An Atlas of Direct Air Capture

Opportunities for Negative Emissions in the United States

March 2023

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About Carbon Solutions

Carbon Solutions LLC is a low-carbon energy startup using cutting-edge research and development and software and services to address energy challenges, including carbon capture and storage, geothermal energy, wind energy, biofuels, energy storage, and the hydrogen economy. Carbon Solutions aims to accelerate low-carbon energy infrastructure development in the US. The Carbon Solutions business vision is focused on three integrated pillars: research and development that advances low-carbon energy science, software development that generates unique tools and data, and services that apply our research and development and software to address emerging energy challenges for our clients.

Learn more: carbonsolutionsllc.com

Graphic design and layout by Elizabeth Abramson

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As a nonpartisan, nonprofit organization, the Great Plains Institute (GPI) is transforming the energy system to benefit the economy and environment. Working across the US, we combine a unique consensus-building approach, expert knowledge, research and analysis, and local action to find and implement lasting solutions. Our work strengthens communities and provides greater economic opportunity through creation of higher-paying jobs, expansion of the nation's industrial base, and greater domestic energy independence while eliminating carbon emissions.

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Abramson, McFarlane, et al., *An Atlas of Direct Air Capture: Opportunities for Negative Emissions in the United States* (Carbon Solutions LLC & Great Plains Institute, March 2023).

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Nationwide Siting Assessment for Direct Air Capture of Carbon Dioxide

This analytical atlas explores areas of the United States that may be best suited to the development and placement of direct air capture (DAC) facilities that achieve net-negative carbon sequestration.

To achieve global climate goals by midcentury, technologies that remove carbon directly from the atmosphere will likely be needed not only to offset continued emissions from sectors that are difficult to decarbonize through traditional strategies but also to draw down high levels of carbon dioxide (CO_2) accumulated in the Earth's atmosphere.

Negative emissions solutions such as afforestation, land use management, bioenergy with carbon capture and storage, and DAC or other carbon dioxide removal technologies will likely be needed to limit global temperature rise to 1.5°C to 2°C.[1]

This atlas examines 17 key factors that impact regional suitability for developing DAC technology and associated infrastructure. Through this analysis, several major regions emerge as prime locations to develop regional DAC hubs, each with unique advantages. This atlas details these siting factors and the identified areas of opportunity across the United States.

Regional opportunity for DAC hub development

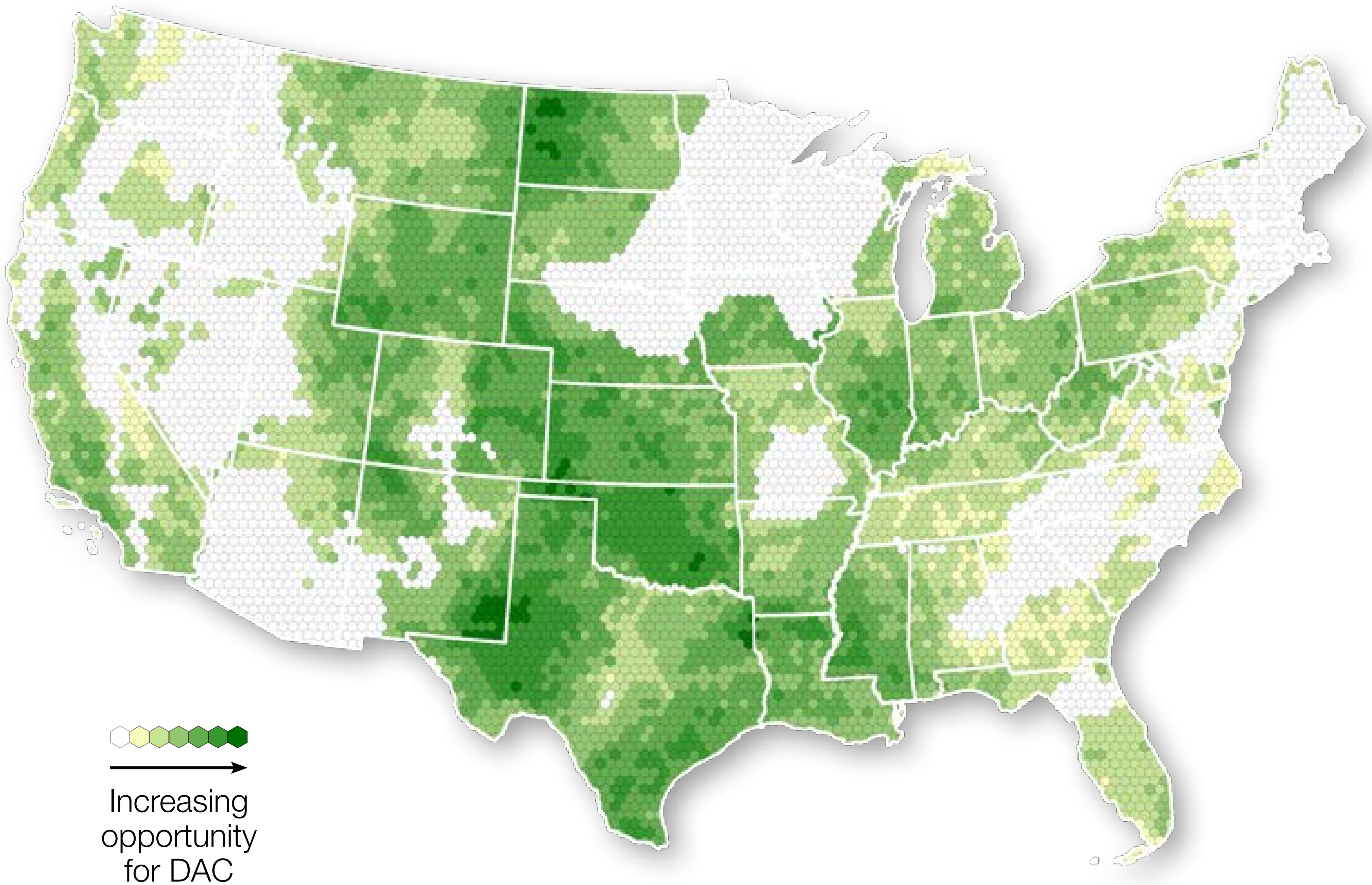

Figure authored by Carbon Solutions, 2023.

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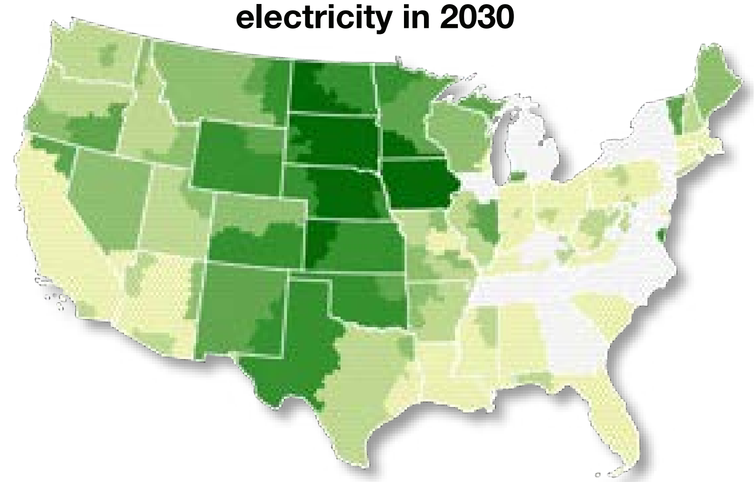
Executive Summary | DAC Siting Across Six Categories

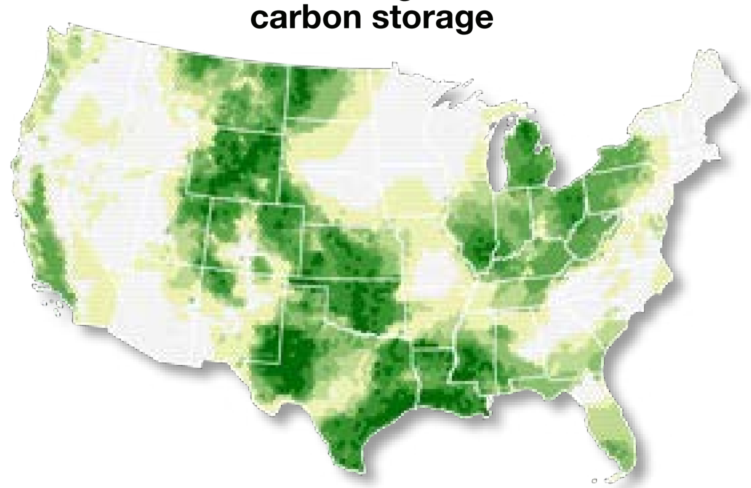
This analysis calculated DAC suitability scores for 17 key siting considerations across six categories. The resulting scores for each category are shown here, with the electricity category split into two maps for 2030 and 2050. An overall DAC suitability score was calculated by aggregating the scores from all six categories.

Low-carbon electricity in 2030

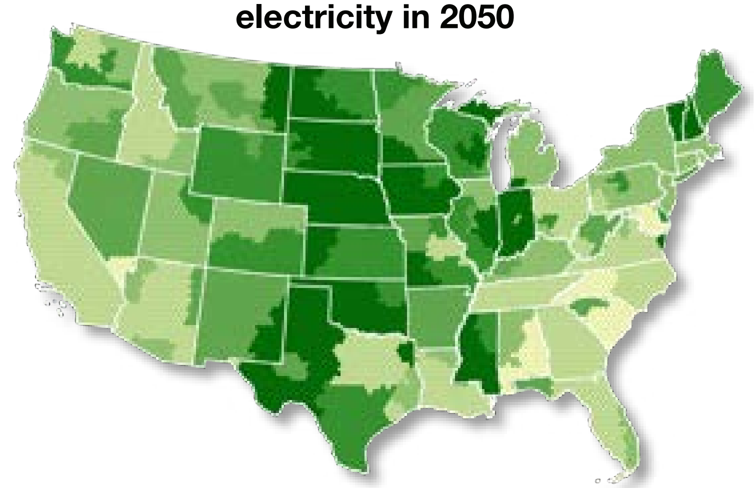


Waste heat recovery

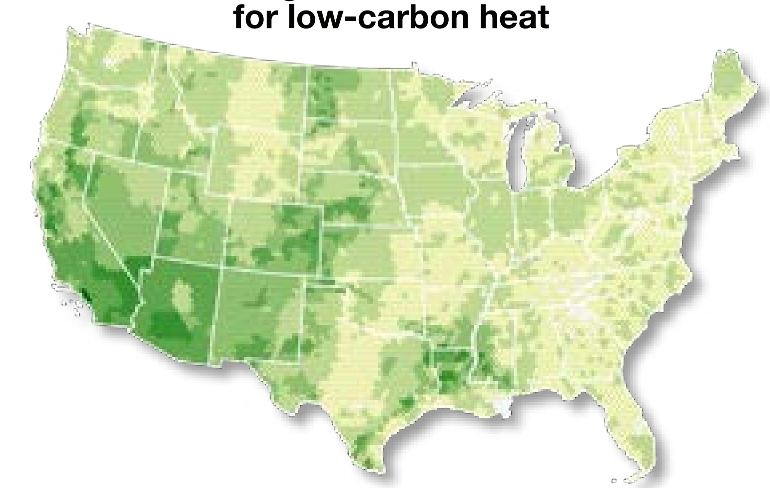
Geologic carbon storage



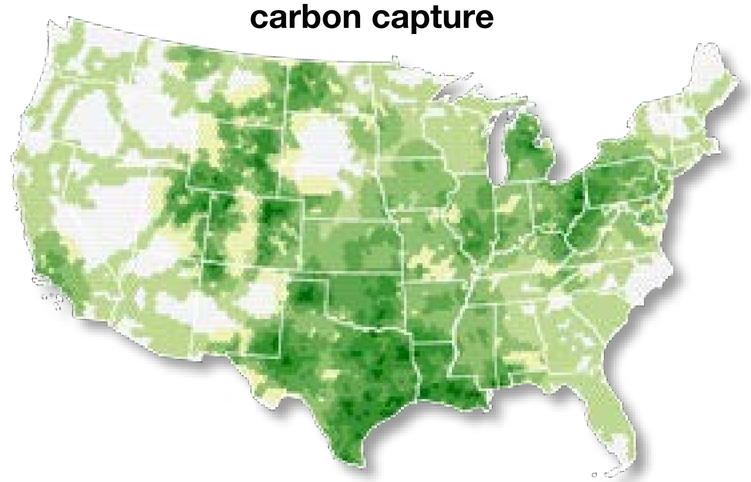
Low-carbon electricity in 2050



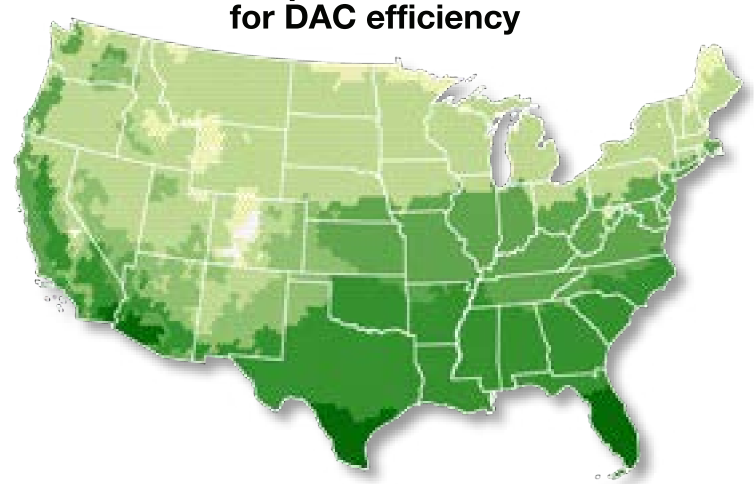
Regional resources for low-carbon heat

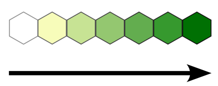


Heat sources with carbon capture



Atmospheric conditions for DAC efficiency





Increasing opportunity for DAC

Figures authored by Carbon Solutions, 2023.

