CHAPTER 7

Direct Air Capture with Storage (DACS) and Renewable Energy

SUMMARY

Direct air capture (DAC) with storage (DACS) has the potential for billion-tonne atmospheric CO_2 removal but will require concurrent buildout of energy resources. For renewable-electricity-powered DACS, the land required for deploying wind or solar-photovoltaic electricity generation limits the maximum potential capacity. However, several regions of the United States have significant potential to generate renewable electricity beyond what is needed for decarbonizing the electrical grid; these regions intersect with the geologic formations required to safely store the CO_2 removed from the atmosphere. Additionally, domestic natural-gas reserves in the United States could enable additional regions to participate in large-scale DACS projects if we decide as a society to tap into these resources.

While the potential for DACS deployment is massive, DACS will likely remain the most expensive form of the CO_2-removal options considered in this report. As such, the ability to reduce the cost of the technology, regulatory mechanisms or incentives, and maturation of a carbon-removal marketplace will likely determine the extent of deployment. However, DACS may bring co-benefits, including allowing communities to evolve from dependence on fossil-fuel-based jobs to carbon-management jobs. In the near term, scientifically guided and rigorous standards for DACS monitoring, reporting, and verification (MRV) are needed across existing and emerging DACS technologies and energy sources, including consideration of all emissions associated with DACS energy sources and the additionality of renewable energy projects.

Key Findings

- For low-temperature adsorbent DACS powered by renewable electricity, the United States has a technical potential capacity of over 9 billion tonnes of CO_2 per year. For high-temperature solvent DACS powered by natural-gas reserve, the United States' technical potential capacity is over 4 billion tonnes of CO_2 per year (**Table 7-1**). The costs predominantly range from \$200 to \$250/tonne CO_2. This estimate is a theoretical maximum constrained by energy and land availability and does not reflect the expected or required level of deployment. However, understanding where and at what scale the opportunity exists is important. Social, ecological, regulatory, and market factors not evaluated in this report will further limit this potential.

CHAPTER SCOPE

This chapter assesses the locations, technical potential capacities, and costs for deploying direct air capture with storage (DACS) across the United States. We evaluated options for deploying low-temperature solid-adsorbent and high-temperature liquid-solvent DACS with two energy sources:

- Renewable energy and the land required to produce it, without competing with decarbonization of the electrical grid or other uses.
- Domestic natural-gas reserves for near-term and high-temperature DACS.

- The West Texas and Upper and Lower Rocky Mountains regions have the largest potential for million-to-billion-tonne adsorbent DACS deployment with renewable energy, while the Appalachia, West Texas, South Central, and Alaska regions have large potential for solvent DACS deployment with natural gas (**Figure 7-1**).
- In the near-term, DACS deployment will identify critical areas for technology improvement and help more rapidly improve the cost of DACS carbon removal; however, scientifically guided and rigorous standards for DACS MRV are needed across existing and emerging DACS technologies and energy sources.
- Regions of high opportunity for DACS overlap with areas of the country that are experiencing persistent job loss in fossil-fuel sectors; prioritizing DACS development in these regions may help maximize socioeconomic co-benefits, such as economic solvency and infrastructure improvements.

Table 7-1. *Land resources required for decarbonizing the US electrical grid (from [1]) and the additional resources available to power DACS. The associated potential for solid-adsorbent DACS powered by renewable electricity is shown both as a maximum potential, irrespective of proximity to geologic storage, and as the subset that is coterminous with geologic storage or a* CO_2 *pipeline. These potential renewable-electricity resources would need to be developed in addition to those needed for grid and industrial decarbonization. The potential for liquid-solvent DACS powered by natural-gas oxycombustion is based on the United States' available natural-gas reserves, assuming some continued natural-gas usage through the end of the century***.**

	Land Area	Generation	Adsorbent DACS Potential
	(million ha)	*(TWh/year)*	*(million tonnes CO_2/year)*
Renewable electricity for grid decarbonization [1]	73	10,000	—
Land-based wind	68	7600	—
Solar photovoltaic	5	2900	—
Renewable energy remaining for adsorbent DACS	120	51,000	35,000
Land-based wind	75	10,000	6900
Solar photovoltaic	45	41,000	28,000
Subset coterminous with CO_2 storage or pipeline	33	13,000	9300
Land-based wind	23	3600	2500
Solar photovoltaic	10	9800	6800
		Natural Gas Reserves	**Solvent DACS Potential**
		(quadrillion Btu)	*(million tonnes CO_2/year)*
Natural gas for solvent DACS		3000	4700
Oxycombustion-fired kiln		3000	4700

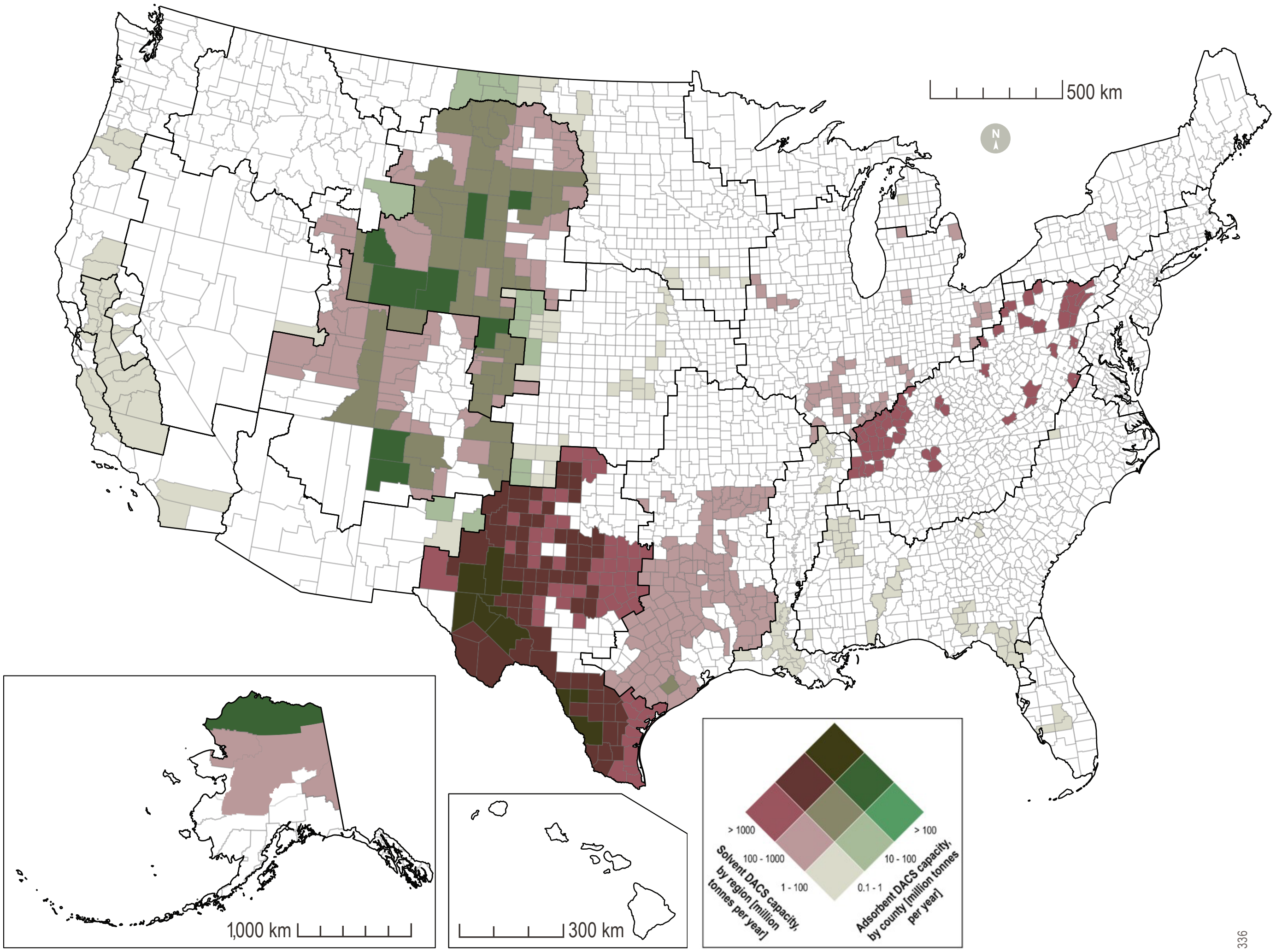


Figure 7-1. *County-level assessment of the potential capacity of solid-adsorbent DACS powered by renewable electricity and region-level assessment of the potential capacity of liquid-solvent DACS with a natural-gas-fired calcination kiln, both co-located with geologic storage. Darker shades of red indicate higher region-level solvent DACS capacity, darker shades of green indicate higher county-level adsorbent DACS capacity. Heavily outlined areas in the map indicate the boundaries of the CO_2 removal regions defined in this report (**Chapter 10**) and highlight US regions with large potential capacity for DACS deployment.*

Introduction

DAC removes CO_2 directly from the atmosphere using purpose-built machines in a two-step process: first, contacting a liquid or solid material with air to selectively react CO_2 with the material and allow the remainder of the air components to pass through; second, regenerating the material using an energy input, usually heat or electricity, to release the CO_2 at high concentration. Operating by cycling the capture material between the two sides of the process—capture and regeneration—allows the material to be reused many times to capture CO_2 from the atmosphere and produce a high-purity CO_2 stream (**Figure 7-2**). When paired with CO_2 compression and geologic storage (DACS), DACS provides a straightforward method of CO_2 removal. DACS is currently deployed globally at the 4000-tonne-per-year scale; being a relatively nascent technology with limited global deployment, the cost of DACS is high compared to other forms of CO_2 removal.

The material used to perform DAC—either a liquid solvent or a solid adsorbent—largely dictates how the process operates. Liquid solvents typically operate in a continuous fashion, with the liquid solvent flowing across a contactor designed to maximize the liquid's exposure to air. In the process pioneered by Carbon Engineering and now being developed by 1PointFive, the liquid solvent is an aqueous solution of a hydroxide. The hydroxide reacts with atmospheric CO_2 to form a carbonate that goes through a series of processing steps, culminating in a calcination step that exposes a solid carbonate to a high-temperature process around 900 °C to release the CO_2 and regenerate the hydroxide [2, 3]. In this process, the air-contacting step and the calcination/regeneration step happen continuously, flowing materials between the different processes. In this chapter, we consider the hydroxide liquid-solvent process, though others (e.g., based on solutions of amino-acid salts) have been proposed [4-7].

In contrast, solid adsorbents operate in a "swing" process in which the solid operates in capture mode for some time, and then operation changes and the solid is regenerated to release high-purity CO_2. Both Climeworks and Global Thermostat have developed this type of process [8-10]. Both companies use an amine-based solid adsorbent fixed to a structured contactor designed to allow high air flow and contact between the adsorbent and CO_2 in the air. The contactor is then sealed from the atmosphere, and the material is heated to around 80–120 °C for regeneration; this is a temperature-swing process. Often, the regeneration process will be performed with some degree of vacuum applied, allowing the use of low-grade steam, in a temperature-vacuum-swing process. The temperature requirement for regenerating amines allows use of industrial steam for direct steaming of the material [11-13].

In addition to amine-based solid adsorbents, many other classes of adsorbents, with different methods of regeneration, have been proposed. These alternatives include thermal-swing processes based on minerals [14], metal-organic frameworks [15-17], and zeolites [18, 19]. Additionally, processes that use a moisture-swing [20], electro-swing [21, 22], or pH swing [23] have also been proposed. Due to a lack of in-depth process and cost information at the time of scoping this report, we have not included a detailed treatment of these processes. As more information becomes available, a full analysis and integration of these processes will be valuable given their potential to be optimized for operation in particular climates and/or to integrate directly with renewable electricity. We highlight the potential advantages and challenges of these emerging approaches to DAC in **Box 7–1**.

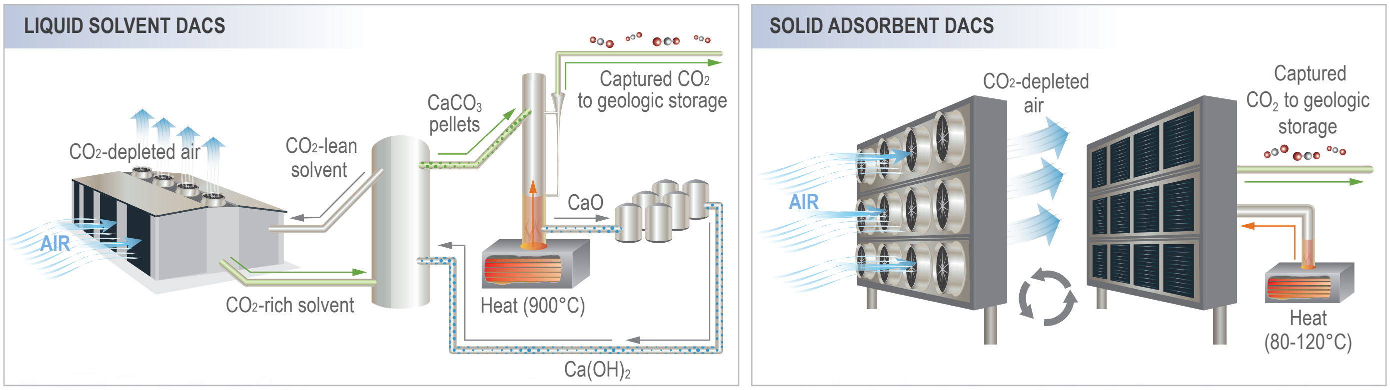


Figure 7-2. *Schematic representations of DACS processes considered in this report. Both liquid-solvent and solid-adsorbent DACS regenerate the material used to separate CO_2 from the air to allow reuse of the material and produce a high-purity stream of CO_2 suitable for geologic storage.*

BOX 7-1

Emerging Approaches to DAC

Though our report focuses on the two dominant forms of DAC today (i.e., solid amine adsorbent with steam regeneration and liquid hydroxide solvent with high-temperature calcination), the many emerging approaches at varying stages of development may prove to be game-changing in terms of energy cost or regional deployment.

Mineral Adsorption. The high-temperature side of the liquid-solvent process can be used independently of the liquid-hydroxide capture process. Specifically, after high temperature regeneration of calcium or magnesium carbonate, the resultant calcium or magnesium oxide is slaked with water and can then capture CO_2. While this process occurs naturally in rocks over years, manipulation of the mineral surface area and the adsorption conditions can accelerate the process. Heirloom operates a 1000-tonnes of CO_2 per year DACS facility using mineral adsorption. These types of processes will typically operate best in hot and humid locations [14, 24].

Solid Physical Adsorption. In contrast to amine-based adsorbents, physical adsorbents (or physisorbents) bind CO_2 relatively weakly, allowing them to be regenerated at low temperature with minimal energy input. Zeolites and metal-organic frameworks are commonly studied examples of physical adsorbents, though some metal-organic frameworks can be appended with amines as well. Processes that use physical adsorbents can suffer from poor selectivity for CO_2 over water due to their weak binding and will do best located in cold and dry locations or paired with a process that pre-dries the air, which allows co-production of water [15, 16, 18, 25-30].

Moisture-Swing Regeneration. Ion-exchange resins with quaternary ammonium ions can selectively adsorb CO_2 from dry atmospheres. Rather than using thermal energy for regeneration, this approach uses water to release CO_2. The material is then exposed to ambient air where it dries and captures CO_2 in a subsequent cycle. While these materials are highly durable, this process will perform best in hot and dry locations to facilitate the drying and capture process and may consume large amounts of high-purity water for regeneration [20, 31, 32].

Electro-Swing Regeneration. Redox-active materials are capable of binding with and releasing CO_2 depending on their charge state, which can be manipulated through charging and discharging the material. This kind of process allows direct application of renewable electricity for regeneration—rather than using it to generate heat—and can be used with appropriately designed liquid solvents or solid adsorbents. These processes are relatively nascent with relatively large uncertainty in material cost and durability, adsorption and regeneration kinetics, and overall energy efficiency [21, 22, 33-35].

pH-Swing Regeneration. CO_2 naturally dissolves in water and establishes chemical equilibrium with bicarbonate and carbonate ions at a distribution that depends on pH. At high pH, the solution is more basic and favors capture of CO_2 as dissolved carbonate; at low pH, the solution is acidic and favors release of gas-phase CO_2. Acid and base can be generated using electricity by an electrodialysis process; uncertainties in this process include the cost, durability, and energy efficiency of the electrodialysis reactors. This method of regeneration is the key process proposed for ocean-based DAC, where the ocean functions as the large surface-area contactor [23, 36, 37].

All DAC processes require large amounts of energy, primarily used during the regeneration step. Though the exact energy requirement varies by the specific technology and the local ambient temperature and humidity, each tonne of CO_2 produced by DAC requires about 8 GJ of energy. At the million-tonne-per-year facility scale, current technologies require a dedicated ~250-MW, firm-energy source [3, 38]. The emissions associated with the energy for DAC (also termed the carbon intensity) matter significantly if they are not also being captured; energy-associated emissions can reduce the net carbon removed by a DACS process or even turn the process from carbon removal to a net carbon emitter if not carefully considered.

