 MPa·km^{-1} was calculated based on the fact that the hydraulic pressure gradient used in this analysis was ~10 MPa·km^{-1}. When assuming a 50% allowable pressure increase, a total increase of 5 MPa·km^{-1}, which corresponds to 90% of 5.5 MPa·km^{-1}, was allowed. Thus, the fracture gradient used in this analysis was 15.5 MPa·km^{-1}, which is at the lower end of the common fracture gradient ranges of 14 MPa·km^{-1} to 23 MPa·km^{-1}.

SAU shapefiles (map of geographic extent) that were pending publication by USGS were substituted with basin-level shapefiles provided by USGS Total Petroleum Assessment. Table 3 summarizes the CO_2 content and heat content value of biomass used for energy and CO_2 content conversions. The shapefile of the existing CO_2 pipeline network in the United States was obtained from Stanford University's Digital Repository and is cited accordingly (41).

1. Carbon Brief (2017) Analysis: Just four years left of the 1.5C carbon budget. *Carbon Br*. Available at https://www.carbonbrief.org/analysis-four-years-left-one-point-five-carbon-budget. Accessed December 6, 2017.
2. Azar C, et al. (2010) The feasibility of low CO_2 concentration targets and the role of bio-energy with carbon capture and storage (BECCS). *Clim Change* 100:195–202.
3. van Vuuren DP, et al. (2013) The role of negative CO_2 emissions for reaching 2 °C-insights from integrated assessment modelling. *Clim Change* 118:15–27.
4. Klein D, et al. (2014) The value of bioenergy in low stabilization scenarios: An assessment using REMIND-MAgPIE. *Clim Change* 123:705–718.
5. Intergovernmental Panel on Climate Change (2014) Summary for policymakers. *Climate Change 2014: Mitigation of Climate Change Working Group III Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge Univ Press, Cambridge, UK), pp 1–33.
6. Tavoni M, Socolow R (2013) Modeling meets science and technology: An introduction to a special issue on negative emissions. *Clim Change* 118:1–14.
7. Kriegler E, Edenhofer O, Reuster L, Luderer G, Klein D (2013) Is atmospheric carbon dioxide removal a game changer for climate change mitigation? *Clim Change* 118:45–57.
8. Peters GP, Geden O (2017) Catalysing a political shift from low to negative carbon. *Nat Clim Change* 7:619–621.
9. Smith P, et al. (2016) Biophysical and economic limits to negative CO_2 emissions. *Nat Clim Change* 6:42–50.
10. Kato E, Yamagata Y (2014) BECCS capability of dedicated bioenergy crops under a future land-use scenario targeting net negative carbon emissions. *Earths Future* 2:421–439.
11. Creutzig F, et al. (2015) Bioenergy and climate change mitigation: An assessment. *Glob Change Biol Bioenergy* 7:916–944.
12. Popp A, et al. (2011) The economic potential of bioenergy for climate change mitigation with special attention given to implications for the land system. *Environ Res Lett* 6:34017.
13. Berndes G, Hoogwijk M, Van Den Broek R (2003) The contribution of biomass in the future global energy supply: A review of 17 studies. *Biomass Bioenergy* 25:1–28.
14. Gough C, Upham P (2011) Biomass energy with carbon capture and storage (BECCS or Bio-CCS). *Greenhouse Gases Sci Technol* 1:324–334.
15. Humpenöder F, et al. (2014) Investigating afforestation and bioenergy CCS as climate change mitigation strategies. *Environ Res Lett* 9:64029.
16. Bradshaw J, Dance T (2005) Mapping geological storage prospectivity of CO2 for the world's sedimentary basins and regional source to sink matching. *Greenhouse Gas Control Technologies*, eds Rubin ES, et al. (Elsevier, New York), pp 583–591.
17. Dooley JJ (2013) Estimating the supply and demand for deep geologic CO_2 storage capacity over the course of the 21st century: A meta-analysis of the literature. *Energy Procedia* 37:5141–5150.
18. Cooper C, et al. (2009) *A Technical Basis for Carbon Dioxide Storage* (CO_2 Capture Project, London).
19. Galik C, Abt R, Wu Y (2009) Forest biomass supply in the southeastern United States—implications for industrial roundwood and bioenergy production. *J For* 107:69–77.
20. Wright M, Brown RC (2007) Establishing the optimal sizes of different kinds of biorefineries. *Biofuels Bioprod Biorefin* 1:246–256.