Acronym Guide

BECCS	—	Bioenergy with CCS
CCS	—	Carbon capture and storage
CHP	—	Combined heat and power
CO_2	—	Carbon dioxide
CO_2e	—	Carbon dioxide equivalent
DAC	—	Direct air capture
DOE	—	US Department of Energy
EIA	—	US Energy Information Agency
EOR	—	Enhanced oil recovery
EPA	—	US Environmental Protection Agency
FOA	—	Funding opportunity announcement
GHG	—	Greenhouse gas
GHGRP	—	EPA GreenHouse Gas Reporting Program
$GtCO_2$	—	Gigaton (1 billion metric tons) CO_2
HIFLD	—	Homeland Infrastructure Foundation-Level Data
IEA	—	International Energy Agency
IPCC	—	United Nations Intergovernmental Panel on Climate Change
kWh	—	Kilowatt-hour
$MtCO_2$	—	1 million metric tons CO_2
MWh	—	Megawatt-hour
NATCARB	—	National Carbon Sequestration Database and Geographic Information System
NETL	—	National Energy Technology Laboratory
NREL	—	National Renewable Energy Laboratory
RDI	—	Regional Deployment Initiative
ReEDS	—	NREL Regional Energy Deployment System model
tCO_2	—	Metric tons CO_2
WHR	—	Waste heat recovery

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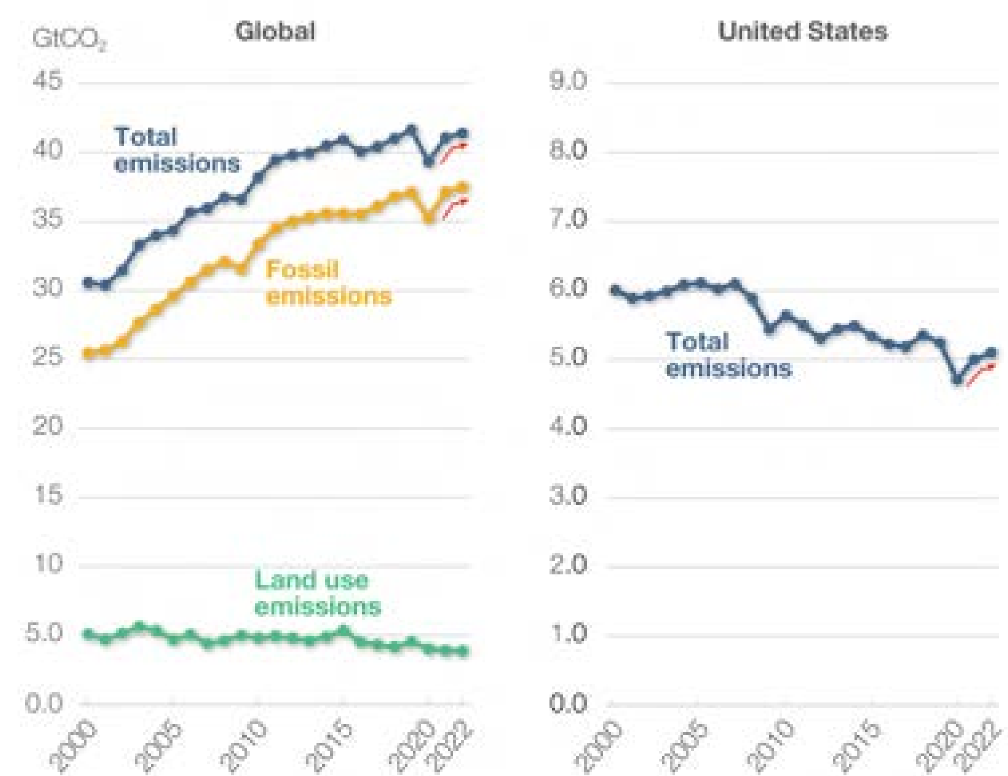
The Need for Direct Air Capture of Carbon Dioxide

Achieving national and international climate targets will likely require technologies that remove carbon directly from the atmosphere. These technologies will be needed not only to offset future emissions from sectors of the economy that are slow or unlikely to decarbonize by midcentury but also to capture atmospheric carbon dioxide (CO_2) from legacy emissions that have already accumulated in the atmosphere. New investment and significant efforts will likely be needed to scale up negative emissions solutions such as afforestation, land use management, bioenergy with carbon capture and storage (BECCS), and direct air capture (DAC) or other carbon dioxide removal technologies to limit global temperature rise to 1.5°C to 2°C.[2]

Rising global emissions

Despite widespread consensus that the world must rapidly reduce emissions, global and US greenhouse gas emissions increased in both 2021 and 2022.[3] These emissions increases largely represent restored economic activity, energy demand, and travel after a low point in 2020 resulting from the COVID-19 pandemic. While nations around the world have pledged to decouple their emission rates from economic growth, continued economic development and population growth are likely to fuel continued emissions increases in the near term.

Global and US emissions trends



Global carbon emissions from fossil fuel combustion rose from 35.3 gigatons CO_2 ($GtCO_2$) in 2020 to 37.1 $GtCO_2$ in 2021 and were estimated to have reached 37.5 $GtCO_2$ in 2022. Emissions from land use change show only a slight decline over the same period.

US emissions from fossil fuel combustion rose from 4.7 $GtCO_2$ in 2020 to 5.0 $GtCO_2$ in 2021 and were estimated to have reached 5.1 $GtCO_2$ in 2022.

Figure authored by Carbon Solutions (2023) based on Global Carbon Project (2022).

Economic development and growth in global demand are likely to fuel continued emissions growth over the next decades, requiring negative emissions to achieve global climate goals or net-zero targets.

US Energy Information Administration (EIA) projections published in their *2022 Annual Energy Outlook* indicate a continued modest decline in US domestic energy-based emissions in the near term due to electric sector decarbonization, increased transportation efficiency, and behavior change.[4] Emissions are projected to rise again in the *Outlook's* reference case and other primary scenarios after 2030 without significant new climate and energy policies.

US emissions projected to rise after 2030

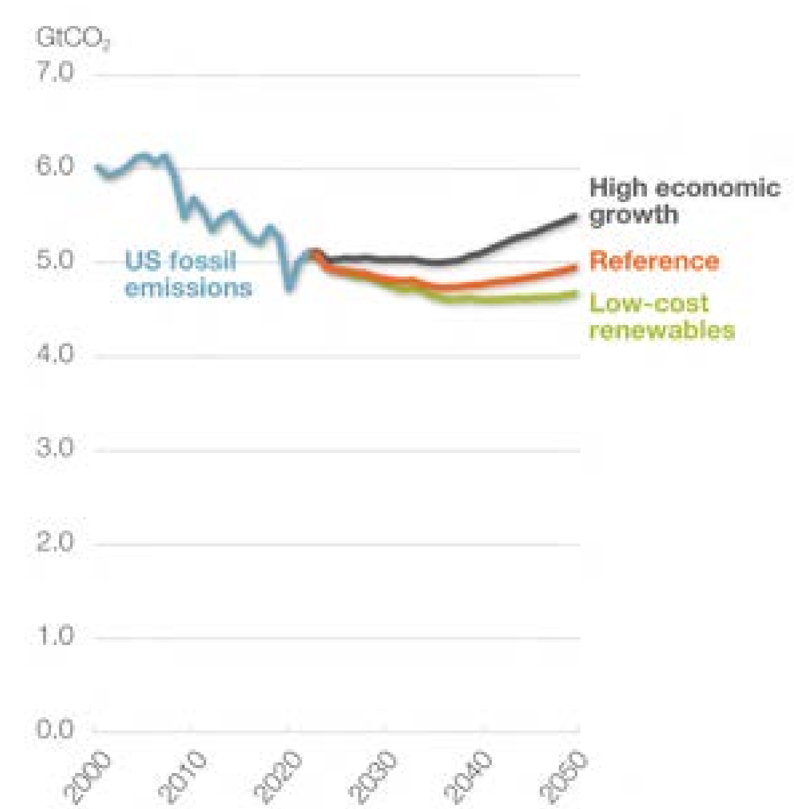


Figure authored by Carbon Solutions (2023) based on Global Carbon Project (2022); EIA Annual Energy Outlook 2022 (November 2022).

The Need for Direct Air Capture of Carbon Dioxide (cont.)

Slow-to-decarbonize sectors

The chemical and mechanical aspects of the production processes for many industrial operations, such as cement production, iron and steel manufacturing, petroleum refining, and basic chemical production, make it highly challenging to abate emissions by switching to low-carbon energy sources. Such industrial processes often have limited or no abatement options beyond carbon capture retrofit and CO_2 removal technologies. Negative emissions from DAC can be used to achieve net zero in a world that still requires cement, steel, and other industrial materials with a positive carbon intensity. With current policies, global industrial emissions are projected to grow from 9.3 $GtCO_2$ in 2021 to 9.7 $GtCO_2$ in 2050.[7]

Global industrial emissions, 2050

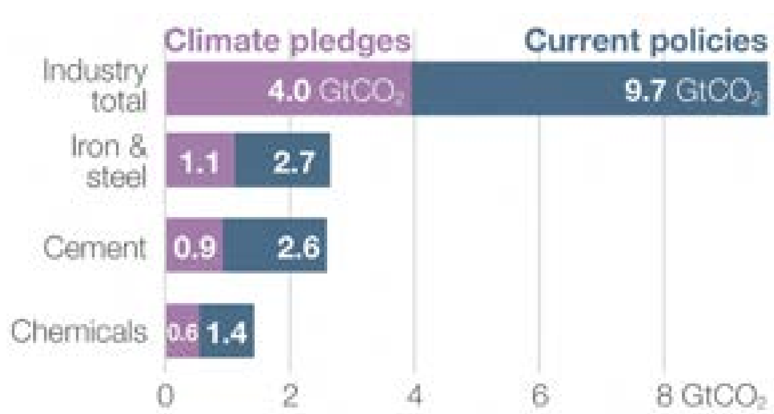


Figure authored by Carbon Solutions (2023) based on IEA *World Energy Outlook 2022* (2022).

The world's remaining carbon emissions budget

UN Intergovernmental Panel on Climate Change (IPCC) carbon budgets illustrate the world's remaining ability to achieve global temperature goals.[5] To ensure at least an 83 percent chance of limiting average global temperature rise to 1.5°C above preindustrial levels, the international community must limit its total remaining emissions to about 180 $GtCO_2$. At current emission rates of 41.4 $GtCO_2$ per year, this 1.5°C carbon budget would run out in less than five years.[6] **A goal of limiting temperature rise to 2°C (83 percent chance) would mean a remaining carbon budget of 780 $GtCO_2$, lasting 18 years at current emission rates.**

A global goal to achieve only a 50 percent chance of limiting temperature rise to 2°C would allow for a global carbon budget of 1,230 $GtCO_2$, lasting 30 years at current rates.

If global emissions exceed the carbon budget and global temperature surpasses 1.5°C or 2°C, net-negative emissions from CO_2 removal technologies like DAC would be required to restore atmospheric concentrations of greenhouse gases (GHGs) to sustainable levels.