Therefore, discussion of economy-wide deployment of DACS is inextricably tied to discussion of energy and where it comes from. In the long-term, low-to-zero-carbon energy sources, such as renewable solar/wind electricity, will be preferred for DACS, and as the United States decarbonizes its electrical grid and other sectors of the economy [39, 40], access to this clean energy will increase. However, any renewable energy used for DACS could also be used for decarbonizing the grid, necessitating consideration of additional renewable-energy development beyond what has been forecasted [41]. Moreover, growth of the DACS industry and expansion of the renewable-electricity sector will need to occur in parallel to meet the United States' ambitious goals of economy-wide decarbonization by 2050 [42].

In this chapter, we present an analysis of the maximum-potential deployment of DACS in the United States and estimates of the costs of carbon removal. We look specifically at solid-adsorbent DACS powered by renewable electricity and constrained by the land available and at liquid-solvent DACS powered by US natural-gas reserves. While nearly all regions of the United States will be able to support some level of DACS, several regions have particularly large opportunities for billion-tonne-scale DACS due to the confluence of available energy resources and geologic storage.

Integration of Direct Air Capture (DAC) with Renewable Electricity

DAC aims to perform a challenging separation—extracting extremely dilute CO_2 (~420 parts per million at the time of publication) from the air—in an accelerated and intensified manner compared to nature-based processes that draw down atmospheric CO_2. The energy use of these emergent processes is high, and as technology developers aim to bring down current costs toward the very ambitious target of $100/tonne CO_2, improvements to energy efficiency are faced with trade-offs when seeking to reduce the also significant capital costs.

For both solvent and adsorbent DAC, most of the process energy requirements are thermal. In solvent DAC, it is primarily the energy required to heat and maintain a kiln at roughly 900 °C. In adsorbent DAC, it is primarily the energy to repeatedly cycle a CO_2-saturated adsorbent from roughly ambient conditions to its regeneration temperature of 80–120 °C. When considering only cost, the evident choice for producing large quantities of thermal energy is the combustion of natural gas. However, if the positive emissions from the combustion of fossil natural gas are not captured, this choice of energy source greatly reduces or even negates the net CO_2 removed by a DACS process.

With a long-term perspective, integrating DACS with renewable electricity will be central to widespread and large-scale deployment. While some technology developers aim to rely on natural gas as a thermal energy source and to simultaneously capture and thus avoid the associated positive emissions, others aim to avoid the use of direct fossil energy sources entirely. The consequences of using natural gas are discussed in further detail below.

With the assumption that the US electrical grid will be decarbonized by 2035 or sometime thereafter, it is sensible to design DACS for operation solely with low-carbon electricity. The use of low-grade or waste heat can also significantly reduce overall energy requirements, especially for adsorbent-based processes that operate with relatively low maximum temperatures compared to those using calcination, like solvent or mineral-looping DAC. In this work, we modeled DACS pathways aimed at the use of primarily renewable electricity or primarily natural gas (**Figure 7-3**).

For liquid-solvent DAC, the process detailed by Carbon Engineering [3] utilizes natural gas to provide the thermal energy for CO_2 recovery and to generate the requisite electrical power for other plant-unit operations. The kiln operates with oxycombustion of natural gas, where natural gas and oxygen are provided as stoichiometric inputs, such that the combustion products are pure CO_2 and water. This CO_2 intrinsically combines with the CO_2 captured from the air in the kiln during calcination, diluting the negative CO_2 from the air with avoided neutral (when stored) CO_2 from natural gas. Electricity for this process comes from a natural-gas combined-cycle power island with absorber-based CO_2 capture, which further dilutes the negative CO_2 being stored.

Alternatively, solvent DAC can operate with a kiln heated by electrical resistive heating, shifting the thermal source from natural gas to electricity. While thermal-energy generation using conversion of electricity to heat via resistive heating is nearly perfectly efficient, indirect (external) heating of a large-scale kiln via resistive heating elements suffers from thermal

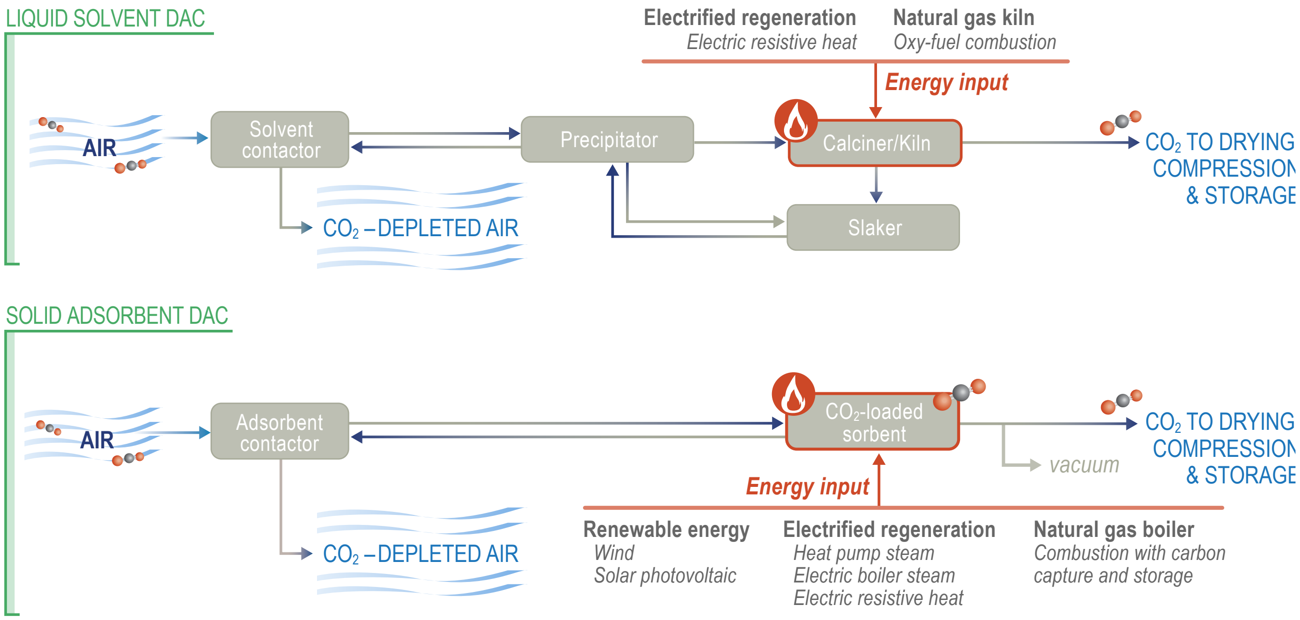


Figure 7-3. *Schematic of DACS processes considered in this report, one based on a liquid solvent and the other on a solid adsorbent, highlighting different sources of energy for regeneration. These processes can both be powered by combustion of natural gas or by converting renewable electricity to heat through various means. This is not an exhaustive list of methods of powering DACS and rather represents options that can be deployed across the United States at a reasonable scale with current technology.*

losses and requires additional capital expense. The kiln body may need to be made with an expensive metal alloy and heating elements would require regular replacement. Large-scale electric, indirectly heated kilns (multi-tonne per hour) have existed for decades but are uncommon due to their additional complexity and high cost of electrical-energy input. Without relevant examples of deployment and integration at scale, the capital and operating expenses contain a high degree of uncertainty. However, growing interest in industrial electrification has spurred renewed efforts in electric kilns, which could also play a significant role in decarbonizing the cement industry and other industries that require high-temperature heat.

In such a process, electricity for heating and other plant operations would be drawn from a low-carbon source rather than produced on-site (which is unlike the “natural-gas combined cycle with CO_2 capture” power plant featured in the natural gas version of DAC). If natural gas were to be considered for solvent-based DAC, it is more efficient to use it to directly fire an oxycombustion kiln than to generate the electricity required for an electric kiln. Unlike adsorbent-based DAC, which can benefit from upgrading low-grade heat to reduce electricity input, the high temperature requirement of the kiln in solvent-based DAC cannot be easily mitigated, and the majority of the thermal energy input must be directly produced from electricity.

For solid-adsorbent DAC, the landscape of energy sources is more manifold and diverse due to the lower temperature requirement. Its typical embodiment is a modular, transient, cyclic process, wherein individual adsorbent contactor modules take up CO_2 for some period of time (adsorption) and subsequently release the CO_2 in a thermal-vacuum-swing step (desorption). Existing cost models and proposed processes consider a range of thermal delivery modes, including the following:

- Indirect – External heating of the adsorbent phase through an impermeable wall (e.g., heat exchange),
- Direct resistive – Resistive heating that is part of or directly in contact with the adsorbent,
- Direct steam – The use of a heat exchange medium (typically steam) directly contacting the adsorbent.

Indirect heating via heat exchange or non-integrated resistive heating is challenging in terms of heating rate and temperature maldistribution. Direct, resistive heating shows promise, especially in terms of overall energy efficiency and process electrification, but has not been used in existing scaled DACS demonstrations. Today’s large-scale DACS demonstrations utilize direct steam regeneration, as steam rapidly heats the adsorbent and its flow strips CO_2 off the adsorbent and out of the contactor in a nearly binary water-CO_2 mixture that is easily separable.

While other adsorbent and regeneration configurations are feasible, here we have focused on vacuum-steam regeneration of amine-based adsorbents for our process, cost, and deployment models. In this configuration, much of the energy required is used in producing steam for the regeneration step. The steam energy required for regeneration in DAC processes today is greater than 10 GJ per tonne of CO_2 recovered. This steam can be generated in a variety of ways [11], including with a natural-gas boiler, from renewable thermal sources (e.g., geothermal or nuclear), with electricity directly using an electric boiler, or by upgrading low-grade or ambient heat using a heat pump powered by electricity.

In our models for scalable deployment, we consider primarily steam from natural-gas boilers or from a system integrating recovered process heat and upgraded low-grade heat with electricity (e.g., in an air-source heat pump). There is great potential for deploying adsorbent DAC using site-specific sources of renewable thermal energy (see **Box 7–2**), but we limited our scaled geospatial analyses to what is readily

BOX 7-2

Low-Carbon Heat Sources for DAC

The relatively low temperature required for regenerating amine-based solid-adsorbent DAC processes allows the use of heat pumps to generate steam, as modeled in this report. While heat pumps can extract heat from the air, the energy efficiency increases with a high-temperature fluid to provide the heat; this is often modeled as “waste heat” from a separate process [38, 43]. US domestic thermal resources could act as a low-carbon heat source for DAC (Appendix 7).

Conventional Hydrothermal. Geothermal fluids can be found in naturally occurring reservoirs within high-permeability rocks beneath the Earth’s surface at temperatures exceeding 70 °C, making them suitable for producing steam with a heat pump. We estimate that domestic hydrothermal resources with known temperature and flow-rate information, predominantly in the western United States, could power nearly 8 million tonnes per year of adsorbent DAC, at costs between \$240 and \$800/tonne CO_2. However, these resources rarely overlap with geologic storage, necessitating CO_2-transport infrastructure or alternative storage/utilization options. In addition, geothermal energy for electricity generation may be a key technology for grid decarbonization in certain regions, reducing the potential availability for DACS.

Enhanced Geothermal. Across the United States, underground rocks are hot enough for geothermal but do not have enough naturally occurring fluid or permeability. In these cases, human-made enhanced geothermal systems can be created to extract this thermal energy by injecting fluid and allowing it to heat up before circulating it back to the surface. Using enhanced geothermal, many more regions of the United States that do not have conventional hydrothermal resources could be utilized [44]. We estimate that, within areas coterminous with geologic storage, approximately 35 million TWh per year energy could be produced at a reasonable depth. However, enhanced geothermal technology is still under development, currently with high costs and significant uncertainty, limiting current widescale deployment.

Solar Thermal. Solar-collector systems use mirrors to concentrate sunlight onto a heat-transfer fluid; depending on the choice of fluid and arrangement of the solar collectors, temperatures from 80 °C to above 550 °C can be achieved [45, 46]. When heat is required, as is the case for adsorbent DAC, converting sunlight directly to thermal energy is more efficient than producing electricity via solar photovoltaic. Using the same suitable land criteria as for solar photovoltaic, we estimate a total potential of solar thermal of approximately 17,000 TWh per year. However, the current cost of solar thermal is high compared to wind or solar photovoltaic electricity generation, with the lowest cost around \$40/MWh, nearly double the cost of solar photovoltaic.

Nuclear. Advanced nuclear power plants could be used to provide both the heat and electricity requirements for DACS. Diverting a portion of low-grade heat from the nuclear plant for DACS reduces the electricity output but increases the overall energy efficiency of the nuclear plant, improving economic viability. While the current outlook for nuclear power-plant deployment and its role within grid decarbonization is uncertain, intentional integration of DACS facilities with new small modular reactors could be a viable pathway toward deploying DACS and expanding the availability of low-carbon firm-electricity resources [11, 47].

available. Heat pumps for steam generation greatly reduce the electricity requirement, as typically more than half of the thermal energy is supplied by the low-grade source, which can even include ambient air.

Heat recovery from outlet regeneration vapor is another avenue for reducing overall energy requirements. When excess steam is used for rapid desorption cycling with a relatively low condensation ratio, the outlet CO_2–steam vapor mixture contains a large quantity of thermal energy. A water condenser is obligatory for drying CO_2 prior to compression. This configuration is amenable to using a heat pump to recover a portion of the excess thermal energy in regeneration, in conjunction with heat from low-grade process sources or air (**Figure 7-4**).

Calculating Net-Carbon Removed

Carbon accounting for DACS is relatively straightforward compared to other CO_2 removal approaches. The quantity of CO_2 being captured, purified, compressed, and stored can be directly measured. Still, full-lifecycle consideration of all process inputs is necessary to determine the net carbon removed. For every tonne of CO_2 injected into a storage well, some fraction of a tonne of CO_2 was emitted in the process of isolating and storing that injected tonne, schematically represented in **Figure 7-5** . Especially in near-term DACS deployments, thorough accounting to verify that CO_2 emitted is less than the amount of CO_2 stored is critical. This can be determined by calculating scope 1 (direct), scope 2 (indirect, from the energy source), and scope 3 (indirect, from the value chain associated with natural gas production and transport) emissions. For the DACS pathways modeled in this report, we do not perform full life-cycle analyses (LCAs), which would include the carbon intensity of building, operating, and maintaining the DACS facilities, but we do account for the carbon intensity of the energy inputs [38].

The carbon intensity of the energy source (i.e., the emissions associated with generating the energy inputs) is the main consideration when calculating net carbon removed. The energy requirements we considered encompass capture, regeneration, and compression of CO_2 but not transport or storage. Fully electrified DAC processes utilizing many current state- or service-operator grid electricity would capture and store less CO_2 than was emitted in generating the electricity used. For near-term DACS deployment, we considered either state-level grid-electricity carbon intensity or purpose-built, non-grid-connected renewable electricity. For long-term deployment projections, we considered a future clean-grid with an average renewable-electricity carbon intensity.

For any process utilizing natural gas, we included upstream leakage of natural gas during extraction and transport in the gross positive emissions, using a 100-year global-warming potential. Using the 20-year global-warming potential of natural gas (~3x the 100-year value) increases the impact of natural-gas leakage. Electricity prices, carbon intensity, and natural-gas prices are listed in **Appendix 7.**

In addition to the global warming effect of upstream methane leakage, a natural-gas-powered DAC process will have uncaptured CO_2 emissions from combustion (i.e., scope 1 emissions). The combustion CO_2 captured will also need to be stored, adding to the overall costs and storage footprint of this DAC process. If one tonne of CO_2 is captured from associated natural-gas combustion for every tonne of CO_2 removed from the air, then the CO_2 storage footprint for removed CO_2 will double.