21. Noothout P, Wiersma F, Hurtado O, Roelofsen P, Macdonald D (2014) *CO_2 Pipeline Infrastructure* (Int Energy Agency Greenhouse Gas R&D Programme, Cheltenham, UK), Rep 2013/18.
22. McCoy ST, Rubin ES (2008) An engineering-economic model of pipeline transport of CO_2 with application to carbon capture and storage. *Int J Greenhouse Gas Control* 2:219–229.
23. Morgan MG, McCoy ST (2013) *Carbon Capture and Sequestration: Removing the Legal and Regulatory Barriers* (Resour Future Publ, New York).
24. Global CCS Institute (2017) *The Global Status of CCS: 2017* (Global CCS Inst, Docklands, VIC, Australia).
25. Secretary of Energy Advisory Board (2016) *Letter Report: Task Force on RD&D strategy for CO_2 Utilization and/or Negative Emissions at the Gigatonne Scale* (US Department of Energy, Washington, DC).
26. Sanchez DL, Kammen DM (2016) A commercialization strategy for carbon-negative energy. *Nat Energy* 1:15002.
27. Langholtz MH, Stokes BJ, Eaton L (2016) *2016 Billion-Ton Report* (US Department of Energy, Washington, DC), Vol I, pp 1–411.
28. US Geological Survey (2013) National Assessment of Geologic Carbon Dioxide Storage Resources—Data. M. Available at pubs.usgs.gov/ds/774/. Accessed January 13, 2018.
29. Michael K, et al. (2010) Geological storage of CO_2 in saline aquifers-A review of the experience from existing storage operations. *Int J Greenhouse Gas Control* 4:659–667.
30. Finley RJ (2014) An overview of the Illinois Basin-Decatur Project. *Greenhouse Gases Sci Technol* 4:571–579.
31. Sapp M (August 15, 2016) Red Tail Energy and EERC get $490,000 grant to study CCS at ethanol plant. *Biofuels Dig*. Available at www.biofuelsdigest.com/bdigest/2016/08/15/red-tail-energy-and-eerc-get-490000-grant-to-study-ccs-at-ethanol-plant/. Accessed August 18, 2017.
32. Egli DB (2008) Comparison of corn and soybean yields in the United States: Historical trends and future prospects. *Agron J* 100:S-79–S-88.
33. Nicot JP, Hosseini SA, Solano SV (2011) Are single-phase flow numerical models sufficient to estimate pressure distribution in CO_2 sequestration projects? *Energy Procedia* 4:3919–3926.
34. Michael K, et al. (2011) Injection strategies for large-scale CO_2 storage sites. *Energy Procedia* 4:4267–4274.
35. US Energy Information Administration (2015) *Annual Electric Generator Report* (US Energy Info Admin, Washington, DC).
36. Sanchez DL, Nelson JH, Johnston J, Mileva A, Kammen DM (2015) Biomass enables the transition to a carbon-negative power system across western North America. *Nat Clim Chang* 5:230–234.
37. Sanchez DL, Callaway DS (2016) Optimal scale of carbon-negative energy facilities. *Appl Energy* 170:437–444.
38. Riahi K, et al. (2015) Locked into Copenhagen pledges–Implications of short-term emission targets for the cost and feasibility of long-term climate goals. *Technol Forecast Soc Change* 90:8–23.
39. Biomass Magazine (2017) Data from U.S. biomass power plants. Available at biomassmagazine.com/plants/listplants/biomass/US/. Accessed October 31, 2017.
40. de Coninck H, Benson SM (2014) Carbon dioxide capture and storage: Issues and prospects. *Annu Rev Environ Resour* 39:243–270.
41. Hart Energy Publishing (2014) Carbon dioxide (CO_2) pipelines in the United States. Available at purl.stanford.edu/yf510bb3744.
42. Boundy B, Diegel SW, Wright L, Davis SC (2011) *Biomass Energy Data Book* (US Department of Energy, Washington, DC), 4th Ed.
43. US Environmental Protection Agency (2016) 40 CFR Appendix Table C-1 to Subpart C of Part 98: Default CO_2 emission factors and high heat values for various types of fuel. Available at https://www.law.cornell.edu/cfr/text/40/appendix-Table_C-1_to_subpart_C_of_part_98. Accessed November 19, 2017.
44. National Energy Technology Laboratory (2012) Greenhouse gas reductions in the power industry using domestic coal and biomass - Volume 1: IGCC (Natl Energy Technology Laboratory, Washington, DC), NETL/DOE-2012/1546. Accessed June 20, 2017.