The global carbon budget

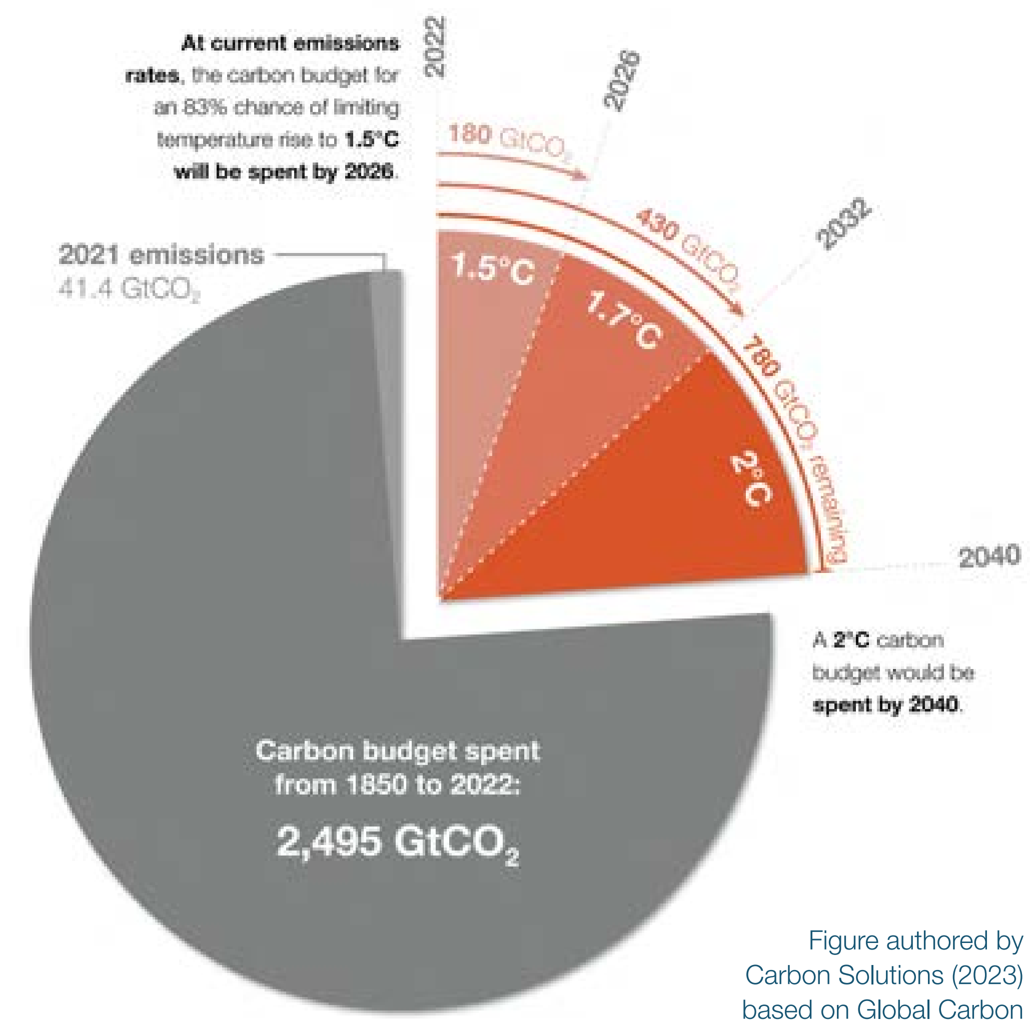


Figure authored by Carbon Solutions (2023) based on Global Carbon Project (2022); IPCC (2021).

Negative emissions technologies like DAC would be required to limit temperature rise to 2°C if global emissions exceed the remaining 18-year carbon budget.[8]

The Role of Carbon Dioxide Removal, Negative Emissions, and DAC in the Global Carbon Budget

The world's ability to achieve its climate goals is influenced by a complex array of pressures driving emissions down in some sectors of the economy and up in others. Analyses from the IPCC and the International Energy Agency (IEA) indicate that negative emissions, DAC, and carbon capture deployment will likely be essential to reaching net-zero global emissions by 2050. In the graph to the right, which is based on the IPCC's P4 scenario, lingering GHG emissions in the coming decades require significant offsets from negative emission strategies and technologies to reach net zero by midcentury.[9]

Negative emissions through carbon removal via DAC and BECCS account for 1.9 $GtCO_2$ in the IEA's Net Zero 2050 Scenario and a range of 3.5 to 16 $GtCO_2$ in the IPCC 2050 scenarios.[10]

Additionally, carbon capture, utilization, and storage, which might share common CO_2 transport infrastructure and storage with DAC operations, achieves annual capture of 7.6 $GtCO_2$ in 2050 in the IEA's net-zero scenario, and a median level of 15 $GtCO_2$ of capture in 2050 in IPCC climate scenarios.[11]

Negative emissions needed to offset temperature overshoot

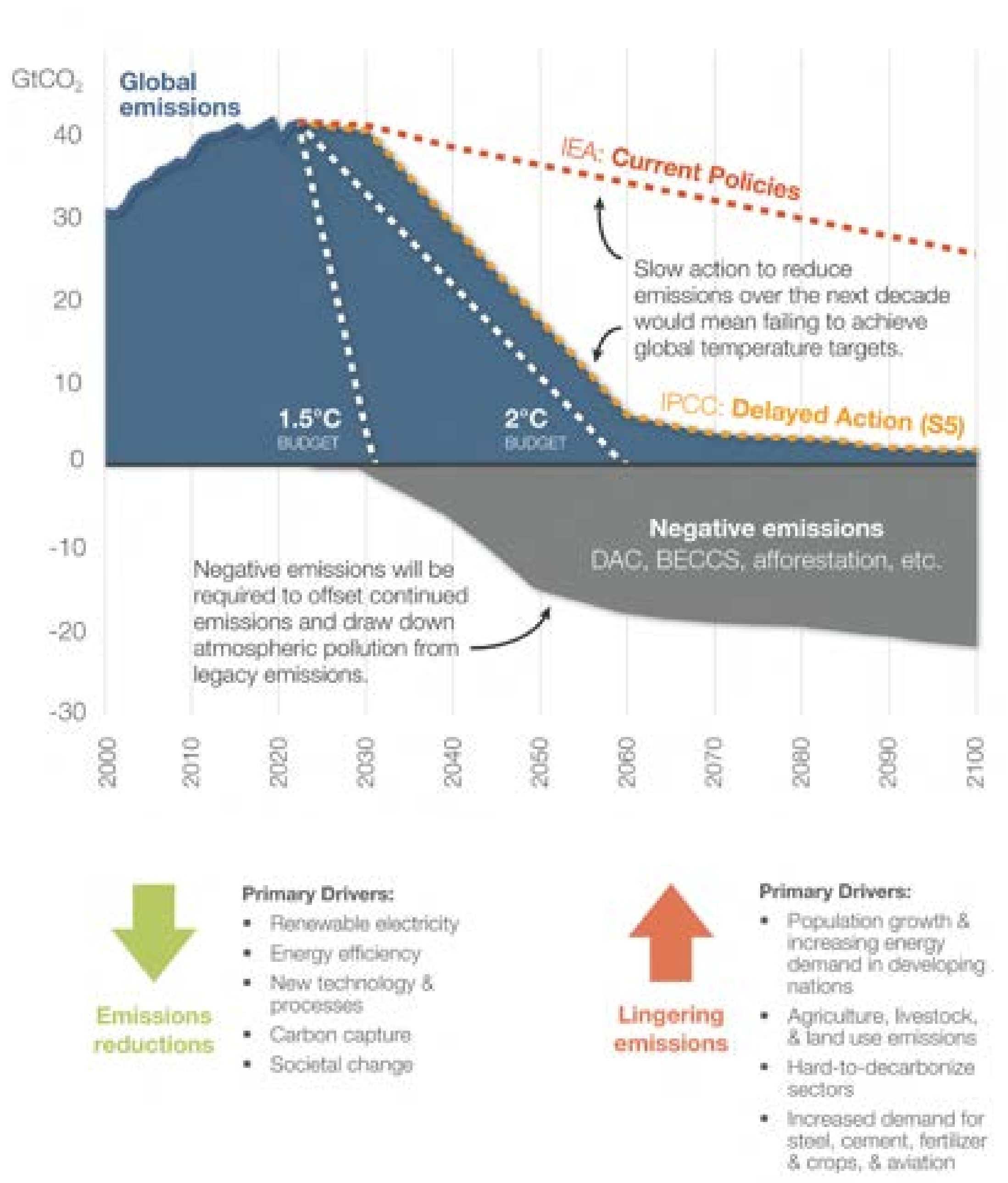


Figure authored by Carbon Solutions (2023) based on Global Carbon Project (2022); IPCC (2018; 2021); IEA (November 2022).

Across IPCC and IEA scenarios, **the need for carbon capture and removal is minimal only when emissions from land use, agriculture, livestock, and afforestation achieve net-negative emissions in the near term.** However, global food and crop demand, which is expected to increase by 35–56 percent by 2050, will be a major determinant of emissions trends in the land use sector.[12] This will likely strain the international community's ability to achieve net sequestration of emissions through land management and biosphere carbon uptake.

Other factors include the relative demand for meat and livestock in global diets, the extent to which certain land management or farming practices (e.g., no-till agriculture) are adopted, reforestation and deforestation rates, and other terrestrial feedbacks such as Arctic permafrost decline.

In the United States, estimates for net emissions from land use vary widely between accounting or modeling methods, resulting in estimates of both net-negative and net-positive emissions depending on the model used.

What is Direct Air Capture?

Direct air capture (DAC) facilities remove CO_2 from the atmosphere and prepare it for transport or permanent and secure geologic carbon storage. Captured CO_2 can also be used in industrial applications or to create synthetic fuel and materials. To capture and compress CO_2, DAC facilities require energy for electricity and heat, both of which can be supplied by low- or zero-carbon sources to make the process carbon-negative.

Multiple types of DAC technologies have been developed or are currently being researched. These can be generally categorized as low-temperature, high-temperature, and electric-only systems. Low-temperature DAC systems typically use solid materials, called sorbents, to capture CO_2, whereas high-temperature systems may use a liquid solvent. Thermal energy (heat) is needed to recover the CO_2 from the sorbent or solvent.

The table below provides the performance and energy requirements per metric ton of CO_2 captured for the three types of DAC systems mentioned above.

Performance and requirements of DAC systems

	Low-Temperature DAC	High-Temperature DAC	Electric-Only DAC
Temperature demand of thermal energy[13]	100°C	900°C	N/A
Electrical energy demand[14] electrical kilowatt-hour (kWh) per metric ton CO_2 (tCO_2)	22 to 1053 kWh / tCO_2	205 to 460 kWh / tCO_2	1,500 kWh / tCO_2
Thermal energy demand[15] thermal kWh per metric ton CO_2	513 to 5,361 thermal kWh / tCO_2	2,664 to 3,500 thermal kWh / tCO_2	N/A
Range of facility capacity[16] metric ton CO_2 per year	10,000 to 1 million tCO_2 / year	1 million tCO_2 / year	1 million tCO_2 / year

Source: An, Farooqui, and McCoy, “The impact of climate on solvent-based direct air capture systems”; Fasihi, Efimova, and Breyer, "Techno-economic assessment of CO_2 direct air capture plants"; National Academies of Sciences, Engineering, and Medicine, *Negative Emissions Technologies and Reliable Sequestration: A Research Agenda*.

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What is Direct Air Capture? (continued)

A DAC facility houses the equipment needed to move large volumes of air over specialized material that separates CO_2 from the surrounding ambient air. It can also contain equipment that collects other process materials for reuse. DAC facilities are designed to maximize contact between air and the CO_2 separation material located at the air contactor (see figure at right).

A typical low-temperature DAC system might consist of many fans and chambers containing a contactor with solid sorbent inside. In the first phase of the capture process, a fan draws air into the contactor, where CO_2 is adsorbed to the solid material. In the second phase, the container with the contactor is sealed and heated to desorb or separate the CO_2 from the sorbent. Vacuum pressure is applied to remove the CO_2, which is then condensed, compressed, and transported for storage or use. The heat required for this process is around 100°C. Low-temperature systems require manual maintenance of the solid sorbents, unlike high-temperature liquid systems.

A high-temperature DAC system can be designed to run continuously, with liquid solvent from individual contactors transported to a central unit where chemical reactions remove the CO_2 under high heat and then deliver the solvent for reuse. In a design by Carbon Engineering, the liquid solvent reacts with air containing CO_2 and is then transported to reactors where calcium carbonate pellets are formed while the original liquid solvent is regenerated.[17] Running this calciner loop requires temperatures of around 900°C. Once out of the calciner loop, the captured CO_2 is condensed and compressed for transport, use, or storage.