SOLID ADSORBENT DAC HEAT INTEGRATION

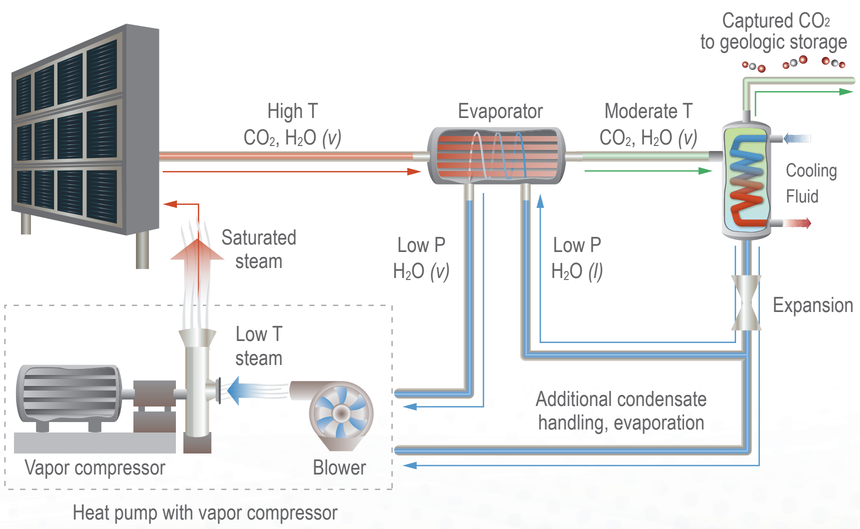


Figure 7-4. *Schematic of heat integration during the regeneration step of solid-adsorbent DAC, wherein heat from excess steam used for CO_2 stripping is used to evaporate a portion of recovered steam condensate as part of a heat pump system featuring steam-vapor compression. The heat-pump system may be multi-stage and receive heat input from desorption CO_2-water vapor mixture, as well as from available low-grade heat or air. Purified CO_2 is sent for final refining and compression after water knockout (not pictured).*

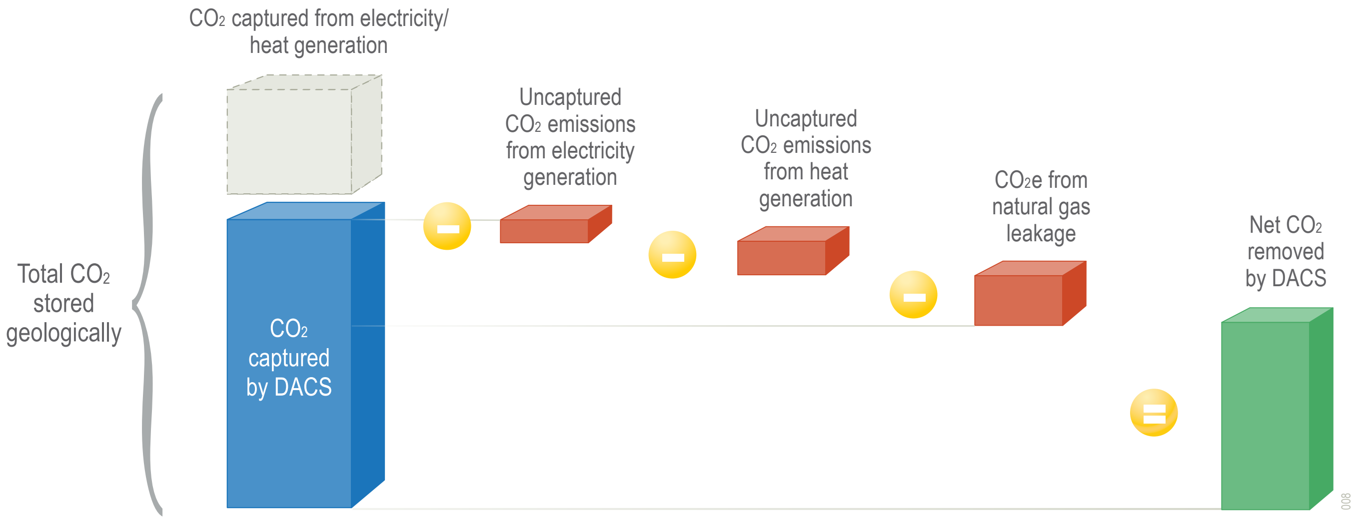


Figure 7-5. *Calculating net carbon removed by DACS. We subtracted the uncaptured emissions from electricity and heat generation, as well as the equivalent* CO_2 *value (*CO_2e*) of natural-gas leakage, from the amount of* CO_2 *captured by DACS to calculate the net* CO_2 *removed by DACS. In some cases, calculating net* CO_2 *removal may result in a negative number, in which case the DACS process results in net* CO_2 *emissions. We also considered the* CO_2 *captured from electricity and heat generation as part of the geologic storage cost in calculating the overall cost of DACS.*

2025 Baseline:
DACS Deployment in the Near-Term

Current and Planned Deployment

Many companies are developing DAC technologies, but they remain nascent from an industrial perspective. Publicly announced and operating liquid-solvent and solid-adsorbent DACS are currently deployed at the thousand-tonne scale. The largest operational solid-adsorbent systems are Climeworks's "Orca" facility (~4000 tonnes of CO_2 per year) and Global Thermostat's pilot facility (~1000 tonnes of CO_2 per year). Carbon Engineering is operating a liquid-solvent pilot facility (~300 tonnes of CO_2 per year). In addition to these existing operations, public announcements indicate that by 2025 a minimum of an additional ~36,000 tonnes of CO_2 per year of adsorbent DACS operations and ~500,000 tonnes of CO_2 per year of solvent DACS operations—Climeworks "Mammoth" project (Iceland) and 1PointFive/Carbon Engineering "Stratos" project (Texas), respectively—will be deployed and operational. These facilities are the baseline "first-of-a-kind" deployments through 2025 considered here. We estimated the capital and operating costs for these first-of-a-kind adsorbent and solvent DACS operations (**Figure 7-6**). DACS cost-model details for near-term and future deployment are found in **Appendix 7**.

The existing and announced Climeworks facilities operate in Iceland using geothermal energy, solid amine-based adsorbents, and basalt subsurface storage in partnership with CarbFix. Existing solvent DACS facilities use natural gas for oxycombustion in the kiln, the CO_2 from which is mixed and stored with the captured CO_2 from the air. The existing Global Thermostat adsorbent DAC facility utilizes steam from a natural-gas boiler. Currently, only Climeworks (Orca) is delivering verified CO_2-removal credits to voluntary purchasers.

Consequences of Using the Electrical Grid

For this study's near-term (2025) DACS deployment, we assumed electricity needs to be fulfilled by the electrical grid. While grid decarbonization is a high priority in almost every net-zero scenario [48, 49], the US grid's current carbon intensity significantly impacts the net quantity of CO_2 removed by DACS through scope 2 emissions associated with fossil-electricity production (**Figure 7-7**) [50]. For example, the total emission rate of California's electric power industry was 68 kg of CO_2/GJ of electricity in 2021 [51]. Thus, if a DACS facility in California required 8 GJ of electricity to capture 1 tonne of CO_2 today, the net CO_2 removed would be only 0.46 tonnes.

Figure 7-8 shows the impact of state-level grid carbon intensity on capture cost—based on the net quantity of removed CO_2—for solid-adsorbent DACS with heat being supplied via an electric heat pump. In states where the majority of industrial electricity is generated from combustion of natural gas or coal, such as Wyoming and Indiana, emissions from electricity production exceed the quantity captured, negating the potential carbon negativity of the process. This issue demonstrates the need for careful consideration of emissions associated with electricity supply

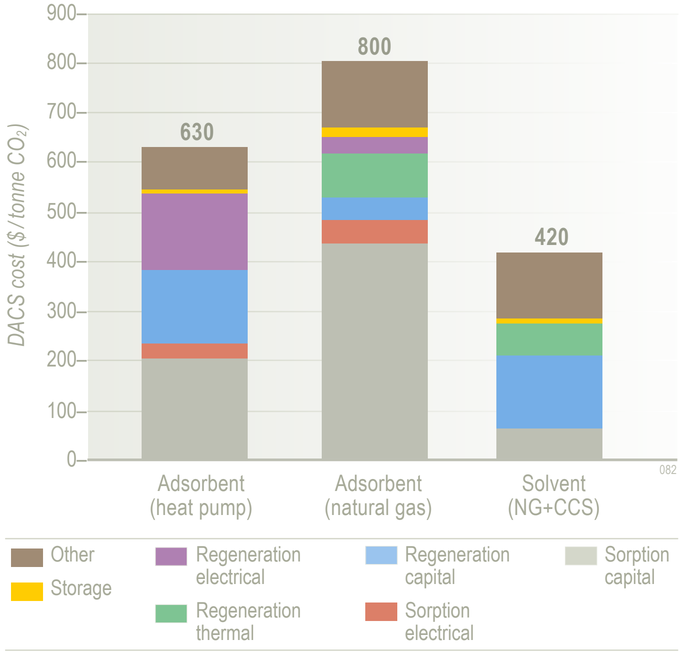


Figure 7-6. *Estimated cost breakdown of first-of-a-kind adsorbent and solvent DACS in 2025, with major cost categories highlighted. Adsorbent DACS is modeled with two different processes: using purpose-built renewable electricity with a heat pump or a natural-gas (NG) boiler to generate steam without capturing the emissions. Solvent DACS is modeled using natural-gas oxycombustion in the calciner, capturing the emissions from this process. The net CO_2 removed in each process is accounted for in the cost breakdowns reported; in this example, adsorbent DACS with NG (without carbon capture and storage (CCS)) has the greatest cost, in large part due to the significant uncaptured emissions from natural-gas boiler steam generation, reducing the net CO_2 removed. The "Other" cost category comprises balance of plant capital costs and labor and maintenance operating costs.*

for near-term DACS deployment. This is especially true for DACS buildout in isolated regions far from grid connections, where additional on-site renewables and long-term electricity storage may be necessary.

Renewable Electricity and Grid Decarbonization

As demonstrated in Figure 7-8, the current electrical grid in the United States is insufficient to provide meaningful amounts of net CO_2 removal via DACS, resulting in exorbitant levelized costs of carbon removal. Therefore, scale-up and deployment of DACS requires concurrent expansion of purpose-built renewable-electricity generation for powering DACS. When given the option, using renewable electricity to decarbonize the electrical grid may take precedence over using that same energy to power DACS to reach national goals of 100% carbon-free electricity by 2035 [39, 40]. This is particularly true in communities that have been harmed by historic emissions from fossil-electricity generation. The burden may be on the developers of both the DACS facility and its renewable-power source(s) to demonstrate that the renewable electricity being used in the DACS facility does not compete with decarbonizing the local community's electrical grid and that additional electricity generation would not have been built within the same timeframe without the demand from the DACS facility.

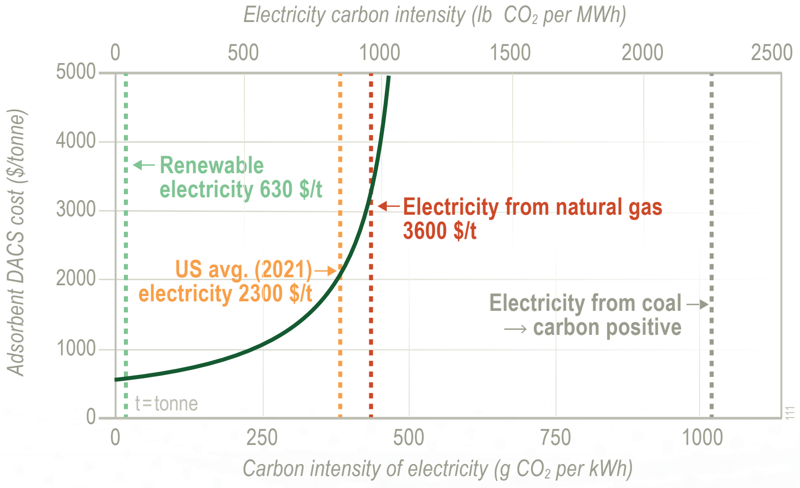


Figure 7-7. *Cost of net CO_2 removed for a first-of-a-kind adsorbent DACS operation using electricity as its sole energy input as a function of the carbon intensity of that electricity. The vertical lines indicate reference points for carbon intensity of electricity: renewable electricity (average of wind and solar); US average generation (all electricity generated by utility-scale electric power plants in the United States in 2021 [30]); electricity from a typical natural-gas, combined-cycle power plant; and electricity from a typical coal power plant.*

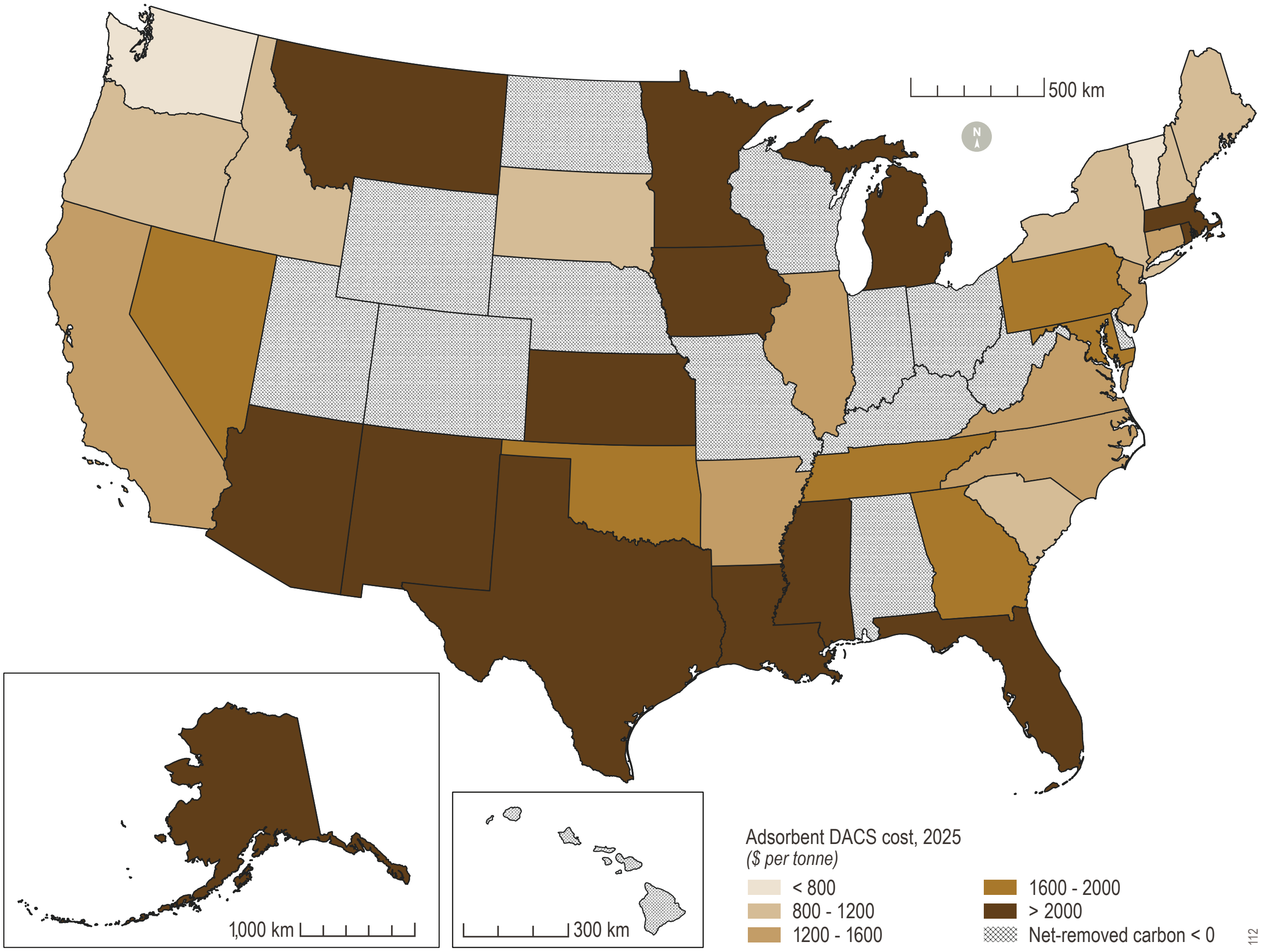


Figure 7-8. *Costs for adsorbent DACS powered by grid electricity with 2021 state-level carbon intensities, illustrating the impact of electricity carbon intensity. Gray dotted regions indicate states where the carbon intensity of the electrical grid results in more CO_2 emitted from electricity production than CO_2 removed by DACS, resulting in an "infinite" cost for carbon removal.*

Consequences of Using Natural Gas

Natural gas is a convenient source of thermal energy with a well-established infrastructure in the United States. Natural-gas production in the United States has continued to increase over the past several decades and has been a driver of reduced carbon intensity of grid electricity as it replaced coal and other more carbon-intensive fossil fuels. However, natural gas is a potent greenhouse gas (GHG) with a significantly greater global-warming potential than CO_2, and while it degrades rapidly in the atmosphere, its near-term warming effects are a substantial concern when considering climate tipping points.

Leakage of natural gas in the upstream extraction and transport systems—scope 3 emissions—must be considered when it is used as an energy source for DACS. A production-weighted average leak rate in the United States is around 3%, but rates vary significantly from less than 1% to above 9%; leakage in Permian Basin natural-gas production is around 5.3% [52-55]. While natural gas producers aim to decrease these rates to <0.5%, this goal is currently considered notional. The levelized cost of DACS is a strong function of upstream natural-gas leakage (**Figure 7-9**), given the high thermal-energy requirements of DACS. The wide range of local natural-gas leakage means that the leakage rate of the local natural-gas source is an important consideration when siting natural-gas-powered DACS. Considering a 20-year global-warming potential for natural gas, a leakage rate of 3% will reduce the net CO_2 removed by about half (even after abating the direct natural-gas combustion emissions), roughly doubling the cost of net CO_2 removed. Improvements to natural-gas systems, including reduction of leakage rates, are central if natural gas is to be considered a long-term viable energy source for DACS. This issue could be partially addressed with use of local natural-gas resources for DACS in fossil-producing regions as grid decarbonization progresses. Use of stranded natural-gas resources could also enable local-use, low-leakage DACS.