Components of a direct air capture facility: High-temperature versus low-temperature systems

This figure illustrates commonalities and differences between high-temperature and low-temperature DAC processes. This figure is not meant to imply that both systems would be employed at a single facility.

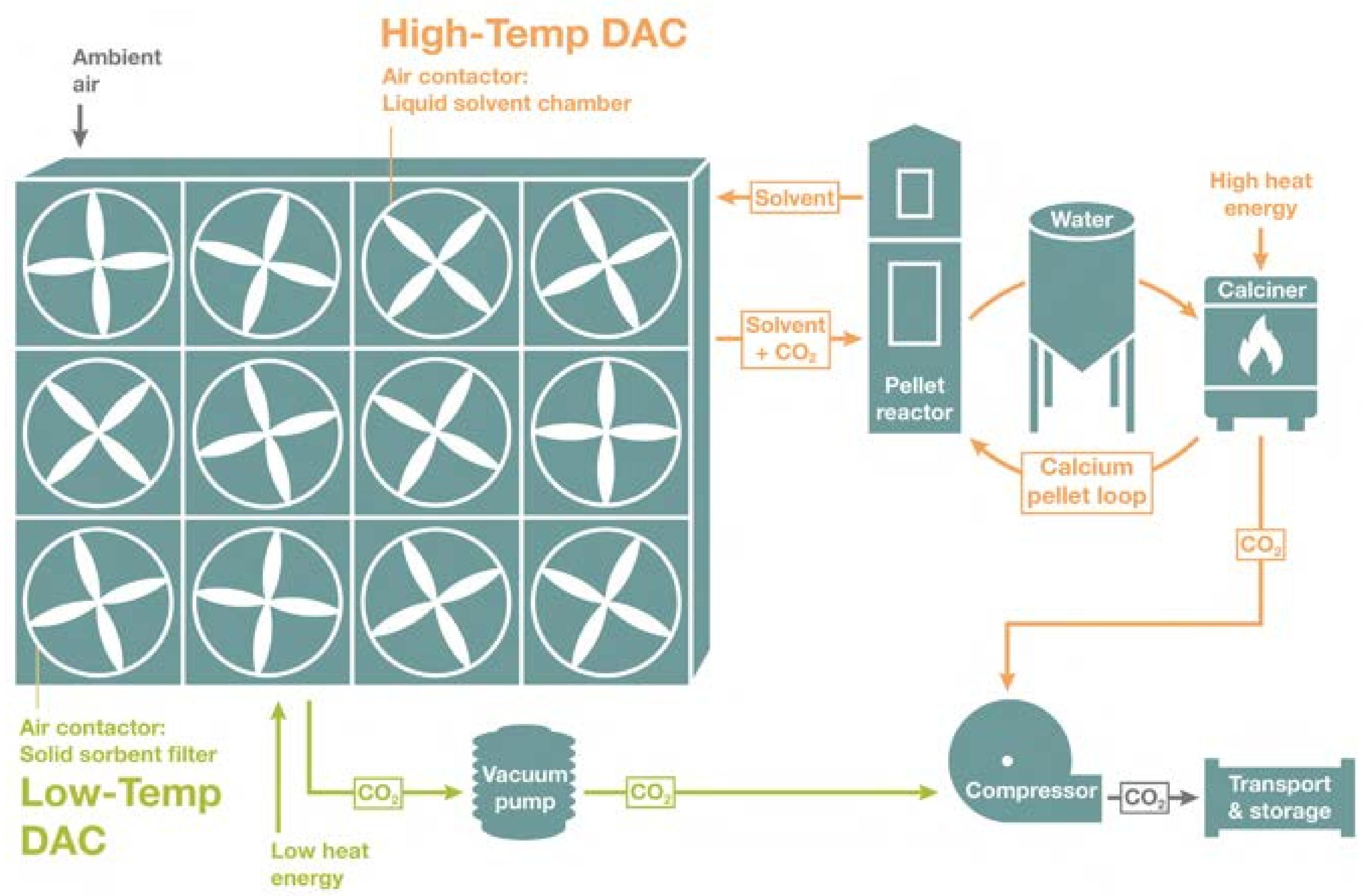


Figure authored by Carbon Solutions, 2023.

US Department of Energy DAC Hubs Program

The Infrastructure Investment and Jobs Act authorizes the US Department of Energy (DOE) and the National Energy Technology Laboratory (NETL) to direct $3.5 billion during fiscal years 2022 to 2026 toward the development of four regional DAC hubs.

Regional DAC hubs may contain a network of DAC projects, potential CO_2 storage options, and transport infrastructure. The first funding opportunity announcement (FOA) for these projects was issued on December 13, 2022, with a second FOA expected in 2024 or later.

Establishing regional DAC hubs may occur in tandem with developing a backbone system of shared CO_2 transport and storage infrastructure, enabling achievement of large-scale net-negative emissions goals and cost-effective economies of scale. Each DAC hub would have a goal of achieving capture and storage capacity of one million metric tons of CO_2 per year, either from a single facility or multiple connected facilities. Similar programs are underway under the Infrastructure Investment and Jobs Act to develop regional clean hydrogen hubs and large-scale carbon capture and storage projects.

The DAC hubs program will support domestic supply chains and manufacturing, the creation of good-paying jobs, and workforce development such as registered apprenticeships. Projects with the greatest lifetime net climate benefit will be given preferential consideration, with lifecycle analyses forming the basis for evaluating the net CO_2 removal of the system.

Other aspects of DAC hub selection include:

- Carbon intensity of local industries
- Geographic diversity of hubs
- Carbon sequestration or utilization potential
- Availability of renewable and low-carbon energy production
- Land and water resources, and existing infrastructure
- Hubs in economically distressed, fossil-producing regions with high levels of coal, oil, or natural gas resources
- Scalability of the proposed project (greater capacity, lower cost per tCO_2 removed)
- Skilled training and long-term employment opportunities for greatest number of residents of the region
- Fit of the site(s) from a social and environmental justice standpoint

There are several CO_2 removal technologies in addition to DAC that may be included in a regional hub, including biomass carbon removal and storage, soil carbon sequestration, afforestation and reforestation, and ocean-based carbon removal, also referred to as direct ocean capture, but these types of projects will not be directly funded under this FOA.

US Department of Energy DAC Hubs Program (continued)

The three topic areas in the FOA for regional DAC hubs are designed to allow the US DOE to fund projects in various maturity phases.

The first topic (TA-1) funds feasibility, analysis, networking, and stakeholder engagement. The second topic (TA-2) is for projects that are further along on these components but require time for front-end engineering design and to advance permitting. The third topic (TA-3) is for even more mature projects and will provide funding for permitting, compliance, and detailed design activities.

Cost-sharing is required, with a maximum federal contribution of 80 percent for TA-1 and 50 percent for TA-2 and TA-3.

All projects under these topics must meet the same technical requirements and community engagement obligations. Analyses like the one featured in this atlas can help evaluate the technical and physical feasibility of proposed DAC hub locations.

US DOE regional DAC hubs timeline

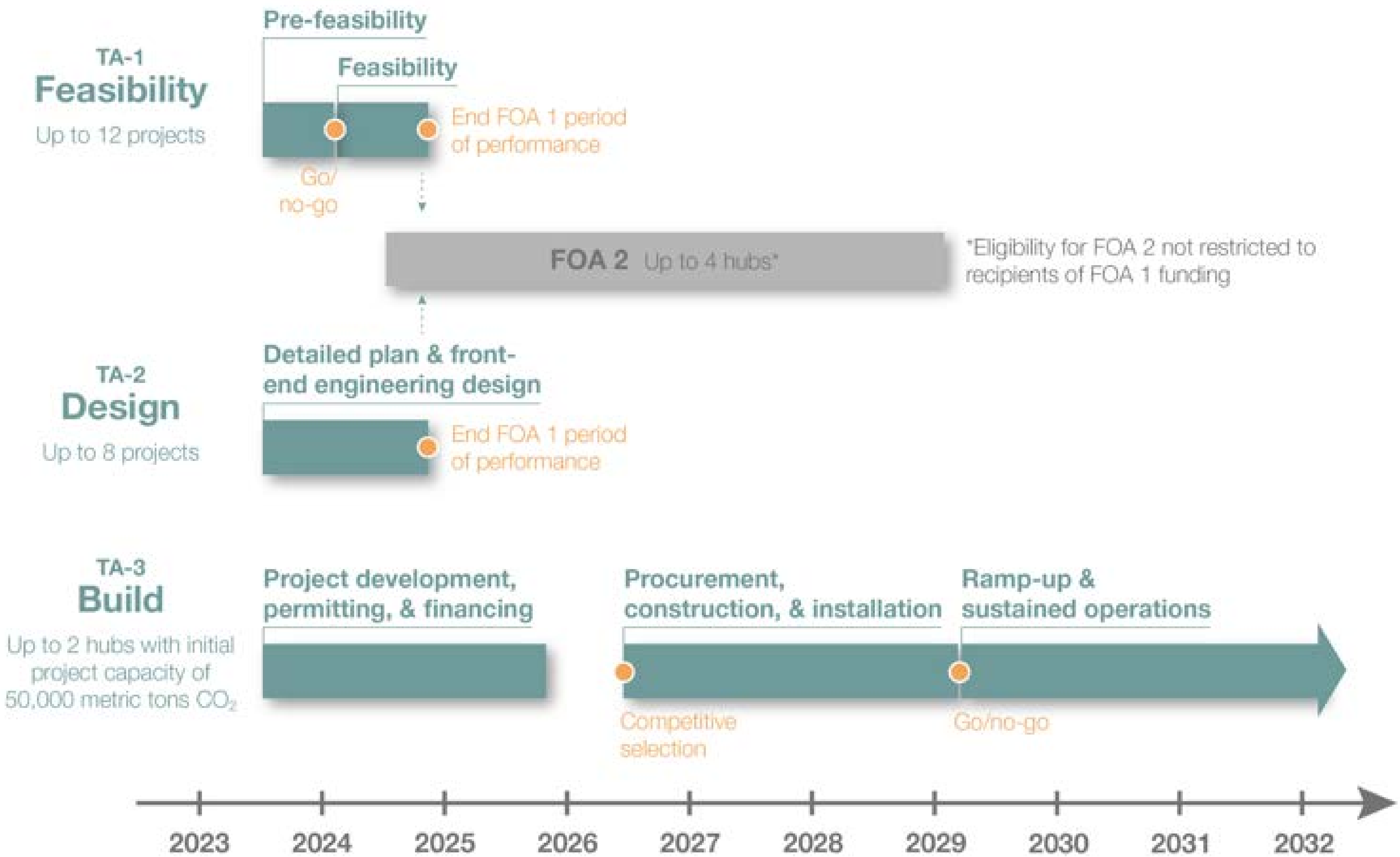


Figure authored by Carbon Solutions (2023) based on DOE Office of Fossil Energy and Carbon Management, Funding Opportunity Announcement Number: DE-FOA-0002735 (2022).

Equity, Environmental, and Energy Justice

Projects funded under US DOE's DAC hubs program must include equity, environmental, and energy justice principles, including continuous meaningful community and labor engagement. These DAC projects will contribute to the federal government's Justice40 Initiative, a whole-of-government plan to ensure that 40 percent of overall benefits of certain types of investments benefit disadvantaged communities who have been historically marginalized, underserved, and overburdened by pollution.[18]

Metrics used by the Justice40 Initiative and DOE to identify disadvantaged communities include indicators of health, housing, legacy pollution, transportation, water/wastewater, workforce development, energy, and climate change, as well as federally recognized tribes and Alaska Native villages. These have been combined into a dataset by the Council on Environmental Quality.[19]

Multiple requirements under the DOE FOA for regional DAC hubs are designed to advance equity, environmental, and energy justice principles and ensure that DAC is deployed responsibly. Projects must complete an in-depth environmental pollution impact assessment, study cumulative pollution including non-CO_2 contamination of air, water, and soil, and track and report outcomes related to community benefits. A community benefits plan is required and has specific criteria for development, implementation, and updates throughout the project.

Disadvantaged communities

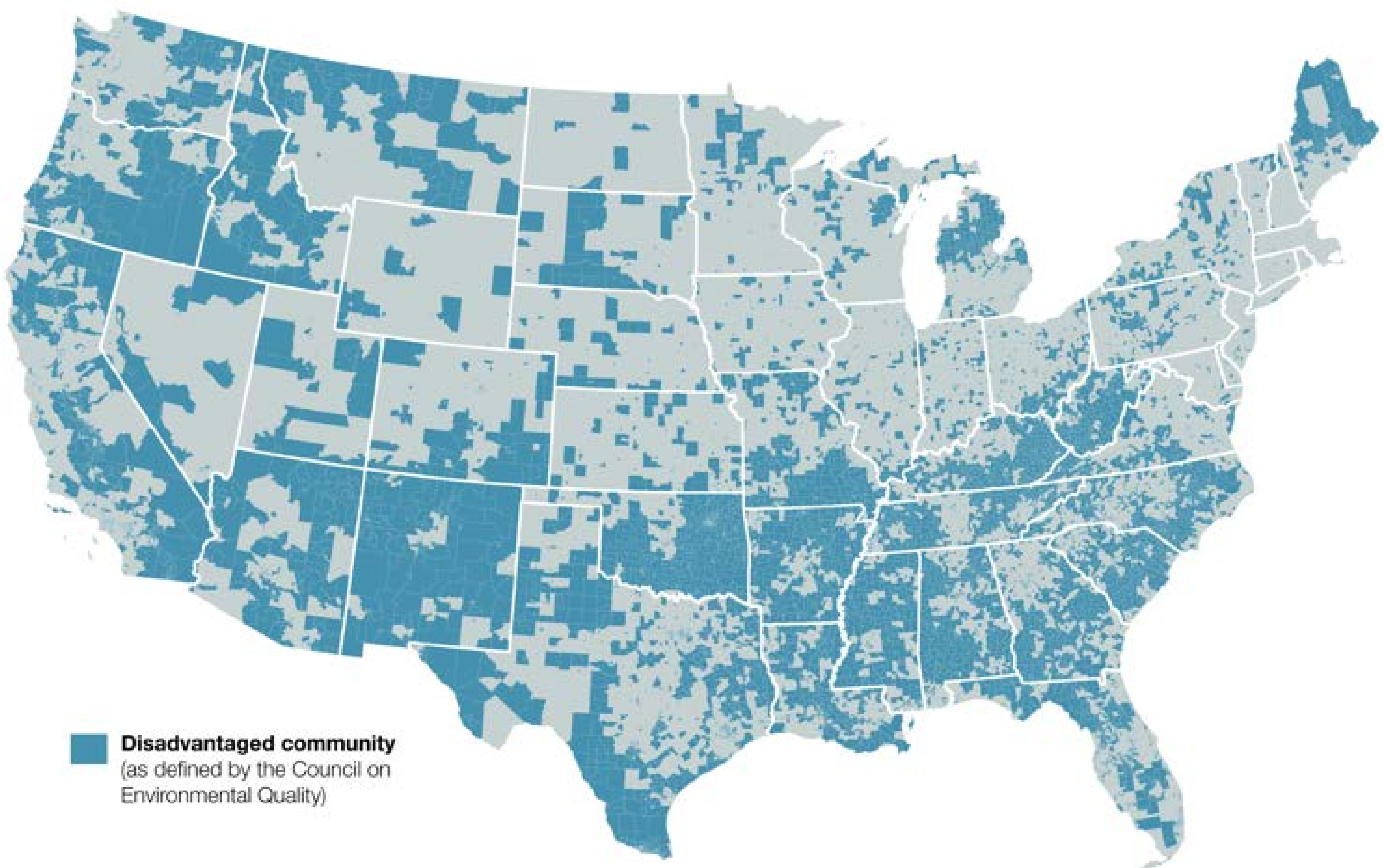


Figure authored by Carbon Solutions (2023) based on Council on Environmental Quality (November 2022).

Siting Considerations for Net-Negative Carbon DAC

The goal of this atlas is to identify optimal areas for regional DAC hubs. For this purpose, Carbon Solutions analysts collected geographic data across a number of feasibility and performance considerations to rank regions of the US for DAC siting suitability according to a common scoring system.

Each physical or technical factor was given a score in this study based on its contribution to DAC suitability (detailed on the next page). These scoring layers were then combined and summed to identify areas of the US with the potential for efficient, cost effective, and successful DAC systems that maximize net-negative carbon emissions. Ideal locations for regional DAC hubs will have most of these characteristics to optimize the performance of these systems at large scales. Siting considerations that improve DAC efficiency and performance include the following:

- Proximity to **geologic CO_2 storage**: this includes proximity to geologic saline formations as well as oil fields with historical enhanced oil recovery (EOR) potential, current activity, or depleted reservoirs.

- Existing **CO_2 transport** infrastructure and proximity to other commodity transport infrastructure to utilize existing right-of-way for new investments.

- Regional resources for **low-carbon sources of electricity**, including electric grid carbon intensity, capacity to meet expected electric load, price of electricity, and renewable energy potential.

- Regional resources for **low-carbon sources of heat**, including geothermal, biomass, and concentrated solar, along with **natural gas infrastructure and power plants** with potential for **carbon capture and storage** (CCS) retrofit.

- Electric power and industrial facilities with potential for **waste heat supply** or combined heat and power (CHP).

- Optimal **climate and atmospheric conditions** for DAC system operation. This study highlighted hot, humid areas favorable for high-temperature liquid solvent DAC system operation.

While not scored in this atlas, additional considerations for DAC siting include water consumption and land use.

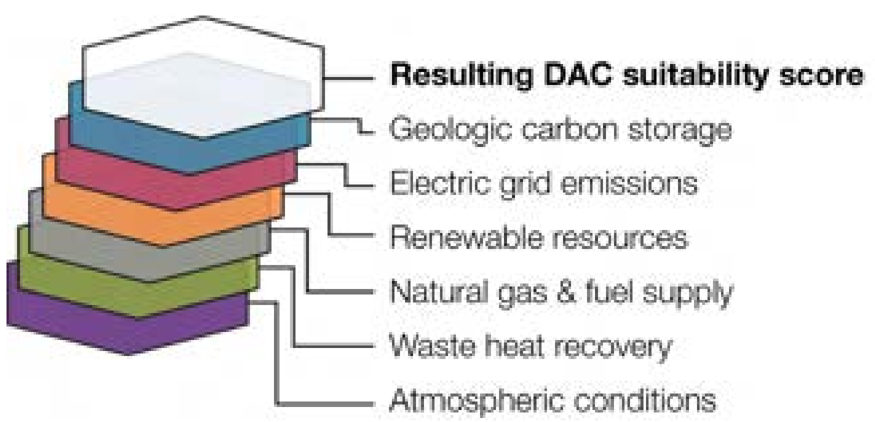
Both low- and high-temperature DAC systems require water as part of their cycles of operation and regeneration. However, water demand estimates vary widely depending on local conditions and DAC system design. In many cases, water use at DAC facilities can be minimized through recirculation and reuse, and some low-temperature DAC system designs actually capture water, producing it as a byproduct.[20] One such proposed technology would capture 0.8 to 2 million metric tons (Mt) of water (0.6 to 1.5 billion gallons) per $MtCO_2$ captured.[21] A study of another hypothetical low-temperature DAC facility was estimated to require 1.6 Mt of water (1.2 billion gallons) per $MtCO_2$ captured.[22] Estimates for water loss due to evaporation at high-temperature DAC systems ranged from 4.7 Mt (3.5 billion gallons) to 8.2 Mt of water (6.1 billion gallons) needed per $MtCO_2$ captured, among varying DAC system designs.[23]

While land constraints and competition affect nearly every negative emissions technology, DAC generally requires less land use than BECCS and afforestation.[24] Land use needs for DAC are primarily determined by the type of low-carbon energy used for power and heat. DAC facilities themselves occupy a comparatively small footprint.

Estimated direct facility land use for a 1 Mt per year low-temperature DAC facility ranges from 0.3 to 2 square miles.[25] These estimates include land use for air contactor arrays, mandatory spacing between the arrays, and other facility operations, but do not include land use for clean energy supply. One study estimates a 0.01 square mile footprint for direct facility land use for a 1 Mt per year high-temperature DAC facility.[26] In one report, achieving a 1 $GtCO_2$ per year DAC capacity through multiple low-temperature DAC facilities required an estimated 24 square miles.[27]

DAC Siting Consideration Scoring Methodology

This analysis examines 17 key siting considerations that influence the performance and efficiency of DAC facilities. These key metrics are scored across a grid of hexagonal cells that span the contiguous United States. For each siting consideration, a grid cell typically receives a score from zero to four, with zero being the least suitable and four being the most. The score for each cell is then aggregated to produce a subtotal score for each broader siting consideration category (e.g., geologic carbon storage and transport infrastructure, electric energy grid factors, as shown in the table to the right). The range of scores for a category varies depending on the number of data layers in the category. All scores are finally aggregated to produce an overall DAC suitability score reflecting the sum of all categories.



The table to the right shows each siting consideration included in this analysis and its associated scoring approach. Additional details about the data sources and rankings are provided with each map on the following pages. See the appendix for a detailed scoring methodology.

DAC suitability: National grid cell scoring considerations

Siting Consideration	Criteria for Highest Score	Score Range From 0 to:
Geologic carbon storage and transport infrastructure		**14**
Saline formation storage	Cell contains SCO_2T^{PRO} model screened saline formations	4
Oil/gas reservoir storage	Cell contains NATCARB oil and gas formation storage data	4
Potential enhanced oil recovery (EOR) site	Cell close to oil field with current or potential EOR activity	4
Existing CO_2 pipeline	Cell close to existing CO_2 pipeline	2
Electric energy grid factors (separate scores for 2030 and 2050 projections)		**24**
Availability of excess electricity, 2030 & 2050	Cell within NREL ReEDS model result for positive net generation above electric load	4, 4
Electric carbon intensity, 2030 & 2050	Cell within NREL ReEDS model result for low carbon intensity	4, 4
Price of electricity, 2030 & 2050	Cell within NREL ReEDS model result for low price of electricity	4, 4
Regional resources for low-carbon heat		**16**
Hydrothermal or enhanced geothermal	Cell contains area with high subsurface temperature	4
Sedimentary basin geothermal	Cell contains area with high sedimentary basin geothermal potential	4
Biomass	Cell contains area with high biomass availability	4
Solar	Cell contains area with high solar irradiance	4
Natural gas availability for heat with carbon capture		**12**
Near-term power plant CCS candidate	Cell close to near-term power sector carbon capture retrofit candidate	4
Natural gas processing plant	Cell close to natural gas processing plant	4
Natural gas pipeline	Cell close to natural gas pipeline	4
Electric power and industrial facilities with waste heat supply or combined heat and power (CHP)		**4**
Existing or potential CHP facility	Cell contains existing or potential CHP/waste heat recovery facility	4
Atmospheric conditions		**4.5**
Air temperature	Cell contains area with high temperature	4
Humidity	Cell contains area with high humidity	0.5
Overall DAC Suitability Score Range		**74.5**

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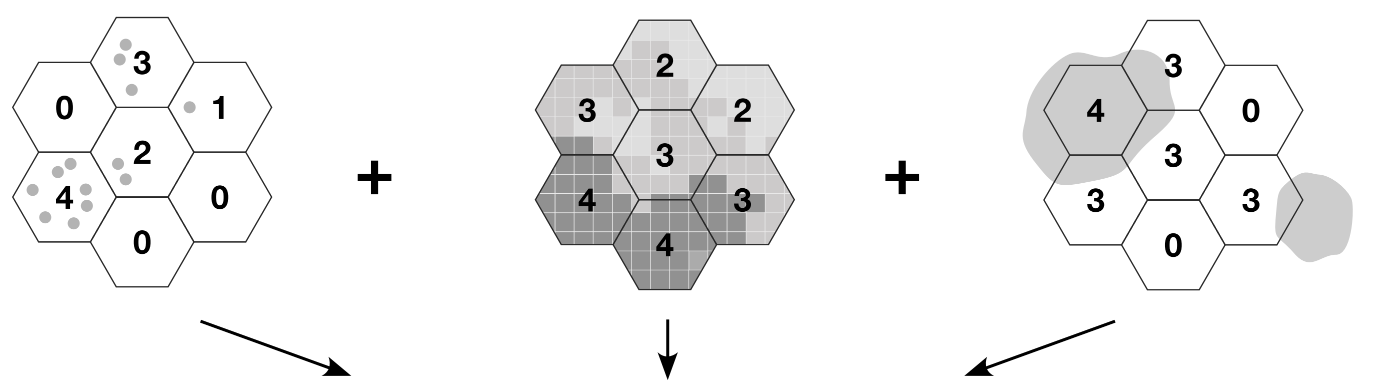
DAC Siting Consideration Scoring Methodology (cont.)