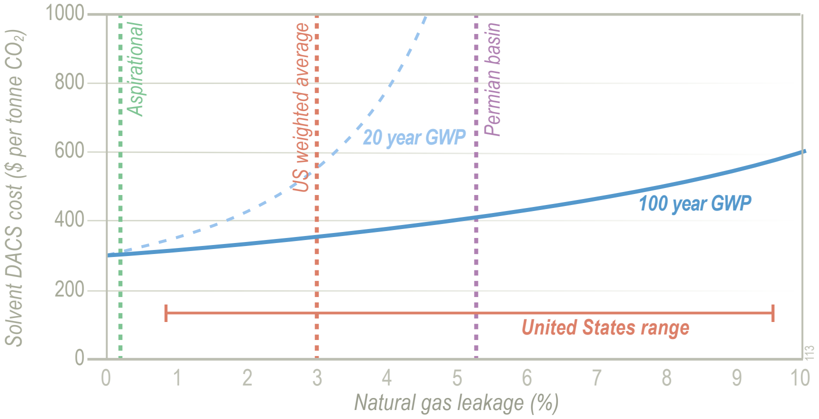


Figure 7-9. *Cost of net CO_2 removed for a first-of-a-kind solvent DAC system using a natural-gas oxycombustion-fired calciner, capturing and storing the emissions from natural-gas combustion. Leakage from the natural-gas system, counted as scope 3 emissions for DACS, escalates the cost of carbon removal, highlighting the importance of proper regulations for natural-gas systems, particularly when used for DACS. Vertical lines indicate reference points for an aspirational industry target, US average leakage rate, and estimated leakage rate in the Permian Basin from natural-gas systems. GWP = Global-Warming Potential conversion factors for methane into CO_2 equivalents from IPCC AR6 report [49].*

As DACS is a carbon-removal climate-mitigation approach meant to contribute to offsetting difficult-to-decarbonize sectors and emissions, the acceptability of significant fossil-fuel inputs in large-scale and long-term DACS deployment must be strongly considered. One concern is the associated geologic storage of excess, non-negative CO_2. With the potential adoption of carbon capture and storage in the decarbonization of heavy industry and grid power generation, alongside projected million-to-billion tonne-scale DACS, using natural gas coupled with capture and storage to power DACS may significantly increase the total amount of CO_2 to be stored in underground geological formations (Figure 7-5). While the storage potential in the United States is significant, it cannot be considered an infinite sink. Finally, there is valid criticism that the use of natural gas for DACS will act in the furtherance of a fossil fuel industry, which has been a primary driver of anthropogenic GHG emissions, CO_2 accumulation, and climate change to date.

Key Takeaways for Near-Term DACS Deployment

Research and development on emerging DAC processes is important for developing next-generation technologies, but deploying DACS today is necessary to achieve cost reductions via a learning-by-doing approach. Developing and operating these early facilities provides valuable information for improving the next facilities that are built and advances the industry as a whole, such that by the time large-scale DACS is required, processes will have matured to the point of economic viability. Large programs, such as the Department of Energy's (DOE's) Regional Direct Air Capture Hubs programs, will be important in this respect [56].

In the near-term, we need scientifically guided and rigorous standards for DACS MRV across existing and emerging DACS technologies and energy sources. Neither grid electricity nor natural gas are inherently problematic for DACS, but we need a better measurement of and accounting for natural-gas emissions to be able to claim net carbon removal. We recommend that DACS developers understand all their scope 1 (direct), scope 2 (indirect, from the energy source), and scope 3 (indirect, from the value chain associated with natural gas production and transport) emissions when performing carbon accounting. Finally, during the transition to a decarbonized electrical grid, generation and use of renewable electricity for DACS needs to be carefully considered from an additionality standpoint to ensure that the electricity would not have otherwise been used to decarbonize a local electrical grid or other sectors of the economy.

2050 Assessment of DACS Potential and Cost

Even with other carbon-removal technologies explored in this report, DACS will likely be necessary to meet federal, state, and industrial net-zero goals. Therefore, we assessed the potential quantity of DACS that *could* be deployed with US energy resources but do not suggest how much *will* be necessary or when it would be built. There is great interest in the United States in developing and deploying DACS before 2050, but we did not attempt to project the rate of deployment in detail nor the specific quantity of DACS that would be deployed in 2050.

Wind and solar photovoltaic have become the cheapest forms of electricity production in the United States and are the most rapidly growing, although energy storage and grid adaptation to intermittency will increase the complexity and levelized cost of deep deployment. These resources will be necessary in enabling US decarbonization goals and are obvious candidates for supplying energy to DACS. Therefore, we assessed the amount of DACS that could be deployed by calculating the amount of wind and solar-photovoltaic electricity available for adsorbent DACS with a heat pump, constrained by the land available for these energy resources.

Due to the high temperature required for the solvent-DACS process, we also assessed the domestic natural-gas reserves that could, if necessary, be used to provide high temperatures in the calciner. We assumed that the supply of chemicals for adsorbents and other materials for DACS facilities would grow as necessary to support the burgeoning DACS industry and hence not limit deployment; further analysis is needed to evaluate this assumption at the billion-tonne scale.

Evaluating Land for Siting Renewable Electricity and DACS

We identified the land suitable for siting both renewable electricity and DACS by considering the current and competing uses for the land. Additional details about this land-suitability analysis are in **Appendix 7**. Briefly, we applied three types of land exclusions to limit the area under consideration for million-tonne-scale DACS: (1) physical land categories deemed unsuitable for building renewable energy or DACS, (2) protected and developed areas, and (3) land already identified for decarbonizing the electrical grid. Land deemed unsuitable was based on the US Geological Survey (USGS) National Land Cover Database (NLCD) and included land categories like wetlands, water bodies, highly forested or cultivated lands, and high-slope areas. Protected areas were identified using the USGS Protected Areas Database (PAD-US) and included public lands and parks, national wildlife refuges, and conservation easements. Finally, to avoid double-counting renewable-electricity production, we also removed from our analysis land identified by the National Renewable Energy Laboratory (NREL) as prioritized for electrical-grid decarbonization [41] since renewable electricity developed on these lands would not be available for DACS. We note that total future demand for renewable electricity will go beyond the demands of the electrical grid due to electrification of other sectors, such as industrial heat decarbonization; this challenge is not accounted for in our analysis and will further limit the renewable electricity available for DACS. Overall, we obtained an estimate of suitable land for significant-scale deployment of renewable-energy generation that allows us to calculate a technical potential for DACS.

Based on this available-land analysis, we calculated the potential renewable-electricity generation by wind or solar photovoltaic and the cost of that electricity. In areas where both wind and solar could be produced, we selected the technology with the higher generation potential (**Figure 7-10**), though selecting for lower cost generated similar results. Through this analysis, we identified 120 million hectares (ha) of land (16% of land area in the contiguous

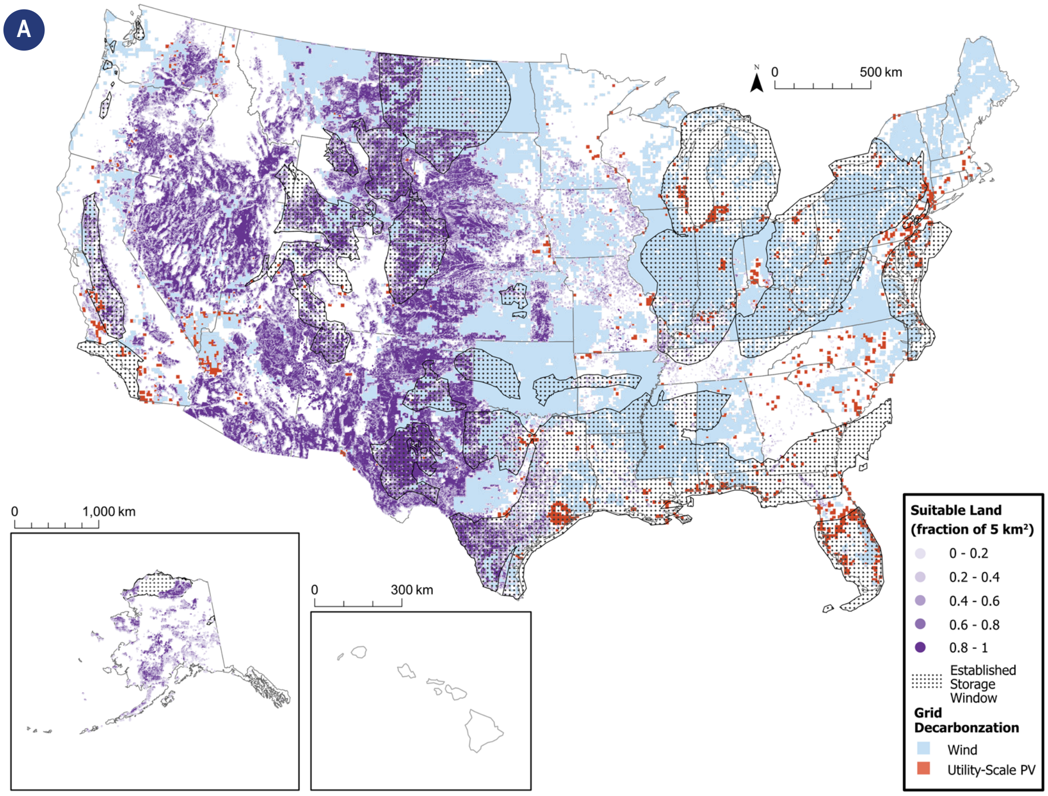
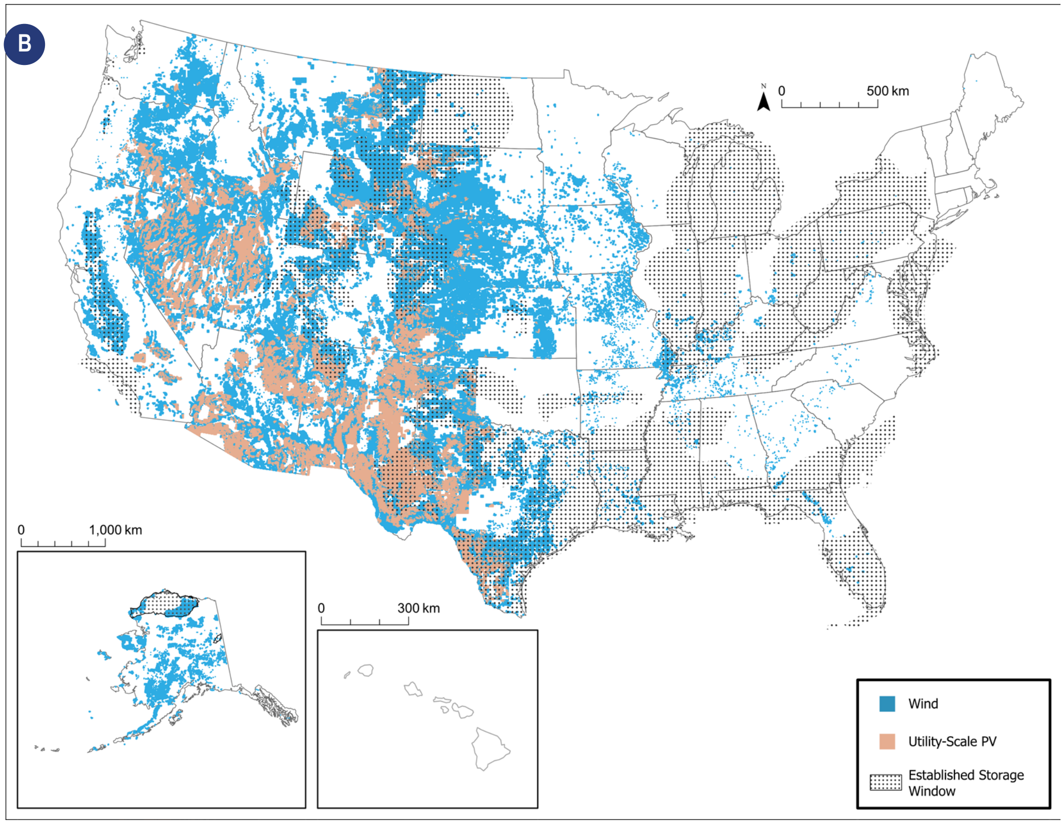
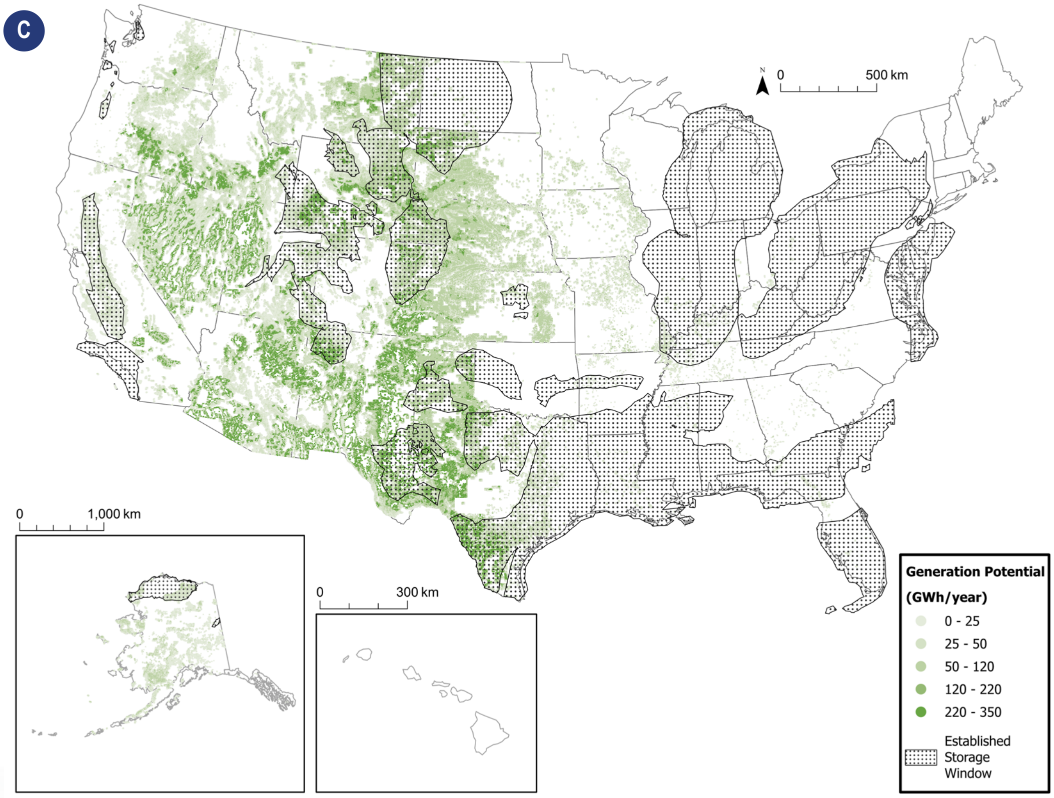


Figure 7-10. *Evaluation of land and renewable energy available for DACS. Gray shaded areas indicate the established geologic storage window. (a) Identified suitable land based on land-use criteria (purple) and the land already identified for grid decarbonization (light blue, wind; red, solar photovoltaic (PV)). (b) Preferred renewable-electricity generation technology on the identified suitable land based on generation potential (blue, wind; light red, solar PV). (c) Estimated renewable-electricity generation potential across all identified suitable land for siting renewable energy and DACS.*

Figure 7-10, *continued.*





United States) with a minimum contiguous area of 5 km^2 that could be developed for additional renewable energy to support DACS deployment. This land for renewable electricity is in excess of the 73 million ha (10% of land area in the contiguous United States) identified for electrical-grid decarbonization.

Alongside land and energy, DACS deployment was also constrained by availability of geological storage. While non-geologic storage options do exist (e.g., CO_2-containing cement), forecasting the location and magnitude of these forms of storage is difficult due to their dependance on future infrastructure development and markets. In this report, we considered DACS-facility siting in locations with geologic-storage potential or with access to a CO_2-transport pipeline. We note that this constraint eliminates significant areas in the western United States with significant potential for renewable-electricity generation but that are not co-located with geologic-storage potential, particularly in the Great Basin and Desert Southwest regions. The relatively low population density of these areas also results in relatively little of this land being prioritized for decarbonizing the electrical grid. Expansion of electricity transmission in these areas could open additional land for generating renewable electricity to support grid decarbonization, DACS, or other pursuits.