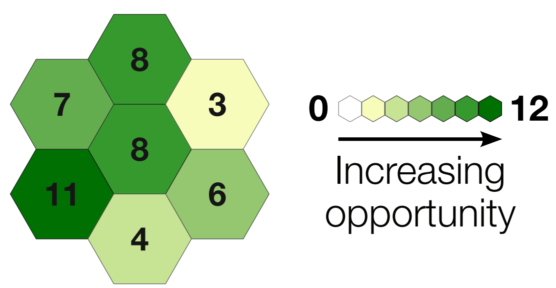
The graphic below illustrates the process used to score hexagon grid cells. Individual data layer scores are summed to produce each cell's category score. The number of individual data layers in a category determines the category's maximum possible score. Category scores are summed to produce each cell's overall DAC suitability score.

1. Each hexagon cell is scored based on whether it coincides with a desirable feature

Individual data layer A | **Individual data layer B** | **Individual data layer C**



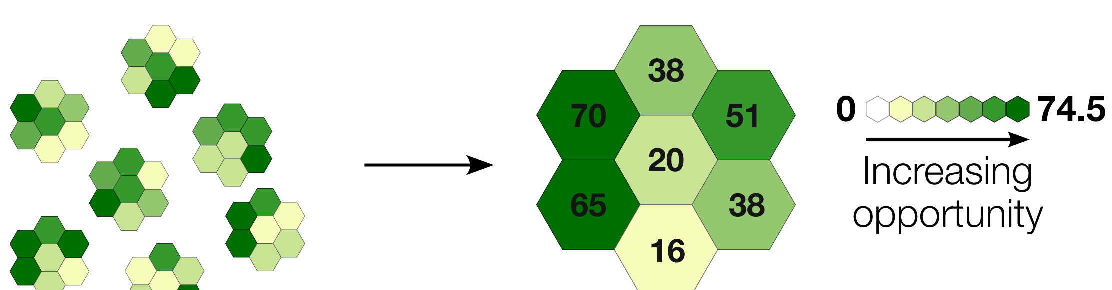
2. Individual data layer scores are added together to produce a category subtotal score



Category subtotal score
(e.g., Geologic carbon storage and transport infrastructure)

Three individual data layers, each with a maximum score of four, result in a maximum possible category score of 12.

3. Finally, all category scores are added together to produce an overall DAC suitability score

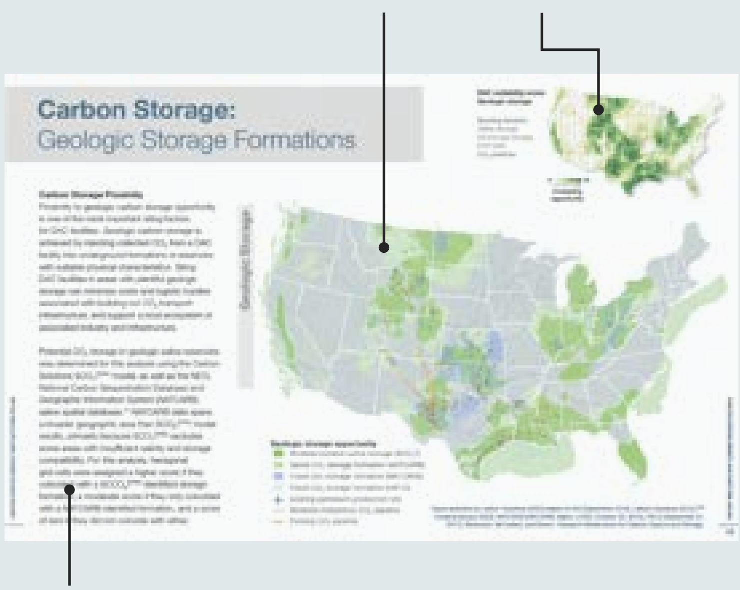


Overall DAC suitability score

How to read each DAC suitability component page

Map of individual data layers
Some data layers that contribute to the category score may not be shown.

Map of category score
Sum of individual layer scores.



Explanation of category's relevance to DAC and scoring criteria

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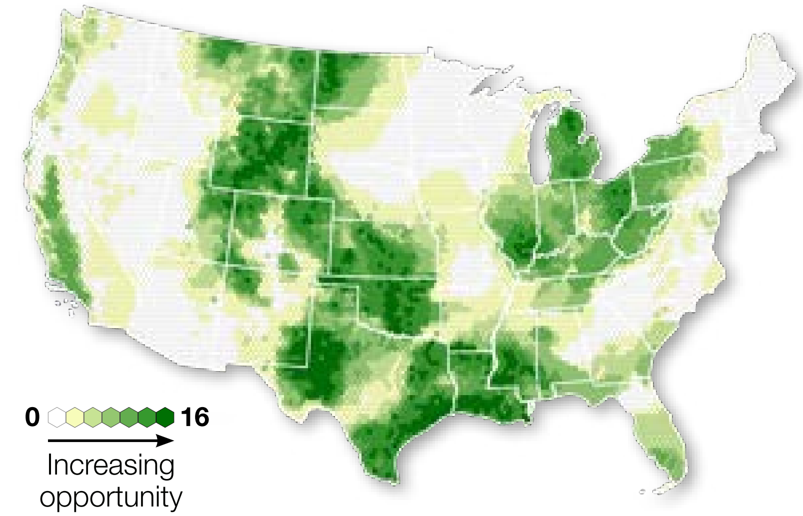
Carbon Storage: Geologic Storage Formations

DAC suitability score
Geologic carbon storage

Scoring factors:
- Saline storage
- Oil and gas storage
- Potential EOR sites
- CO_2 pipelines



Geologic carbon storage proximity

Proximity to geologic carbon storage opportunity is one of the most important siting factors for DAC facilities. Geologic carbon storage is achieved by injecting collected CO_2 from a DAC facility into underground formations or reservoirs with suitable physical characteristics. Siting DAC facilities in areas with plentiful geologic carbon storage can minimize costs and logistic hurdles associated with building out CO_2 transport infrastructure and support a local ecosystem of associated industry and infrastructure.

Potential CO_2 storage in geologic saline formations was determined for this analysis using the Carbon Solutions SCO_2T^{PRO} model, as well as the NETL National Carbon Sequestration Database and Geographic Information System (NATCARB) saline spatial database.[28] NATCARB data spans a broader geographic area than SCO_2T^{PRO} model results, primarily because SCO_2T^{PRO} excludes some areas with insufficient salinity and storage compatibility. For this analysis, hexagonal grid cells were assigned a higher score if they coincided with a SCO_2T^{PRO}-identified storage formation, a moderate score if they only coincided with a NATCARB-identified formation, and a score of zero if they did not coincide with either.

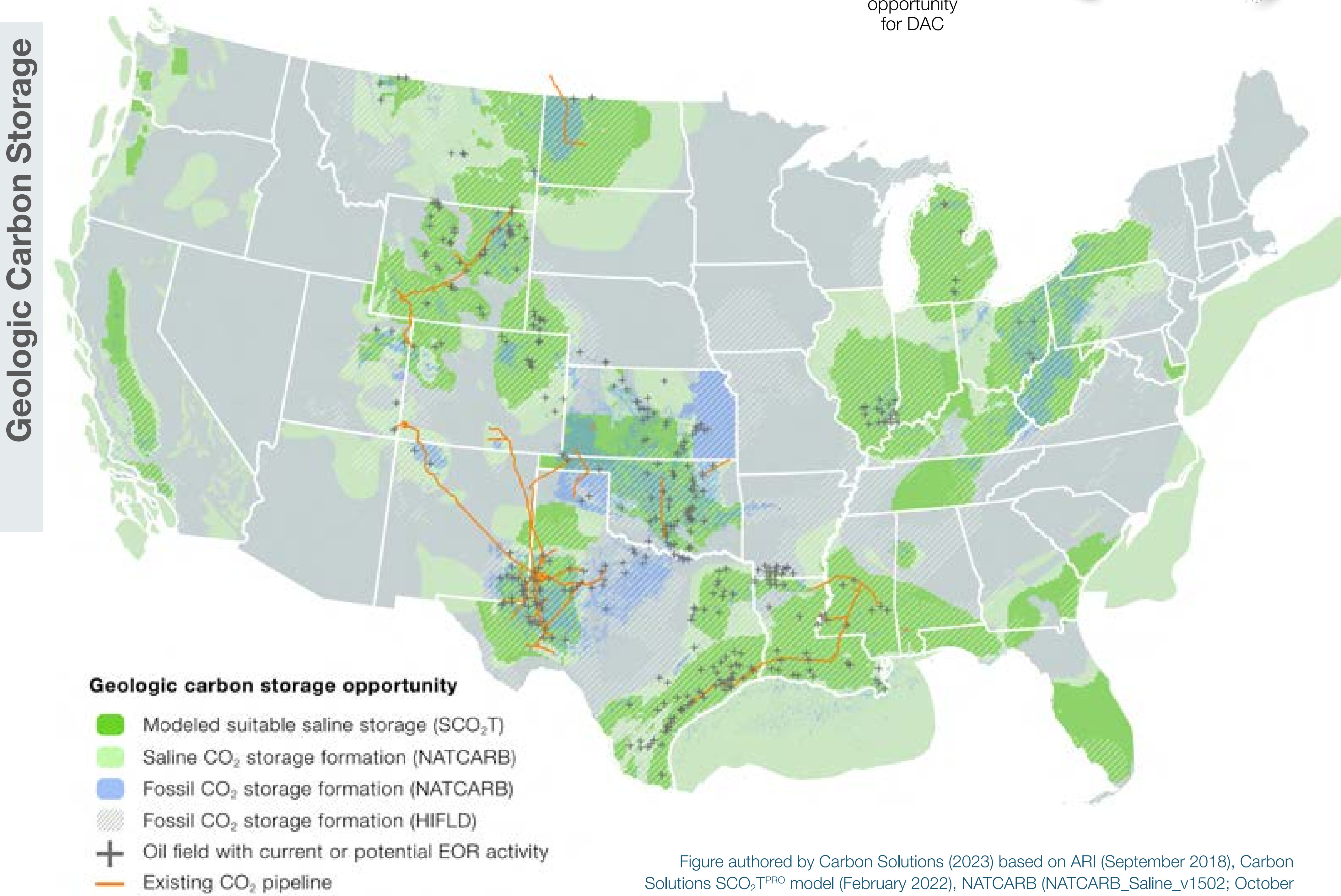


Figure authored by Carbon Solutions (2023) based on ARI (September 2018), Carbon Solutions SCO_2T^{PRO} model (February 2022), NATCARB (NATCARB_Saline_v1502; October 30, 2015), Homeland Infrastructure Foundation-Level Data (HIFLD) (September 21, 2017).

Carbon Storage: Geologic Storage Formations

Oil and gas basins

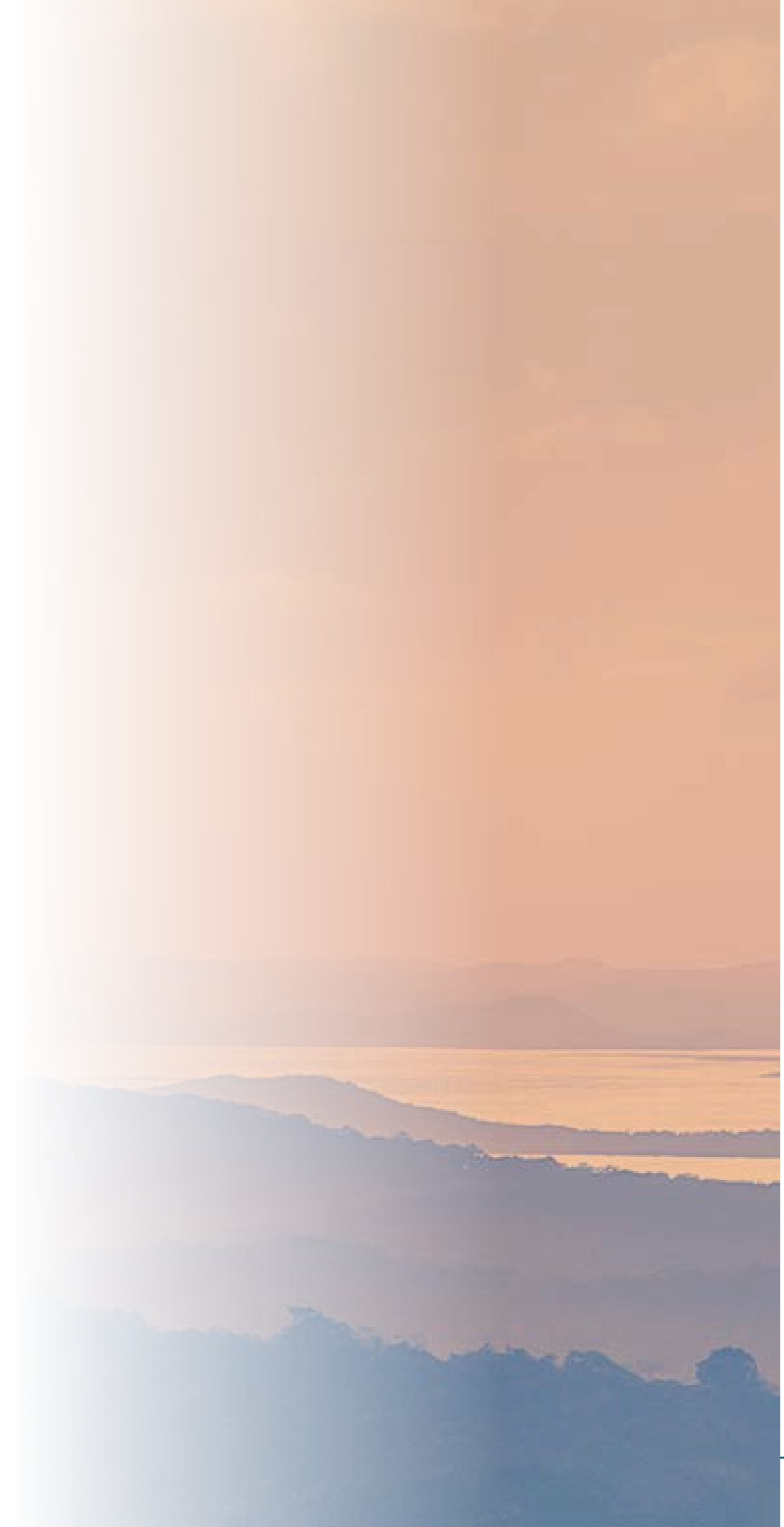
Depleted oil and natural gas reservoirs are geologic formations with the potential for carbon storage, based on their prior history of trapping other fluids and compatibility with CO_2 storage. This analysis drew upon data from NATCARB and the Homeland Infrastructure Foundation-Level Data (HIFLD) repository to evaluate proximity to oil and gas basins.[29] Hexagon grid cells received the highest score if they overlapped with a NATCARB formation, a moderate score if they overlapped with the more general HIFLD data layer, and a score of zero if they did not overlap with either.

Developed oil fields with current or potential EOR activity were also included, with cells assigned a higher value the closer they were to such a field.

CO_2 transport infrastructure

Developing DAC facilities in regions with on-site CO_2 storage potential is key to minimizing the cost of processing and transporting CO_2. DAC facilities sited in locations lacking local geologic carbon storage opportunities may need to transport captured CO_2 over moderate to long distances for permanent storage. Such facilities could take advantage of existing infrastructure to minimize individual planning and construction costs incurred in the development of new transport infrastructure. To reflect this dynamic, grid cells close to existing CO_2 transport infrastructure received a higher score than cells not located near such infrastructure.

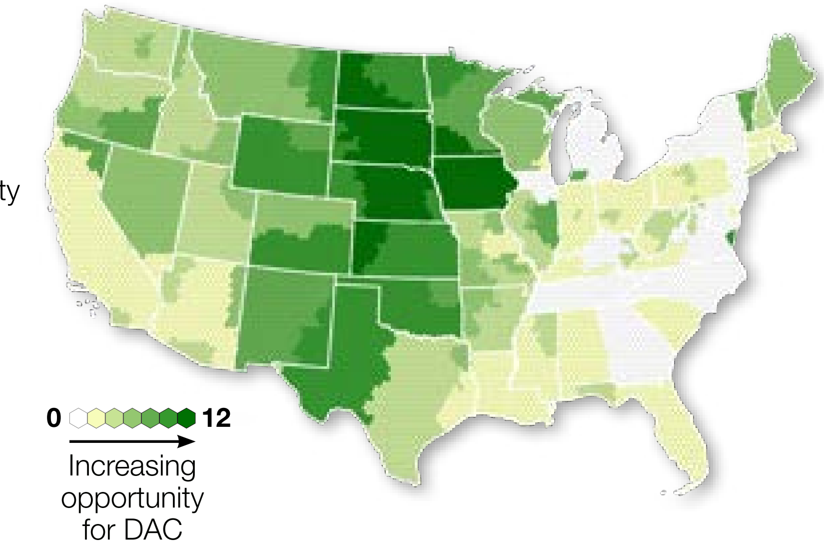
Given the importance of having access to geologic carbon storage opportunities, whether via local injection or via CO_2 transport infrastructure, a grid cell's overall DAC suitability score was set to zero if the cell did not overlap with any saline or oil and gas formation and was not within 20 miles of existing CO_2 transport infrastructure.



Low-Carbon Electricity:
2030 Electric Grid Carbon Intensity

DAC suitability score
2030 electric grid

Scoring factors:
- Grid carbon intensity
- Net load
- Electricity cost



The electrical energy demand of DAC facilities ranges from around 22 to 1500 kWh per metric ton CO_2 captured. This energy demand must be met with low- or zero-carbon energy supply for DAC to be an effective negative emissions strategy. Therefore, a robust, low-cost supply of renewable electricity is an important factor in siting regional DAC hubs.

For this analysis, electric load, carbon intensity, and electricity price around the US in 2030 and 2050 were sourced from NREL's Regional Energy Deployment System (ReEDS) model.[30] Locations with a higher 2030 long-run marginal emission rate represent areas where added energy usage from DAC facilities would be most carbon-intensive. As such, areas with a high long-run marginal emission rate received a lower score.

Electric Grid GHG Intensity 2030

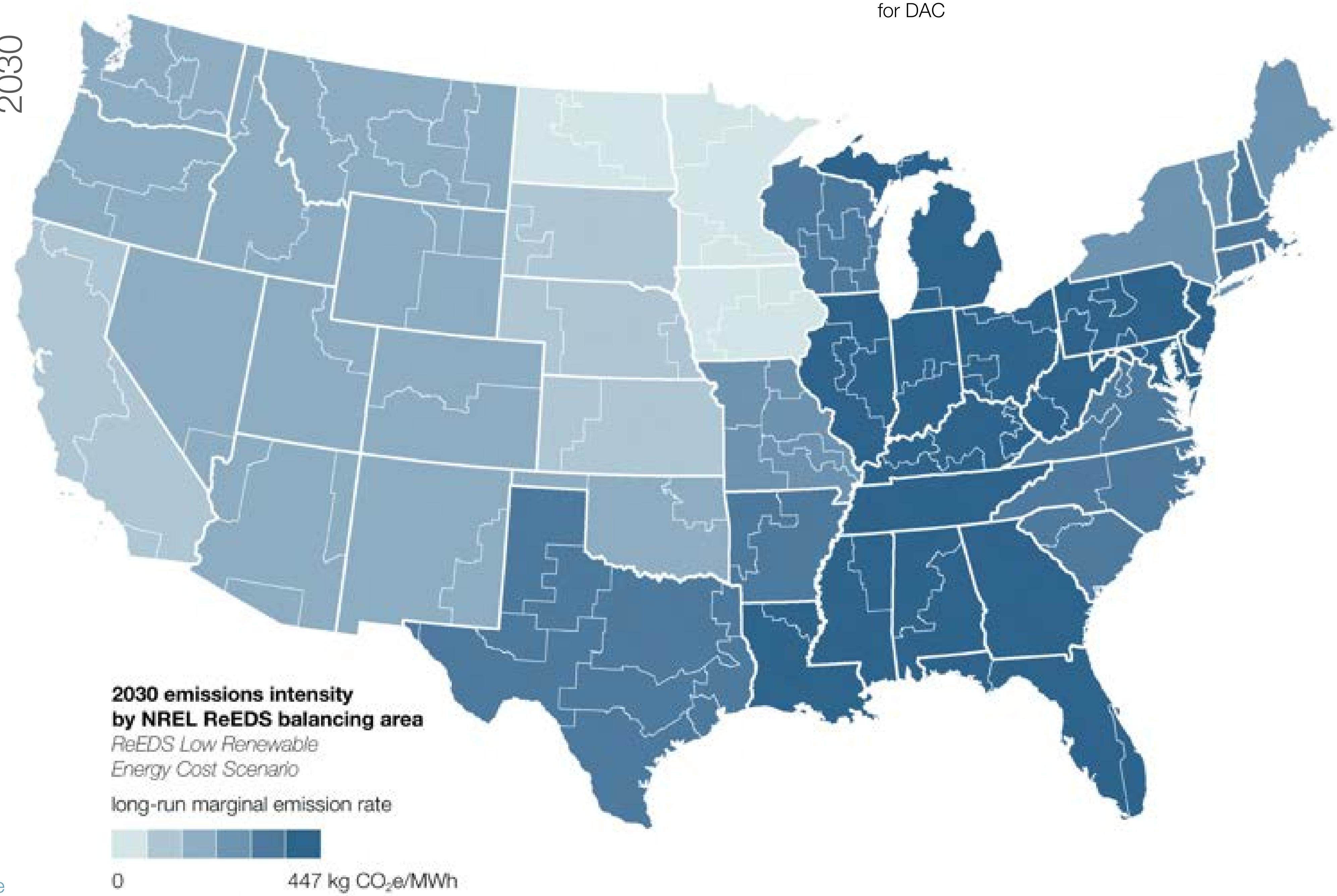
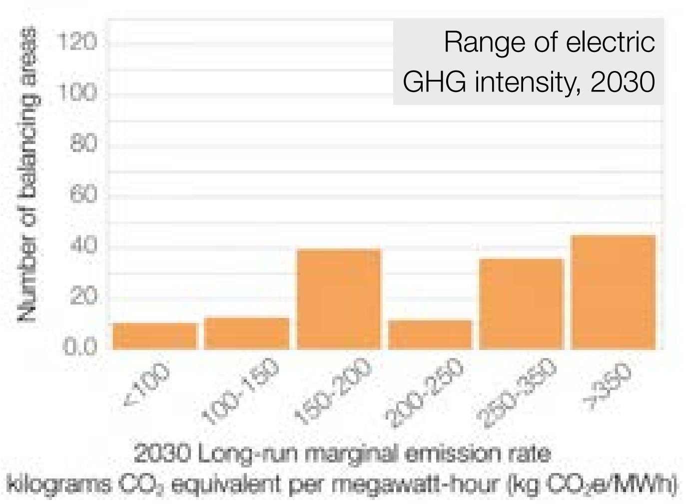


Figure authored by Carbon Solutions (2023) based on NREL ReEDS Cambium 2021 Low Renewable Energy Cost (December 2021).

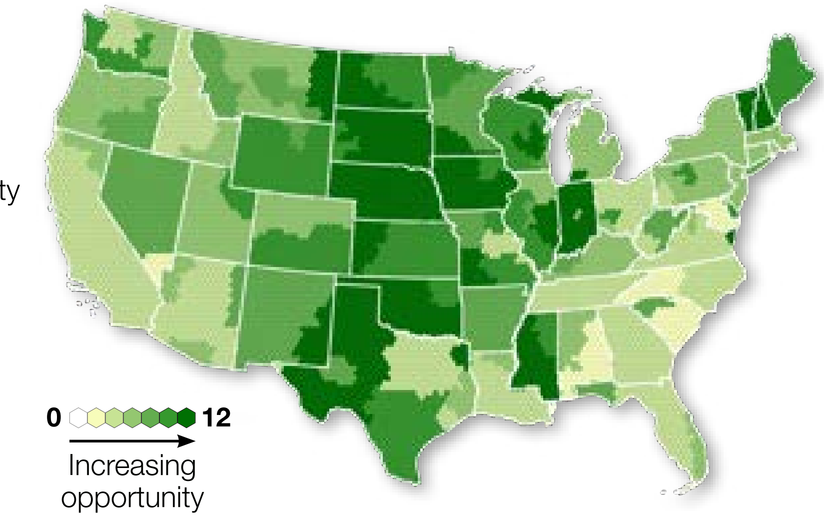


The ReEDS model projects a wide range of electric generation carbon intensity across the United States in 2030 as compared to the reduced range achieved in 2050, shown on the following page.