We estimate that approximately 33 million ha of land (4% of land area in the contiguous United States) meet our land-suitability criteria for siting renewable energy and DACS and are also coterminous with geologic storage or a CO_2 pipeline. This land is concentrated in just a few regions of the United States that define areas of high opportunity for deployment of renewable energy and DACS: West Texas and the Upper and Lower Rocky Mountains. We estimate that approximately 13,000 TWh/year of renewable electricity could be produced on this land using wind and solar photovoltaic; an amount similar to the renewable electricity needed for grid decarbonization. The land intensity of renewable-electricity production for DACS is lower than that for grid decarbonization due to the larger relative dependence on solar-photovoltaic electricity, which can be produced at a larger areal density. One caveat: recent analysis suggests that existing estimates of renewable-energy technical potential may be too high due to emerging development of local zoning ordinances around setbacks on wind and solar installations [57]; this will further limit the amount of renewable electricity available for DACS. Nevertheless, our results show that a large amount of land with good quality renewable resources is still available for deploying renewable electricity for DACS, even when grid decarbonization is prioritized.

Impact of Location and Climate

As discussed above, the most prescriptive factors in siting DACS will be land availability, geologic storage regions, and availability of renewable energy (primarily electricity but also renewable or waste heat for adsorbent DACS). However, the local temperature and humidity (dew point) (**Figure 7-11**) are also key in considering DACS deployment, as they can affect system performance, water usage, energy requirements, and decisions around which technology to select for a particular region.

For solvent DAC processes, water in the air contactor is lost because it evaporates from the solvent into the air. Thus, local climate will affect how much water is used in the process: drier and hotter conditions will increase water losses [3, 58]. In addition, for liquid-solvent DAC, ambient temperature and

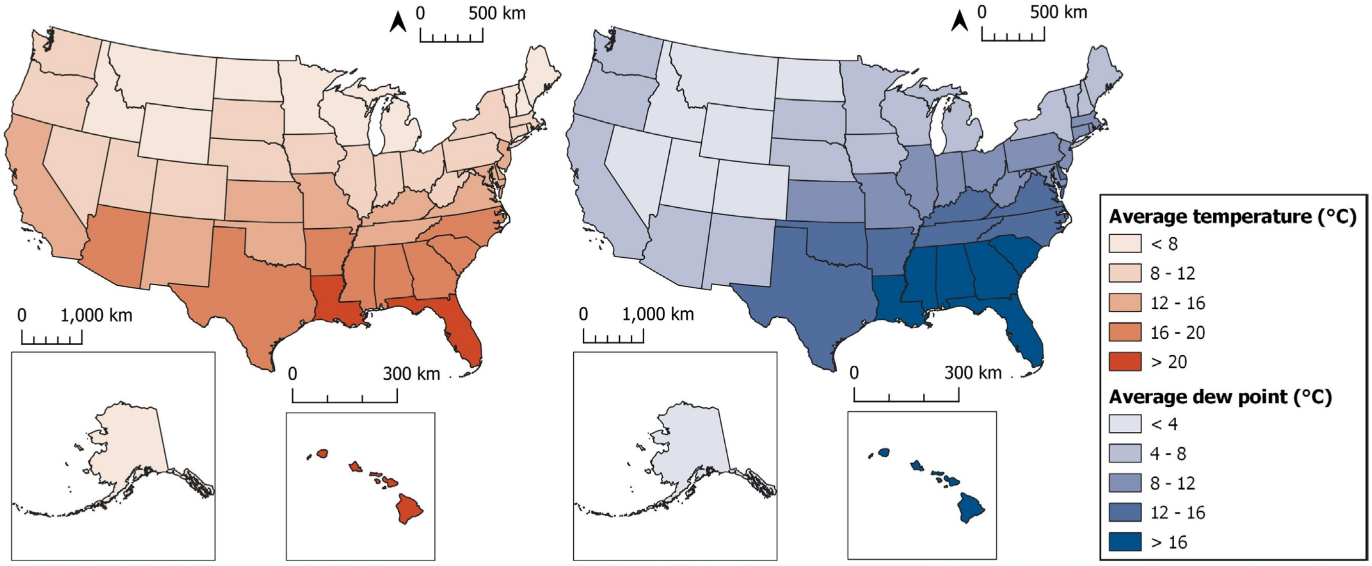


Figure 7-11. *Annual average temperature and dew point by state; data from 2020. Variation in local temperature and humidity (dew point) across the country will affect DAC system performance, water usage, energy requirements, etc.*

humidity have moderate and minor impacts, respectively, on the rate of capture and overall energy requirements. Specifically, capture rate can increase 10%–15% under a 10 °C temperature increase. Systems with lower capture rates are less energy efficient [59], thus hot, humid regions tend to be preferable as they increase capture performance and energy efficiency while minimizing evaporative water losses.

Local climate impacts not only the performance of solid-adsorbent DAC processes, but also the selection of a particular technology. For example, amine-based adsorbent DAC, the basis of our modeling, generally performs with greater productivity per mass of adsorbent in regions that are colder and more humid [59-62] due to the improved CO_2 chemisorption. Thus, colder, more humid regions are preferred for deploying this specific adsorbent DACS technology. Other adsorbent DAC technologies may perform better in locations that are drier (**Box 7–1**). Another consideration is that, while colder environments improve productivity, they also increase the magnitude of temperature swing required for desorption if using a fixed desorption condition, as is typical with steam-driven regeneration.

Daily variations in humidity and temperature are another consideration. Adsorbent DAC typically operates in sub-hour cycles, and as local conditions swing during a regular diurnal cycle, performance may also swing by a factor of ~2 [60]. Performance is also seasonally dependent, and different operating conditions or adsorbents may function better during different times of the year. Below-freezing temperatures are an additional complicating factor, potentially causing components to freeze in DAC systems that contain liquid water (e.g., from condensing steam). Environments with frequent sub-freezing temperatures, such as Alaska or the Upper Midwest, may require alternative operating modes and additional process complexities and costs. However, some work has demonstrated alternative thermal cycles that can be used when operating at very low adsorption temperatures that result in smaller required temperature swings [17, 28].

The co-adsorption of water greatly impacts CO_2 adsorption. Depending on the specific adsorbent and process configuration, extremely dry or humid environments may lead to inefficiencies, such as reduced working capacities or increased energy requirements. Environments with greater ambient humidity will result in increased co-adsorption of water on solid adsorbents [62]. This can lead to an increase in CO_2 adsorption capacity for amine-based adsorbents but a decrease for physical adsorbents (Box 7-1). Removing adsorbed water and drying the adsorbent during the regeneration step may also impose an additional energy load depending on the adsorbent, but not in all cases [62, 63]. For the vacuum-steam regeneration process modeled in our analysis, CO_2 is stripped from the adsorbents under high partial pressures of water, and the adsorbent is not dried during regeneration.

We did not include the impact of altitude on the productivity of DAC processes as part of our model. We expect it would have minimal impact on the outcome of our analysis due to the strong chemical bonds formed between CO_2 and the specific adsorbents and solvents we modeled [64, 65]. Altitude may impact materials that bind CO_2 less strongly, such as physical adsorbents (Box 7-1), due to the decreased barometric pressure (and hence, partial pressure of CO_2) at altitude, particularly important for the Rocky Mountains regions.

Projecting the Cost of DACS

To project the future cost of DACS in the United States through 2050, we considered a technology learning-by-doing analysis, beginning with first-of-a-kind deployments through 2025 [66, 67]. First-of-a-kind total DACS capacity was 41,000 tonnes of CO_2 per year for adsorbent DACS and 500,000 tonnes of CO_2 per year for solvent DACS. Adsorbent DACS deployments planned through 2025 may be considered pre-commercial-scale, but the modular nature of the process means the core technology unit will not be directly scaled. We considered a blend of component-specific learning rates for the pieces of equipment comprising each DAC technology modeled (**Table 7-2**) [38, 68-71]. Modular and emergent components, like adsorbent materials and contactors, were generally assigned greater learning rates [71, 72]. In addition to learning rates on capital expenditures, we included a minor learning rate for variable operating costs for solvent DACS to account for improvements in energy efficiency, heat integration, and process improvements. For adsorbent DACS, we applied learning to the thermal-energy requirement, fit to a target final value at our projected 2050 deployment. The major process unit for adsorbent DAC (i.e., the contactor for adsorption and regeneration) is modular and does not benefit from economies of scale. Major process units for solvent DAC are scalable and will benefit from scaling laws but will benefit less from learning-by-doing.

Using three separate learning rate levels (low, moderate, high), we calculated DACS costs through 1000-million-tonnes-per-year global deployment for each technology **(Figure 7-12**). Table 7-2 provides additional details regarding equipment-specific learning rates. Our application of learning rates is not prescriptive to precisely how we expect the specific component costs within each DAC technology to decrease with time. Rather, the mix of learning rates attempts to represent the overall potential for learning-by-doing to

Table 7-2. *Component-based learning rates for solvent- and adsorbent-DAC-technology learning. We used "moderate" learning rates for all baseline 2050 analyses; learning cost curves reflecting "low" and "high" rates are shown as the lower and upper limits, respectively, of the shaded sections in Figure 7-12.*

Solvent			
Component	*Moderate*	*Low*	*High*
Contactor	10%	5%	15%
Pellet reactor	5%	2.5%	10%
Calciner-slaker	5%	2.5%	10%
Air-separation unit	0%	0%	5%
Drying and compression	0%	0%	2.5%
Power island	0%	0%	2.5%
Filters	0%	0%	2.5%
Variable operating costs	2.5%	2.5%	2.5%

Absorbent			
Component	*Moderate*	*Low*	*High*
Adsorbent and contactor	12%	10%	15%
Heat pump	10%	5%	12%
Fans	5%	2.5%	7.5%
Vacuum pumps	0%	0%	2.5%
Drying and compression	0%	0%	2.5%
Thermal-energy input	7.6 GJ/t	9.8 GJ/t	5.4 GJ/t

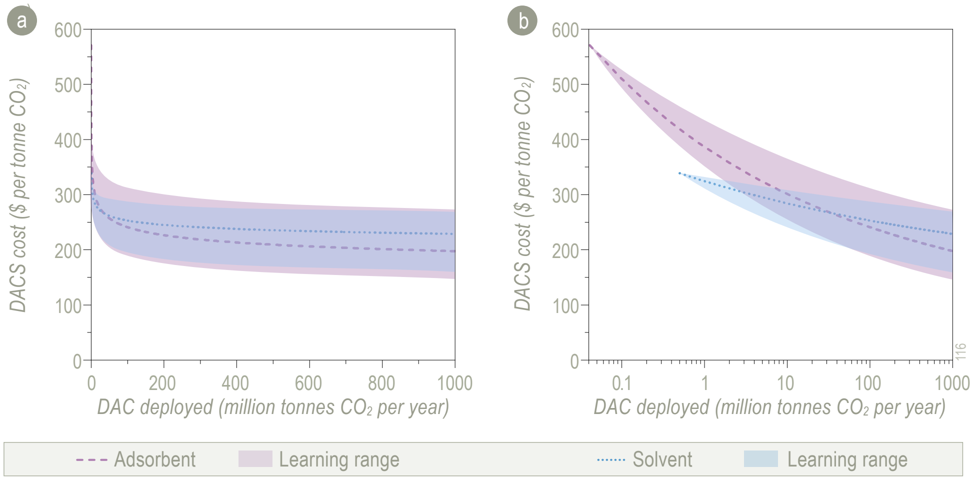


Figure 7-12. *Cost of solvent and adsorbent DACS as a function of global deployed capacity for that technology. Costs shown are projected through 1000 million tonnes per year of deployment on (a) linear and (b) logarithmic scales. Costs for CO_2 transport and geologic storage are not included. Costs will also vary based on local climate and energy price.*

reduce the ***total*** levelized cost. We used component-specific rates as a tool to provide some additional granularity into the potential for learning within a proposed DACS process. Widely used components, like compressors or fans, will likely not benefit from additional deployment specifically associated with DACS. However, overall plant design and integration, installed cost factors, supplier production, and other factors will bring down costs of integrating well-established unit components.

Cost estimates for first-of-a-kind deployments of adsorbent DACS were greater than those of solvent DACS, roughly \$570/tonne CO_2 versus \$340/tonne CO_2, respectively (**Appendix 7**). However, we projected the cost of adsorbent DACS would cross over and become slightly lower, on average, by the time each technology is deployed at the 20–50 million-tonne-per-year scale. Adsorbent DAC benefits from slightly greater component learning rates due to its modular nature and it being based on more novel components. The core unit of adsorbent DAC, the sorbent material and contactor, is an emergent technology and will benefit greatly from improvements in iterative design, material lifetime, and both chemical and hardware manufacturing. While adsorbent DACS initially has a greater cost, it is also currently at a smaller first-of-a-kind scale, so at the same deployed scale it will have progressed through a greater number of doublings.

Given the significant uncertainty in learning, as exhibited by the low-moderate-high learning ranges, we cannot definitively conclude which of the two DACS technologies will reach a lower cost at full learning. Our estimated DACS deployment through 2050, based on a moderate global DACS-deployment scenario, was 1000 million tonnes per year [73], which we divided evenly between the two DACS types. At this level of deployment, our projections estimate that adsorbent and solvent DACS costs will be in the ranges of \$160–\$280/tonne CO_2 and \$170–\$270/tonne CO_2, respectively. Considering moderate component learning rates and learning on capital costs only, the overall learning rates for adsorbent and solvent DACS are 9.7% and 3.9%, respectively. These learning rates are a result of our component-based learning assumptions and are generally lower than simpler single rates used in learning projections due to major unit operations, in solvent DACS especially, that are mature and for which we do not estimate significant learning to be achievable.

The Potential for Billion-Tonne-Scale DACS Deployment in 2050

We calculated the maximum technical potential capacity for large-scale solid-adsorbent-DACS deployment based on the available land for siting renewable electricity and solid-adsorbent DACS intersecting with known geologic storage reservoirs and/or a CO_2 pipeline. While most regions in the United States have some capacity for DACS, the largest opportunity for deployment is concentrated in just a few regions: West Texas, Upper and Lower Rocky Mountains, and parts of the Upper and Lower Midwest that border the Rocky Mountains regions. The potential capacity for solid-adsorbent DACS powered by renewable electricity is shown in green in **Figure 7-13**, with darker shades of green indicating larger potential for deployed DACS capacity.

We estimated the levelized cost of carbon removal by projecting capital costs based on estimated global deployment in 2050 and operating costs based on state-level energy costs (**Appendix 7**). We used daily average temperature and humidity to calculate a weighting factor on the adsorbent-module productivity [60]. The adjusted productivity, averaged over the year, affected the adsorbent required for the defined DACS-facility scale, affecting the cost of net CO_2 removed. We averaged costs and aggregated them by county, shown in blue in Figure 7-13, with darker shades of blue indicating lower costs for solid adsorbent DACS. The effect of climate can be partially seen in Figure 7-13; however, the geospatial variance in energy costs was generally of greater scale than the cost-impact resulting from adsorbent performance. Differences in yearly temperature distributions between regions tended to have a greater effect on adsorbent DACS performance and cost than differences in relative humidity. Water use and availability, as well as pre-drying considerations, are potentially impactful factors not captured in our modeled cost results. The regions with the lowest costs are generally the regions expected to have the lowest costs for producing electricity and storage: the Upper and Lower Rocky Mountains and West Texas. **Box 7-3** provides additional discussion.

We also calculated the potential for liquid-solvent-DACS deployment, powered by local natural-gas—to achieve the high temperature required for regeneration—and capturing most emissions from the natural gas combustion. In performing this analysis, we did not intend to imply that US natural-gas reserves will be used to perform DACS; rather, we performed this analysis to understand where natural-gas-fired DACS may continue to play an important role. However, for some communities that have significant risk of economic crisis triggered by job loss in the oil and gas sector, developing natural-gas-fired DACS may help these communities participate in the transition to a carbon-management economy.

We used estimates of technically recoverable natural gas in conjunction with current and future estimates of US natural-gas consumption to forecast the amount of the natural-gas reserves that would be available for DACS (**Appendix 7**) [41, 74-76]. In total, we estimate that the US natural-gas reserves have a technical potential to provide energy for more than 4 billion tonnes per year of DAC for 50 years. As noted earlier, the emissions from burning natural gas, whether captured or released, can impact the carbon negativity of a process. The US regions with large natural-gas reserves, unsurprisingly, have large potential for deploying natural-gas-fired DAC: the Marcellus shale play and Utica shale play in Appalachia, the Wolfcamp shale play in the Permian Basin of West Texas, the

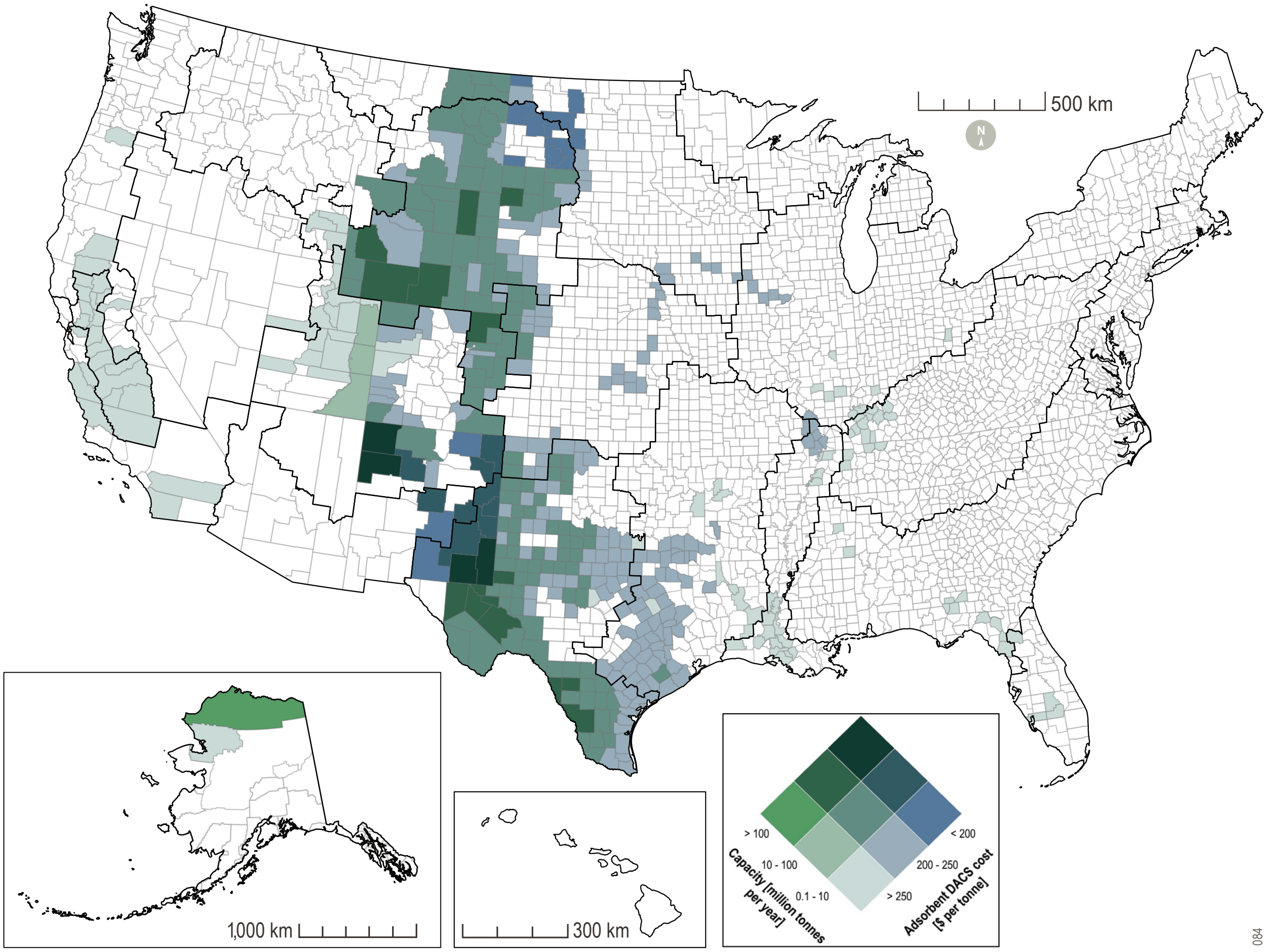


Figure 7-13. *County-level assessment of potential capacity of solid-adsorbent DACS powered by renewable electricity and co-located with geologic storage. Costs are based on adsorbent DACS utilizing a heat pump to provide the thermal energy for regeneration and utilizing renewable grid electricity. Costs include storage and are for net* CO_2 *removed. Darker shades of green indicate higher county-level capacity; darker shades of blue indicate lower cost for DACS. Heavily outlined areas indicate the boundaries of the regions defined in this report to highlight the US regions with large potential capacity for DACS deployment.*

BOX 7-3

What's Up with the Rocky Mountains?

As indicated in **Figure 7-13**, the Upper Rocky Mountains region, predominantly Wyoming, is promising for deploying large amounts of renewable-electricity-powered DACS in the future. However, **Figure 7-8** earlier in this chapter could lead one to conclude that this region is not appropriate for siting DACS due to extremely high costs or net-carbon positivity associated with using the current electrical grid. This discrepancy highlights the necessity of low-carbon-energy resources for DACS feasibility and the importance of decarbonizing the electrical sector and developing additional low-carbon electricity.

Haynesville-Bossier shale play in South-Central, and the North Slope of Alaska. **Figure 7-14** shows each region's potential capacity in red, with darker shades of red indicating larger potential for deployed DACS capacity due to larger natural-gas reserves.

We used a similar methodology to estimate the levelized cost of carbon removal by natural-gas-fired DACS as we used for solid-adsorbent DACS. We adjusted liquid-solvent-DACS-facility scale and energy requirements as impacted by local climate effects [59] and used a uniform natural-gas price across the United States. Water use is affected by local climate, as discussed in more detail in **Chapters 8 – Cross-Cutting and 9 – EEEJ,** but the very low cost of process water has a negligible effect on total cost of CO_2 removal. Hence, most of the variation in liquid-solvent-DACS cost in Figure 7-14 is due to the cost of geologic storage and local climate.

Figure 7-15 shows the combined supply curve for solid-adsorbent and liquid-solvent DACS. In total, we estimate the United States has the potential to deploy over 9 billion tonnes per year of CO_2-removal capacity via solid-adsorbent DACS (using renewable electricity to provide the heat required for regeneration) and over 4 billion tonnes per year via liquid-solvent DACS (using natural gas to provide the high temperature required for regeneration). It is highly likely that we will only require a small fraction of this capacity to meet net-zero emission goals, leaving ample capacity to fulfill additional demand for the CO_2 required for formation of carbon-based products and fuels. While the supply curve in **Figure 7-15** suggests that solvent DACS will generally be more expensive than adsorbent DACS (it appears more to the right on the supply curve), we note that the error bars on DACS cost in Figure 7-12 demonstrate that costs for both technologies are expected to fall to within the same general range by the time they have been deployed at

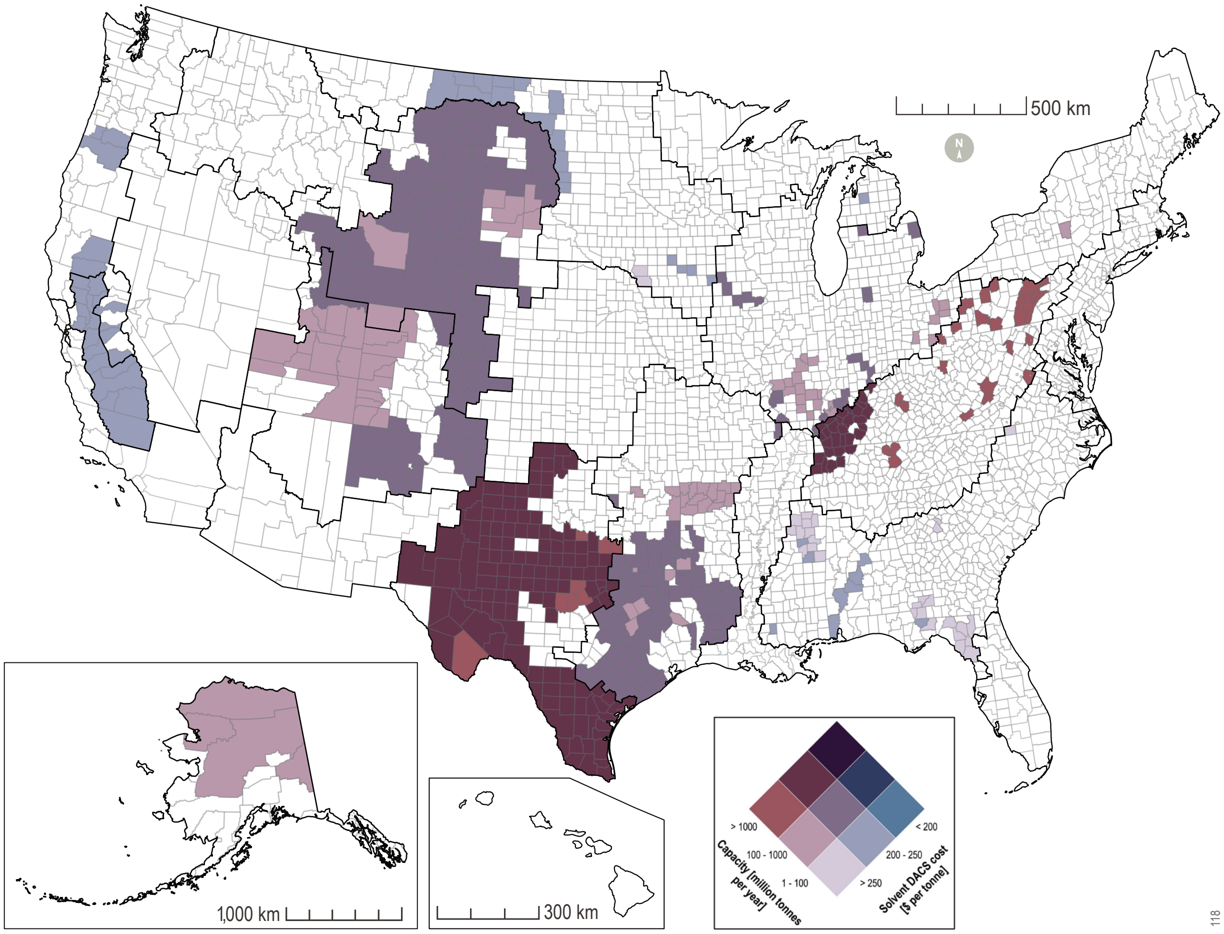


Figure 7-14. *Region-level assessment of potential capacity of liquid solvent DACS with a natural-gas fired calcination kiln co-located with geologic storage. Costs are based on solvent DACS utilizing natural-gas reserves located across the United States. Darker shades of red indicate higher region-level capacity, darker shades of blue indicate lower cost for DACS. Heavy outlined areas indicate the boundaries of the regions defined in this report to highlight the regions of the United States with large potential capacity for DACS deployment.*

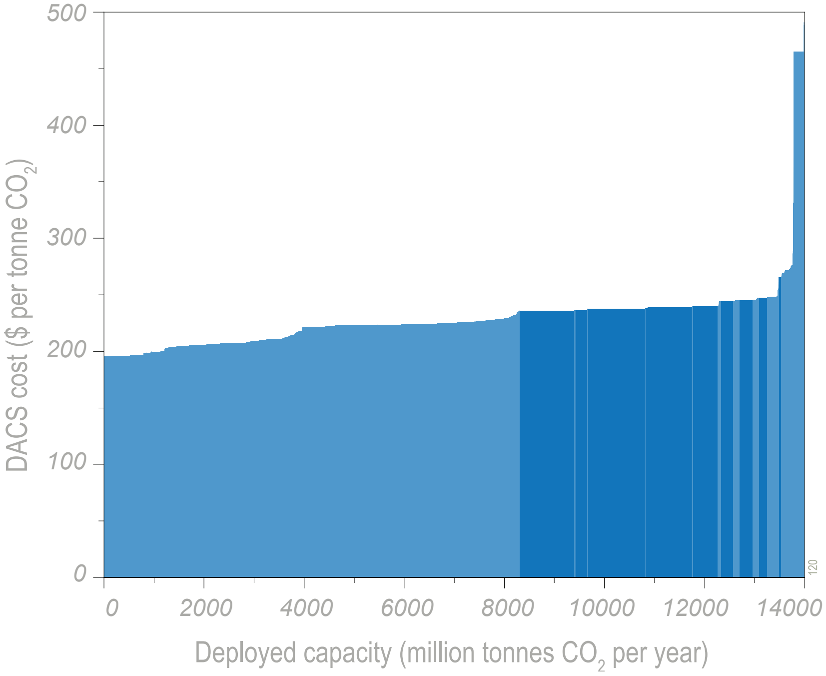


Figure 7-15. *Supply curve for total DACS potential capacity across the United States. Adsorbent DACS powered by renewable electricity (light blue), weighted average costs by county. Solvent DACS powered by natural-gas reserves (dark blue), costs by region. Costs for this supply curve were projected at the 500-million-tonne-per-year deployment level for both technologies and so do not reflect cost reduction from additional deployment.*

the 100-million-tonne-per-year scale. Moreover, as noted earlier in the chapter, solvent DACS paired with natural gas is currently being deployed at a larger scale than adsorbent DACS and has lower near-term cost. Therefore, even if adsorbent DACS ultimately ends up being less expensive than solvent DACS when deployed at large scale, we expect that both classes of technology will play a significant role in providing CO_2 removal.

It is important to caveat these results by noting that this is the technical potential for DACS co-located with geologic storage; social, ecological, regulatory, and market factors not evaluated here will likely further limit this potential. Relaxing the constraint of co-location with geologic storage would allow access to significant additional quantities of renewable energy, particularly additional solar photovoltaic electricity in the Great Basin and Desert Southwest regions and additional wind electricity in the Upper and Lower Midwest regions. This expansion would require either significant expansion of high-capacity electricity transmission or CO_2 transportation. Alternatively, these regions may be of interest for deployment of renewable electricity and DAC purpose-built for formation of carbon-based products rather than for storage.

Key Takeaways for Long-Term DACS Deployment

Due to significant amounts of potential renewable energy and technically recoverable natural gas, the United States has the ability and opportunity to deploy massive amounts of large-scale DACS—enough to achieve national net-zero emission goals, aid other nations that are not as resource-rich in their own net-zero goals, and provide CO_2 for other uses, such as forming carbon-based products and fuels. However, doing so will take unprecedented investments in expansion of land-based wind and solar-photovoltaic resources beyond what will be required for electric-grid decarbonization, in addition to the capital investment required for construction of the DACS facilities.

For DACS powered by renewable energy, the opportunity is primarily distributed in the western and southwestern parts of the nation, co-located with renewable-energy potential and where the population density, and hence local electricity demand, is lower. For DACS powered by natural gas, the opportunities are co-located with large shale reserves. While we have evaluated a *technical potential* for large-scale DACS deployment here, it is important to note that social, ecological, regulatory, and market factors will limit this potential. For example, we may as a society decide that at a certain point, we will no longer continue to produce natural gas, despite still having significant reserves. We may intentionally limit the amount of solar-photovoltaic renewable energy produced due to ecological concerns with covering large areas of the land with solar panels; alternatively, we may be limited by external forces or supply-chain issues associated with procuring the critical materials required for solar-panel manufacture. These and other factors are important when considering the potential capacity for DACS deployment.

EEEJ Considerations for Renewable Energy and DACS

DACS, like many large-scale industrial projects, poses opportunities for co-benefits and potential negative impacts. In this section, interested parties can compare the trade-offs for DACS, both solvent- and adsorbent-based, and make recommendations for the maximization of co-benefits and the avoidance or minimization of potential negative impacts (**Table 7-3**).

The key co-benefits for DACS are socioeconomic in nature—specifically, its geospatial overlap with counties experiencing persistent job losses in the "traditional energy" sectors [77, 78]. Counties whose workforces are predominantly based in carbon-intensive industries, such as fossil-fuel extraction or fossil-fuel-based electricity generation, are at risk of

Table 7-3. *DACS potential co-benefits and negative impacts for nearby communities.*

Potential **Co-benefits** to Communities & Recommendations for Maximizing Potential Co-benefits	Potential **Negative** Impacts to Communities & Recommendations for Minimizing Potential Negative Impacts
Direct jobs [84] DACS facilities will require skilled workforce. Size of facility and proximity to transport and/or storage infrastructure will influence jobs potential. Negotiate workforce agreements and local hiring commitments pre-permitting.	Renewable energy demand [70, 85] DACS facilities have high energy requirements. Compare renewable energy required for DACS power to suitable land that must first meet community decarbonization needs, both current and future.
Indirect jobs [84] Additional infrastructure development and improvements required for facility may introduce additional interest and commerce in region. Use open-source economic model to forecast potential indirect job creation; share results with local communities.	Noise pollution Fans associated with air contactors and noises associated with construction and traffic. Use an acoustic attenuation model based on site design and topography to assess how the expected decibels at the site will transfer; require green belts (or other method) to attenuate noise to down to background levels before reaching residents.
County- and state-tax revenue Negotiate (pre-permitting) that a percentage of revenue from generating and selling CO_2-removal credits be committed to causes chosen based on public feedback.	Water demand [70, 85, 86] DACS has potential to require some water per tonne of CO_2 captured (1.6 tonnes for adsorbent, 3–6 tonnes for solvent). Transparently reporting water demand (Mt water/Mt CO_2) pre-permitting can help communities plan. Ideally, constructing in regions not expected to experience future water stress or choosing technology with minimal water consumption. Some DACS processes can co-produce water, which may be of interest to some communities.
Funding for local causes Negotiate (pre-permitting) a percentage of profits that will be shared through a local community-benefit fund.	Land demand [85] Construction on marginal or remote lands that are not identified by local governments as vital to long-term growth. Clear communication with landowners in region.
Early-adopter identity Local community may value being an early adopter of DACS technology and may publicly signal their interest and commitment toward carbon management.	Chemical use (on-site and off-site) Transparent and parallel discussions with communities at both the DACS site and the chemical manufacturing location regarding workplace safety, track record of safety incidents, innovations and monitoring beyond regulatory requirements, risk analysis, and waste-management plan for solvents/adsorbents.
	Community hesitancy or distrust Early, broad, and accessible community education about DACS technology, through trusted messengers, can help build trust and reduce hesitancy around DACS projects.

Potential **Co-benefits** to Communities & Recommendations for Maximizing Potential Co-benefits	Potential **Negative** Impacts to Communities & Recommendations for Minimizing Potential Negative Impacts
Infrastructure near site Buildout of DACS facilities will necessitate infrastructural development and improvements related to roads, culverts, and high-speed internet, among others. Include community in discussions regarding infrastructure build-out and identify points for improvement that have the greatest shared benefit. Initial regional assessment of infrastructure deficiencies is advisable.	Methane leakage Specific to DACS facilities utilizing natural-gas-powered facilities, either for heating or energy supply. Quantification of methane emissions from the transport, power, and operation of DACS facilities, as well as associated manufacturing plants, will allow its inclusion in the project's LCA.
	Community hesitancy or distrust Early, broad, and accessible community education about DACS technology, through trusted messengers, can help build trust and reduce hesitancy around DACS projects.
	Traffic impacts Additional traffic to and from facility, particularly during construction. Locating DACS facilities in regions not identified as being unduly impacted by traffic [87] is advisable.
	Incomplete decommissioning Sharing plans (including site restoration), financial commitments, and carbon-intensity estimates that cover future decommissioning of DACS plants may help build trust.
	Construction impacts Negotiation of "Good Neighbor Agreements" between project developer and surrounding residents will result in better relationships, and environmental standards for noise, safety, traffic, parking, and dust must be monitored and adhered to.
	Uncertain air emissions Both forms of DACS may have associated air emissions: hydroxide aerosols and calcium carbonate solids from solvent and ammonia and other volatile organic compounds during oxidation from adsorbent. Share air emission data from pilot plant (if applicable) and negotiate emissions/air monitoring on-site for potential pollutants.

economic and public health crises if their workforces are not transitioned purposefully amidst decarbonization [79, 80]. Beyond solely jobs, counties will earn additional tax revenue and county residents can negotiate for public goods in their "community-benefit agreement" negotiation phase (e.g., profit sharing or infrastructure improvements). By prioritizing counties with the greatest job-loss rates in fossil-fuel sectors, dependence on fossil-fuel jobs for economic solvency, and room for infrastructure improvements (e.g., broadband and paved roads), policymakers could help maximize the socioeconomic co-benefits of DACS.

The overarching potential negative impacts of DACS are dependent on resource competition, such as cheap renewable-energy resources, water, and land. Who owns this land is also a concern for DACS facilities, which will be leasing or purchasing lands for operation, financially benefitting either public landowners or private landowners in rural areas. There is an opportunity to allow equitable-opportunity distribution of these financial benefits across the diverse US populations. Another prevailing concern is that, if optimized solely for "traditional-energy communities," which face greater environmental injustices on average, there will be inequitable siting of DACS facilities in vulnerable communities that are not equipped for advocacy or emergency response [81].

Without parallel development of community capacity to engage in project development from an informed place of power, as well as development of community-approved operating guidelines, DACS facilities risk contributing to historical and ongoing industrial-siting injustices in the United States (e.g., [82]). By investing in community capacity building around DACS in regions highlighted by this report

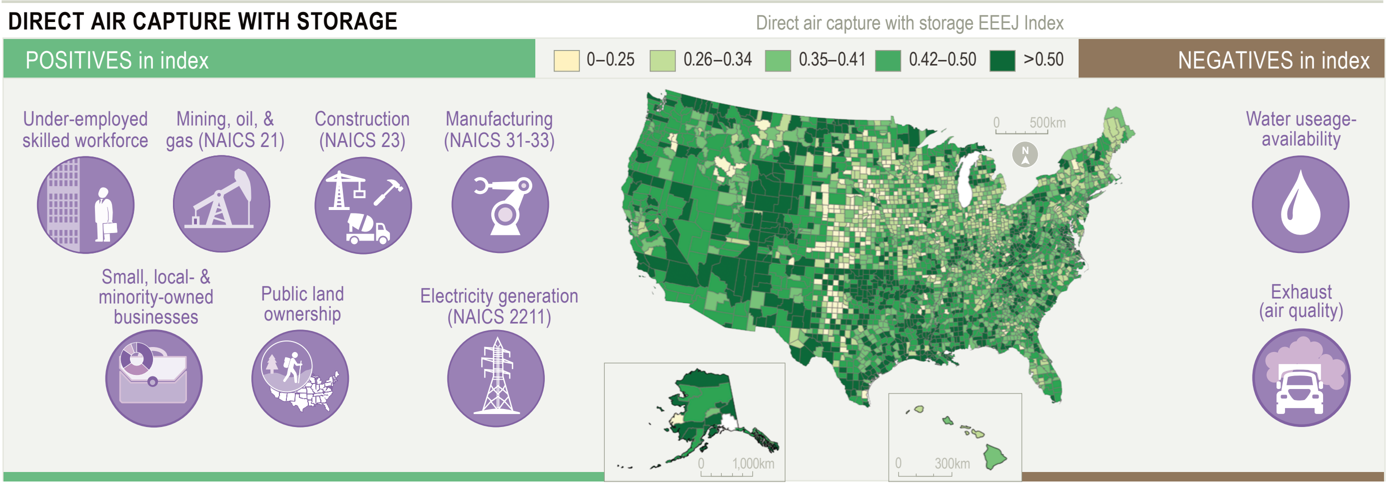


Figure 7-16. *Map of the EEEJ index for direct air capture with storage, alongside each variable that contributed, positively or negatively, to the index. The index is normalized from 0 to 1, where higher values represent a potentially greater opportunity for socio-economic co-benefits, including reemployment of skilled workforces and public pore space that distributes revenues to the tax base. Higher values also represent a smaller potential for negative environmental impacts, such as competition for scarce water resources or air pollution risks from the construction and/or operation phases, indicated by diesel-derived PM2.5.*

as having DACS potential, policymakers could increase community support for projects, which is key to this industry's successful scale-up. Previous research has shown that if there is local opposition to a renewable energy project, which is foundational to any DACS facility, there is an ~50% chance that the project will be cancelled permanently and an ~34% chance that it will incur costly delays in permitting [83]. Due to the urgency of climate change and the formidable scale-up challenges that DACS faces in helping the United States meet its net-zero targets while transitioning at-risk workforces, DACS projects cannot afford to waste time or resources with stoppage or delays. Thus, it is paramount that projects be strategically proposed in counties that have the capacity and interest to engage (with early engagement from the onset) and stand to maximally benefit from the project with minimal risk.

An average "EEEJ index" value, presented here for each county, could allow project developers to efficiently synthesize socioeconomic and environmental data relevant to DOE's energy equity and environmental justice (EEEJ) goals [88], for both solvent- and adsorbent-based DACS (**Chapter 9**). In these indices, values closer to 1 represent opportunities for co-benefits and values closer to 0 represent lower likelihood for co-benefits and potentially greater challenges pertinent to EEEJ considerations. The impact of each variable, positively or negatively, on the overall EEEJ index value for each county is presented in **Figure 7-16**. Following the construction of each index, a comparison to the Center for Disease Control's Social Vulnerability Index (SVI) is conducted to assess for potential biases in the index toward vulnerable counties (**Figure 7-17**). Evaluating SVI alongside this report's EEEJ index may be useful for policymakers and project developers in determining potential priorities, such as protecting a region's most vulnerable communities from air pollution or carefully considering the development of an industrial DACS presence in a county least equipped to respond to potential negative impacts, if they occur. Further examination of the socioeconomic and environmental contexts considered for each county identified in this chapter can be found in the dedicated EEEJ chapter (**Chapter 9**).

Conclusions

There is massive potential for powering and deploying DACS in the United States—14 billion tonnes of carbon removal per year if we are willing to make the significant investment required to harness all our resources. These include opportunities for renewable-electricity-powered solid-adsorbent DACS in West Texas and the Upper and Lower Rocky Mountains, as well as additional opportunities for tapping into natural-gas reserves to power liquid-solvent DACS in Appalachia, West Texas, South-Central, and the North Slope of Alaska. While the potential for DACS deployment is large, DACS will likely remain the most expensive CO_2-removal option out of those considered in this report, and as such, deployment will likely be limited by (1) the ability to reduce the cost of the technology, (2) regulatory mechanisms or incentives, and (3) maturation of a carbon-removal marketplace.

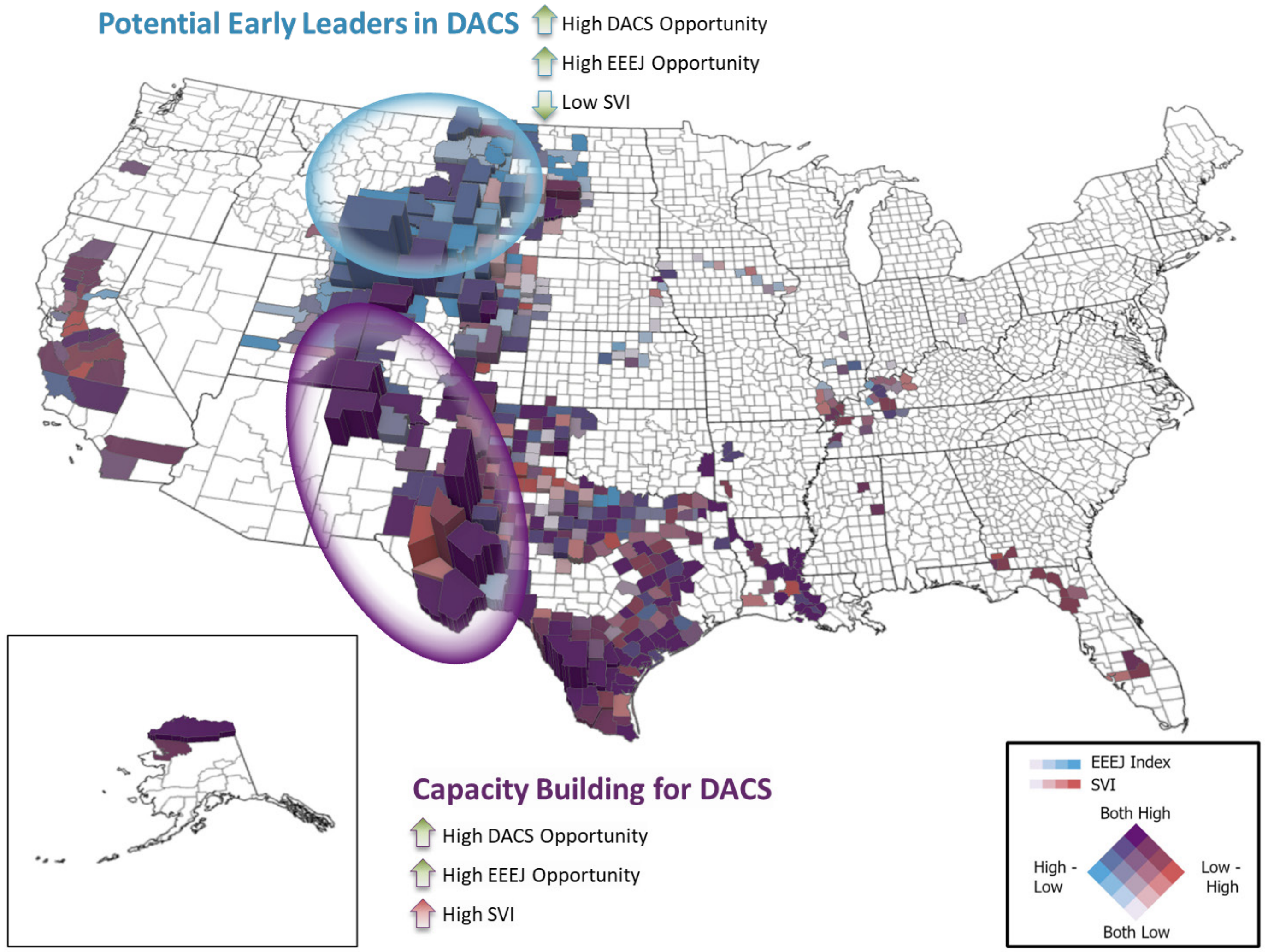


Figure 7-17. *Map of EEEJ index data (blue) and the CDC's Social Vulnerability Index (red) for the US counties with high potential for renewable energy and adsorbent DACS deployment. The height of the county represents the relative potential for* CO_2 *removal via renewable-electricity-powered adsorbent DACS. The map is annotated to reflect this report's hypothesis around DACS deployment: if a county has high opportunity for co-benefits and low social vulnerability, then they may be better poised to become early leaders in the practice. Similarly, counties with high opportunity for co-benefits, but also high social vulnerability, may benefit from investments in local capacity building to engage the community on the topic of DACS.*

Many actions can be taken in the near-term to help maximize the benefits of early DACS deployment and minimize negative externalities. We need better regulations around measuring and controlling natural-gas emissions and scientifically guided and rigorous standards for DACS monitoring, reporting, and verification (MRV) across existing and emerging DACS technologies and associated energy sources. We need to be cognizant of potential competing uses for renewable electricity, taking care not to hinder decarbonization of the electrical grid in our efforts to improve the carbon negativity of DACS processes. Finally, DACS development has an opportunity to help communities that are dependent on fossil-fuel jobs purposefully evolve to jobs in carbon management, spurring infrastructure improvements and maximizing socioeconomic benefits to these communities.

References

1. Paul Denholm, et al. Examining Supply-Side Options to Achieve 100% Clean Electricity by 2035 (NREL/TP6A40-81644). 2022. National Renewable Energy Laboratory (NREL), Golden, CO, USA; https://doi.org/10.2172/1885591.
2. 1PointFive. Carbon Removal at Scale. Accessed 2023. Published by 1PointFive; Available from https://www.1pointfive.com/.
3. David W. Keith, et al., A Process for Capturing CO_2 from the Atmosphere. Joule, 2018. ***2***(8): p. 1573-1594, https://doi.org/10.1016/j.joule.2018.05.006.
4. Charles A. Seipp, et al., CO_2 Capture from Ambient Air by Crystallization with a Guanidine Sorbent. Angewandte Chemie International Edition, 2017. ***56***(4): p. 1042-1045, https://doi.org/10.1002/anie.201610916.
5. Flavien M. Brethomé, et al., Direct air capture of CO_2 via aqueous-phase absorption and crystalline-phase release using concentrated solar power. Nature Energy, 2018. ***3***(7): p. 553-559, https://doi.org/10.1038/s41560-018-0150-z.
6. Xingguang Xu, et al., Next generation amino acid technology for CO_2 capture. Journal of Materials Chemistry A, 2021. ***9***(3): p. 1692-1704, https://doi.org/10.1039/D0TA10583J.
7. Radu Custelcean, et al., Direct air capture of CO_2 with aqueous peptides and crystalline guanidines. Cell Reports Physical Science, 2021. ***2***(4): p. 100385, https://doi.org/10.1016/j.xcrp.2021.100385.
8. Christoph Beuttler, Louise Charles, and Jan Wurzbacher, The Role of Direct Air Capture in Mitigation of Anthropogenic Greenhouse Gas Emissions. Frontiers in Climate, 2019. ***1***, https://doi.org/10.3389/fclim.2019.00010.
9. Climeworks. Lead the Race Toward Net Zero. Accessed 2023. Published by Climeworks; Available from https://climeworks.com/.
10. Global Thermostat. The Air Carbon Solution. Accessed 2023. Published by Global Thermostat; Available from https://www.globalthermostat.com/.
11. Noah McQueen, et al., Cost Analysis of Direct Air Capture and Sequestration Coupled to Low-Carbon Thermal Energy in the United States. Environmental Science & Technology, 2020. ***54***(12): p. 7542-7551, https://doi.org/10.1021/acs.est.0c00476.
12. Christoph Gebald, Nicolas Repond, and Jan Andre Wurzbacher. Steam assisted vacuum desorption process for carbon dioxide capture. 2019. U.S. Patent; US 10,279,306 B2 Climeworks AG; Zurich (https://patents.google.com/patent/US10279306B2/).
13. Peter Eisenberger and Graciela Chichilnisky. System and method for removing carbon dioxide from an atmosphere and global thermostat using the same. 2017. U.S. Patent; US 9,555,365 B2; Global Thermostat Operations LLC; United States (https://patents.google.com/patent/US9555365B2/).
14. Noah McQueen, et al., Ambient weathering of magnesium oxide for CO_2 removal from air. Nature Communications, 2020. ***11***(1): p. 3299, https://doi.org/10.1038/s41467-020-16510-3.
15. Thomas M. McDonald, et al., Capture of Carbon Dioxide from Air and Flue Gas in the Alkylamine-Appended Metal–Organic Framework mmen-Mg2(dobpdc). Journal of the American Chemical Society, 2012. ***134***(16): p. 7056-7065, https://doi.org/10.1021/ja300034j.
16. Muhammad Munir Sadiq, et al., A Pilot-Scale Demonstration of Mobile Direct Air Capture Using Metal-Organic Frameworks. Advanced Sustainable Systems, 2020. ***4***(12): p. 2000101, https://doi.org/10.1002/adsu.202000101.
17. Guanhe Rim, et al., Sub-Ambient Temperature Direct Air Capture of CO_2 using Amine-Impregnated MIL-101(Cr) Enables Ambient Temperature CO_2 Recovery. JACS Au, 2022. ***2***(2): p. 380-393, https://doi.org/10.1021/jacsau.1c00414.
18. Donglong Fu, Youngkyu Park, and Mark E. Davis, Confinement effects facilitate low-concentration carbon dioxide capture with zeolites. Proceedings of the National Academy of Sciences, 2022. ***119***(39): p. e2211544119, https://doi.org/10.1073/pnas.2211544119.

19. Donglong Fu and Mark E. Davis, Toward the feasible direct air capture of carbon dioxide with molecular sieves by water management. Cell Reports Physical Science, 2023. ***4***(5): p. 101389, https://doi.org/10.1016/j.xcrp.2023.101389.

20. Xiaoyang Shi, et al., Moisture-Driven CO_2 Sorbents. Joule, 2020. ***4***(8): p. 1823-1837, https://doi.org/10.1016/j.joule.2020.07.005.

21. Sahag Voskian and T. Alan Hatton, Faradaic electro-swing reactive adsorption for CO_2 capture. Energy & Environmental Science, 2019. ***12***(12): p. 3530-3547, http://dx.doi.org/10.1039/C9EE02412C.

22. Xing Li, et al., Redox-tunable Lewis bases for electrochemical carbon dioxide capture. Nature Energy, 2022. ***7***(11): p. 1065-1075, https://doi.org/10.1038/s41560-022-01137-z.

23. Ibadillah A. Digdaya, et al., A direct coupled electrochemical system for capture and conversion of CO_2 from oceanwater. Nature Communications, 2020. ***11***(1): p. 4412, https://doi.org/10.1038/s41467-020-18232-y.

24. Heirloom. Restoring balance to our atmosphere. Accessed 2023. Published by Heirloom; Available from https://www.heirloomcarbon.com/.

25. Kenji Sumida, et al., Carbon Dioxide Capture in Metal–Organic Frameworks. Chemical Reviews, 2012. ***112***(2): p. 724-781, https://doi.org/10.1021/cr2003272.

26. Amrit Kumar, et al., Direct Air Capture of CO_2 by Physisorbent Materials. Angewandte Chemie International Edition, 2015. ***54***(48): p. 14372-14377, https://doi.org/10.1002/anie.201506952.

27. Donglong Fu and Mark E. Davis, Carbon dioxide capture with zeotype materials. Chemical Society Reviews, 2022. ***51***(22): p. 9340-9370, https://doi.org/10.1039/D2CS00508E.

28. MinGyu Song, et al., Cold-Temperature Capture of Carbon Dioxide with Water Coproduction from Air Using Commercial Zeolites. Industrial & Engineering Chemistry Research, 2022. ***61***(36): p. 13624-13634, https://doi.org/10.1021/acs.iecr.2c02041.

29. Avnos. Carbon Negative. Water Positive. Avnos is commercializing the most advanced technology in the Direct Air Capture of CO_2. Accessed July 2023. Published by Avnos; Available from https://www.avnos.com/.

30. Removr. Scaling carbon removal to avoid global warming. Accessed 2023. Published by Removr; Available from https://www.removr.no/.

31. Tao Wang, Klaus S. Lackner, and Allen Wright, Moisture Swing Sorbent for Carbon Dioxide Capture from Ambient Air. Environmental Science & Technology, 2011. ***45***(15): p. 6670-6675, https://doi.org/10.1021/es201180v.

32. Carbon Collect. Passive, scalable cabon capture technology. Accessed 2023. Published by Carbon Collect; Available from https://carboncollect.com/.

33. Yayuan Liu, et al., Electrochemically mediated carbon dioxide separation with quinone chemistry in salt-concentrated aqueous media. Nature Communications, 2020. ***11***(1): p. 2278, https://doi.org/10.1038/s41467-020-16150-7.

34. Jeffrey M. Barlow and Jenny Y. Yang, Oxygen-Stable Electrochemical CO_2 Capture and Concentration with Quinones Using Alcohol Additives. Journal of the American Chemical Society, 2022. ***144***(31): p. 14161-14169, https://doi.org/10.1021/jacs.2c04044.

35. Verdox. Electric carbon removal for a Net-Zero future. Accessed 2023. Published by Verdox; Available from https://verdox.com/.

36. R. Sharifian, et al., Electrochemical carbon dioxide capture to close the carbon cycle. Energy & Environmental Science, 2021. ***14***(2): p. 781-814, https://doi.org/10.1039/D0EE03382K

37. Captura. Welcome to the Future of Carbon Capture. Accessed 2023. Published by Captura; Available from https://capturacorp.com/.

38. Sarah Deutz and André Bardow, Life-cycle assessment of an industrial direct air capture process based on temperature–vacuum swing adsorption. Nature Energy, 2021. ***6***(2): p. 203-213, https://doi.org/10.1038/s41560-020-00771-9.

39. The White House. Fact Sheet: President Biden to Catalyze Global Climate Action through the Major Economies Forum on Energy and Climate. 2023. Available from https://www.whitehouse.gov/briefing-room/statements-releases/2023/04/20/fact-sheet-president-biden-to-catalyze-global-climate-action-through-the-major-economies-forum-on-energy-and-climate/.

40. The White House. Fact Sheet: President Biden Sets 2030 Greenhouse Gas Pollution Reduction Target Aimed at Creating Good-Paying Union Jobs and Securing U.S. Leadership on Clean Energy Technologies. 2021. Available from https://www.whitehouse.gov/briefing-room/statements-releases/2021/04/22/fact-sheet-president-biden-sets-2030-greenhouse-gas-pollution-reduction-target-aimed-at-creating-good-paying-union-jobs-and-securing-u-s-leadership-on-clean-energy-technologies/.

41. Paul Denholm, et al. Examining Supply-Side Options to Achieve 100% Clean Electricity by 2035. 2022. National Renewable Energy Laboratory. NREL/TP-6A40-81644, Golden, CO; https://www.nrel.gov/docs/fy22osti/81644.pdf.

42. United States Department of State and United States Executive Office of the President. The Long-Term Strategy of the United States: Pathways to Net-Zero Greenhouse Gas Emissions by 2050. 2021. https://www.whitehouse.gov/wp-content/uploads/2021/10/US-Long-Term-Strategy.pdf.

43. Grazia Leonzio and Nilay Shah, Innovative Process Integrating Air Source Heat Pumps and Direct Air Capture Processes. Industrial & Engineering Chemistry Research, 2022. ***61***(35): p. 13221-13230, https://doi.org/10.1021/acs.iecr.2c01816.

44. Chad Augustine, et al. Enhanced Geothermal Shot Analysis for the Geothermal Technologies Office (NREL/TP-5700-84822). 2023. National Renewable Energy Laboratory (NREL), United States; https://doi.org/10.2172/1922621.

45. Parthiv Kurup and Craig Turchi. Initial Investigation into the Potential of CSP Industrial Process Heat for the Southwest United States (NREL/TP-6A20-64709). 2015. National Renewable Energy Lab. (NREL), , Golden, CO, USA; https://doi.org/10.2172/1227710.

46. Craig S. Turchi, et al. CSP Systems Analysis- Final Project Report (NREL/TP-5500-72856). 2019. National Renewable Energy Lab. (NREL), Golden, CO, USA; https://doi.org/10.2172/1513197.

47. Daniel Slesinski and Scott Litzelman, How Low-Carbon Heat Requirements for Direct Air Capture of CO_2 Can Enable the Expansion of Firm Low-Carbon Electricity Generation Resources. Frontiers in Climate, 2021. ***3***, https://doi.org/10.3389/fclim.2021.728719.

48. Eric Larson, et al. Net-Zero America: Potential Pathways, Infrastructure, and Impacts, Final report. 2021. Princeton University, Princeton, NJ; Available at https://netzeroamerica.princeton.edu/the-report.

49. M. Pathak, et al., 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, et al., Editors. 2022, Cambridge University Press: Cambridge, UK and New York, NY, USA (https://doi.org/10.1017/9781009157926.002).

50. U.S. Energy Information Administration (EIA). State Electricity Profiles: Full Data Tables. Accessed July 2023. Published by U.S. EIA; Available from https://www.eia.gov/electricity/state/unitedstates/state_tables.php.

51. U.S. Energy Information Administration (EIA). Electricity: State Electricity Profiles. Accessed July 2023. Published by U.S. EIA; Available from https://www.eia.gov/electricity/state/.

52. Evan Sherwin, et al., Quantifying oil and natural gas system emissions using one million aerial site measurements. Under review at Nature Portfolio, 2023, https://doi.org/10.21203/rs.3.rs-2406848/v1.

53. Yuzhong Zhang, et al., Quantifying methane emissions from the largest oil-producing basin in the United States from space. Science Advances, 2020. ***6***(17): p. eaaz5120, https://doi.org/10.1126/sciadv.aaz5120.

54. Yuanlei Chen, et al., Quantifying Regional Methane Emissions in the New Mexico Permian Basin with a Comprehensive Aerial Survey. Environmental Science & Technology, 2022. ***56***(7): p. 4317-4323, https://doi.org/10.1021/acs.est.1c06458.

55. Ramón A. Alvarez, et al., Assessment of methane emissions from the U.S. oil and gas supply chain. Science, 2018. ***361***(6398): p. 186-188, https://doi.org/10.1126/science.aar7204.

56. U.S. Department of Energy Office of Clean Energy Demonstrations (OCED). Regional Direct Air Capture Hubs. Accessed July 2023. Published by OCED; Available from https://www.energy.gov/oced/regional-direct-air-capture-hubs.

57. Anthony Lopez, et al., Impact of siting ordinances on land availability for wind and solar development. Nature Energy, 2023. ***8***(9): p. 1034-1043, https://doi.org/10.1038/s41560-023-01319-3.

58. Lorenzo Rosa, et al., The water footprint of carbon capture and storage technologies. Renewable and Sustainable Energy Reviews, 2021. ***138***: p. 110511, https://doi.org/10.1016/j.rser.2020.110511.

59. Keju An, Azharuddin Farooqui, and Sean T. McCoy, The impact of climate on solvent-based direct air capture systems. Applied Energy, 2022. ***325***: p. 119895, https://doi.org/10.1016/j.apenergy.2022.119895.

60. Marwan Sendi, et al., Geospatial analysis of regional climate impacts to accelerate cost-efficient direct air capture deployment. One Earth, 2022. ***5***(10): p. 1153-1164, https://doi.org/10.1016/j.oneear.2022.09.003.

61. Valentina Stampi-Bombelli, Mijndert van der Spek, and Marco Mazzotti, Analysis of direct capture of CO_2 from ambient air via steam-assisted temperature–vacuum swing adsorption. Adsorption, 2020. ***26***(7): p. 1183-1197, https://doi.org/10.1007/s10450-020-00249-w.

62. John Young, et al., The impact of binary water–CO_2 isotherm models on the optimal performance of sorbent-based direct air capture processes. Energy & Environmental Science, 2021. ***14***(10): p. 5377-5394, http://dx.doi.org/10.1039/D1EE01272J.

63. John Young, et al., Process-informed adsorbent design guidelines for direct air capture. Chemical Engineering Journal, 2023. ***456***: p. 141035, https://doi.org/10.1016/j.cej.2022.141035.

64. Achintya R. Sujan, et al., Poly(glycidyl amine)-Loaded SBA-15 Sorbents for CO_2 Capture from Dilute and Ultradilute Gas Mixtures. ACS Applied Polymer Materials, 2019. ***1***(11): p. 3137-3147, https://doi.org/10.1021/acsapm.9b00788.

65. Jiazhu Luo, et al., Effective adsorption of Ultra-dilute CO_2 over Polyethyleneimine-based adsorbent for H_2 purification. Separation and Purification Technology, 2022. ***299***: p. 121686, https://doi.org/10.1016/j.seppur.2022.121686.

66. Noah McQueen, et al., A review of direct air capture (DAC): scaling up commercial technologies and innovating for the future. Progress in Energy, 2021. ***3***(3): p. 032001, https://dx.doi.org/10.1088/2516-1083/abf1ce.

67. Mai Bui, et al., Carbon capture and storage (CCS): the way forward. Energy & Environmental Science, 2018. ***11***(5): p. 1062-1176, http://dx.doi.org/10.1039/C7EE02342A.

68. Sonia Yeh and Edward S. Rubin, A review of uncertainties in technology experience curves. Energy Economics, 2012. ***34***(3): p. 762-771, https://doi.org/10.1016/j.eneco.2011.11.006.

69. Keywan Riahi, et al., Technological learning for carbon capture and sequestration technologies. Energy Economics, 2004. ***26***(4): p. 539-564, https://doi.org/10.1016/j.eneco.2004.04.024.

70. Mahdi Fasihi, Olga Efimova, and Christian Breyer, Techno-economic assessment of CO_2 direct air capture plants. Journal of Cleaner Production, 2019. ***224***: p. 957-980, https://doi.org/10.1016/j.jclepro.2019.03.086.

71. Abhishek Malhotra and Tobias S. Schmidt, Accelerating Low-Carbon Innovation. Joule, 2020. ***4***(11): p. 2259-2267, https://doi.org/10.1016/j.joule.2020.09.004.

72. John Young, et al., The cost of direct air capture and storage can be reduced via strategic deployment but is unlikely to fall below stated cost targets. One Earth, 2023. ***6***(7): p. 899-917, https://doi.org/10.1016/j.oneear.2023.06.004.

73. International Energy Agency (IEA), Executive Summary, in Direct Air Capture 2022. 2022, IEA: Paris (https://www.iea.org/reports/direct-air-capture-2022/executive-summary).

74. U.S. Energy Information Administration (EIA). Natural Gas: Dry Natural Gas Proved Reserves. Accessed July 2023. Published by U.S. EIA; Available from https://www.eia.gov/dnav/ng/ng_enr_dry_a_EPG0_r11_bcf_a.htm.

75. U.S. Energy Information Administration (EIA). Assumptions to the Annual Energy Outlook 2023: Oil and Gas Supply Module. 2023. U.S. EIA, Washington, DC; https://www.eia.gov/outlooks/aeo/assumptions/pdf/OGSM_Assumptions.pdf.

76. U.S. Energy Information Administration (EIA). Natural Gas Explained: Use of Natural Gas. Accessed July 2023. Published by U.S. EIA; Available from https://www.eia.gov/energyexplained/natural-gas/use-of-natural-gas.php.

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

78. Brian F. Snyder, Vulnerability to decarbonization in hydrocarbon-intensive counties in the United States: A just transition to avoid post-industrial decay. Energy Research & Social Science, 2018. ***42***: p. 34-43, https://doi.org/10.1016/j.erss.2018.03.004.

79. Max Vanatta, et al., The costs of replacing coal plant jobs with local instead of distant wind and solar jobs across the United States. iScience, 2022. ***25***(8): p. 104817, https://doi.org/10.1016/j.isci.2022.104817.

80. Travis Young, et al., Mining, loss, and despair: Exploring energy transitions and opioid use in an Appalachian coal community. Energy Research & Social Science, 2023. ***99***: p. 103046, https://doi.org/10.1016/j.erss.2023.103046.

81. Timothy Q. Donaghy, et al., Fossil fuel racism in the United States: How phasing out coal, oil, and gas can protect communities. Energy Research & Social Science, 2023. ***100***: p. 103104, https://doi.org/10.1016/j.erss.2023.103104.

82. Zana Cranmer, et al., Energy distributive injustices: Assessing the demographics of communities surrounding renewable and fossil fuel power plants in the United States. Energy Research & Social Science, 2023. ***100***: p. 103050, https://doi.org/10.1016/j.erss.2023.103050.

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

84. John Larsen, Whitney Jones, and Galen Hiltbrand. Capturing New Jobs and New Business: Growth Opportunities from Direct Air Capture Scale-Up. 2020. Rhodium Group, https://rhg.com/research/capturing-new-jobs-and-new-business/.

85. Sabine Fuss, et al., Negative emissions—Part 2: Costs, potentials and side effects. Environmental Research Letters, 2018. ***13***(6): p. 063002, https://dx.doi.org/10.1088/1748-9326/aabf9f.

86. Katie Lebling, et al. Direct Air Capture: Assessing Impacts to Enable Responsible Scaling (Working Paper). 2022. World Resources Institute., Washington, DC:; https://doi.org/10.46830/wriwp.21.00058.

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

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