Low-Carbon Electricity:
2050 Electric Grid Carbon Intensity

DAC suitability score
2050 electric grid

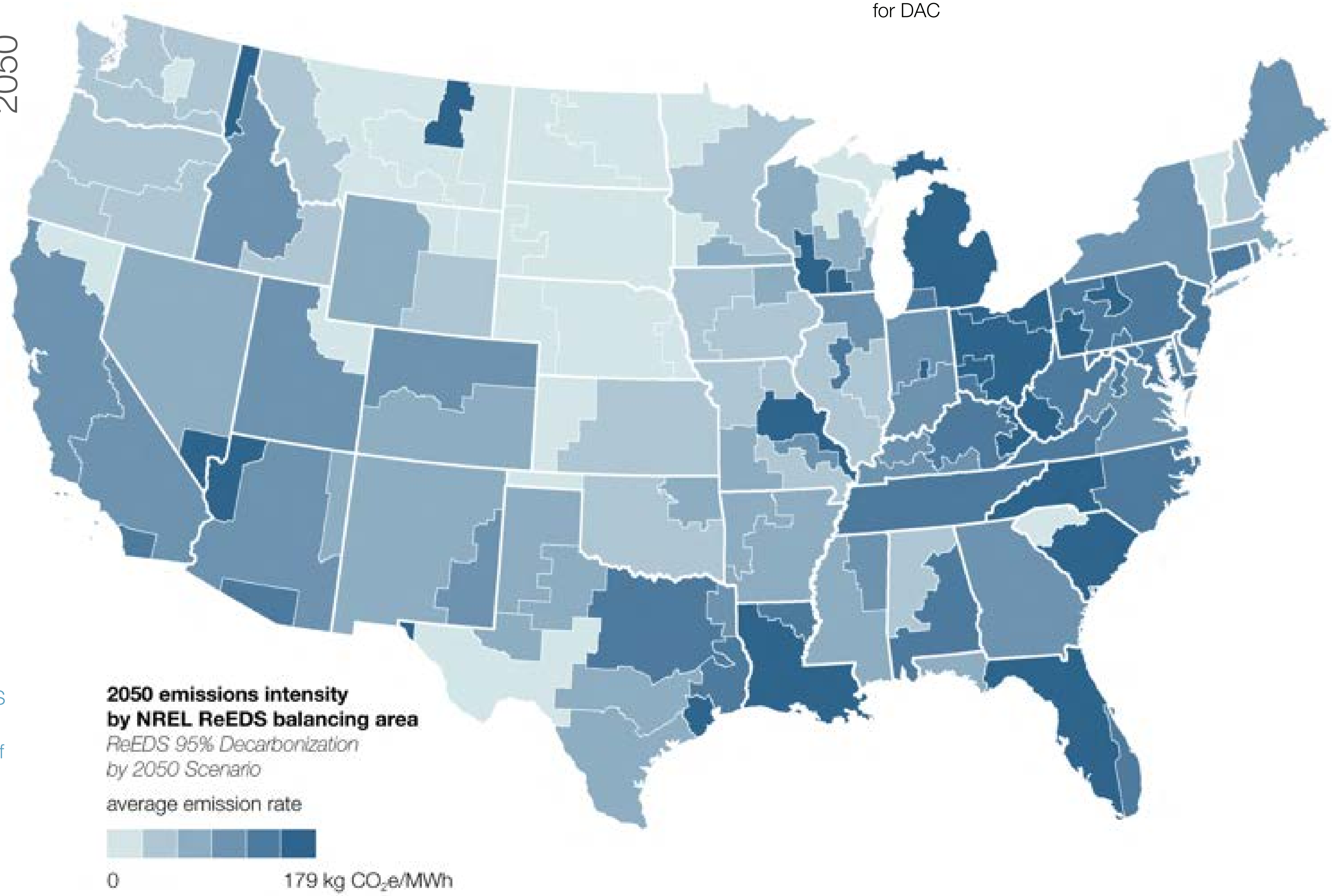
Scoring factors:
- Grid carbon intensity
- Net load
- Electricity cost

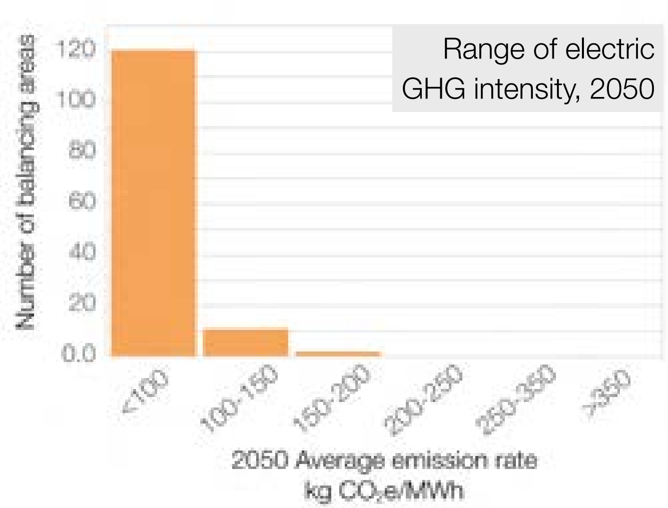


Likewise, areas projected to have more carbon-intensive electric grids in 2050 received a lower score than areas projected to produce less carbon-intensive energy. However, the entire electric grid is projected to become much cleaner by 2050.

While the main map at the right shows average projected emission rates across the country, the scoring results shown in the inset map also incorporate scores for electricity cost and net projected load. Areas with positive net generation, representing a surplus of energy availability, received high scores, as did areas with a low projected cost of electricity.

Electric Grid GHG Intensity 2050

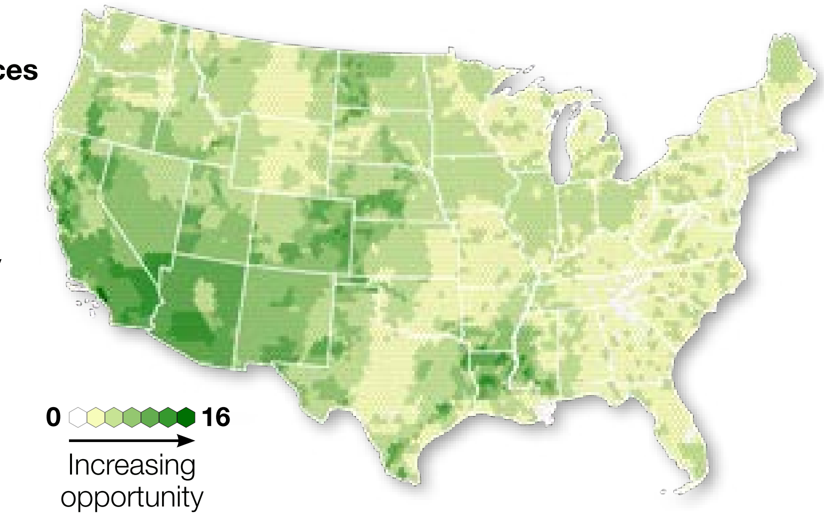




Under a midcentury decarbonization scenario, the ReEDS model projects a much lower range of electric generation carbon intensity by 2050, as compared to the wide range in 2030 shown on the previous page.

Figure authored by Carbon Solutions (2023) based on NREL ReEDS Cambium 2021 Mid-case 95 by 2050 (December 2021).

Sources of Low-Carbon Heat: Geothermal, Biomass, and Solar



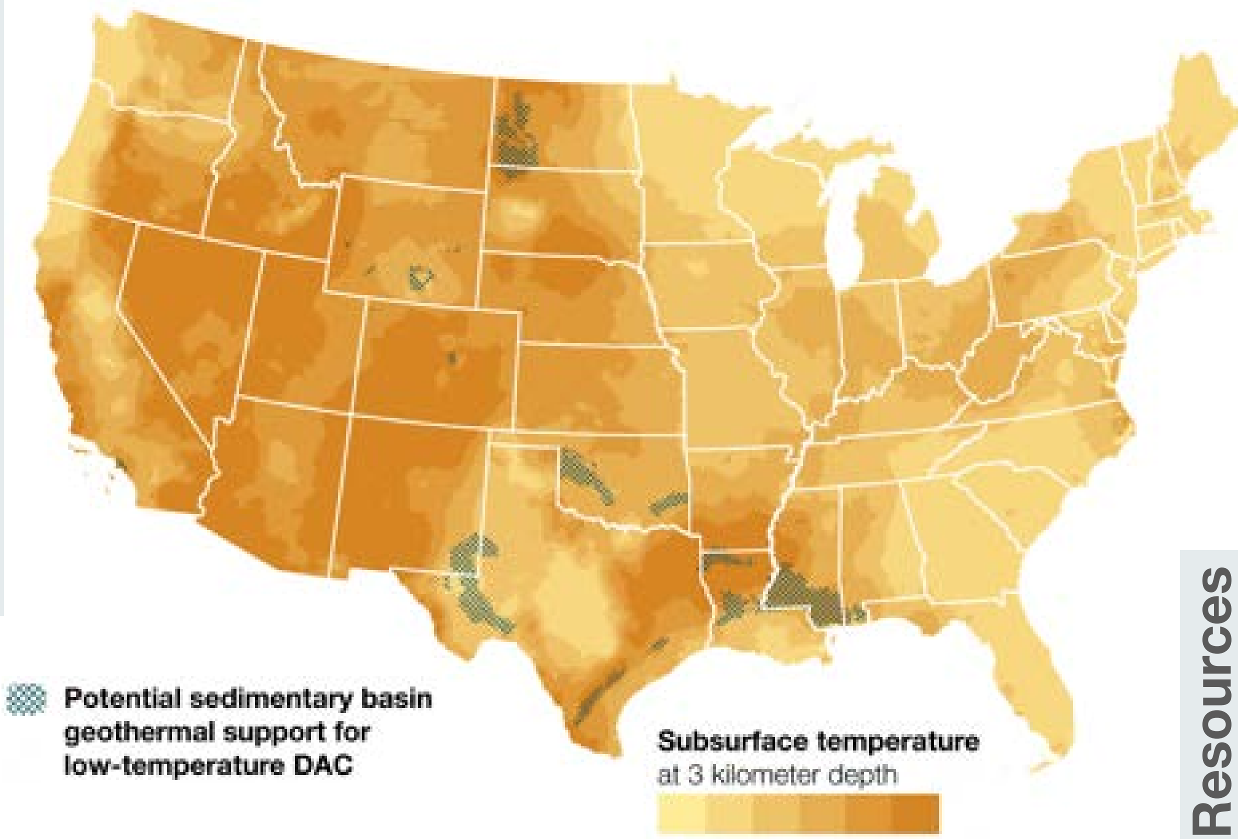
In addition to low-carbon sources of electricity, DAC facilities require low-carbon sources of heat (except in the case of an electric-only system). Renewable heat sources that would benefit the siting of a regional DAC hub include geothermal, biomass, and concentrated solar energy. Non-renewable options, such as natural gas with CCS and industrial facilities with waste heat supply, are considered separately.

Geothermal

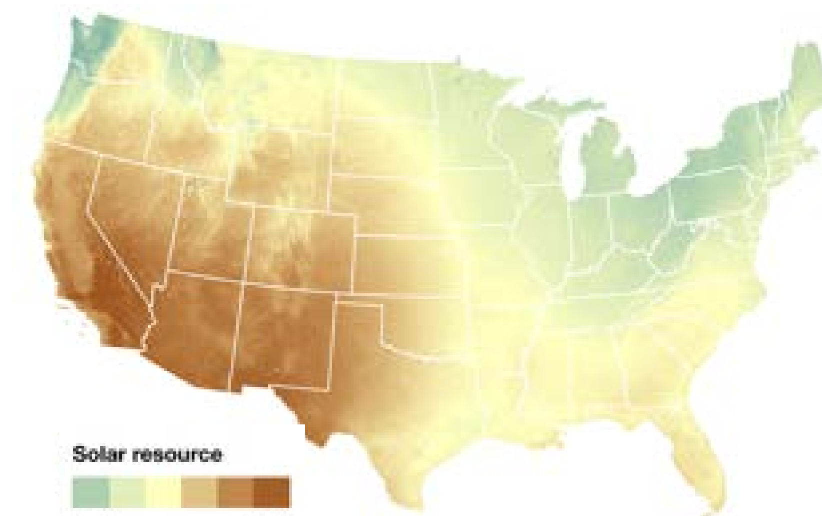
Carbon Solutions modeling identified areas with potential for sedimentary basin geothermal energy to support low-temperature DAC facilities. Areas with high heat and reservoir transmissivity were assigned the highest scores.

Subsurface temperature data from Los Alamos National Laboratory was used to evaluate the regional potential for hydrothermal and/or enhanced geothermal resources to power DAC facilities.[31] With a minimum threshold of 100°C for low-temperature DAC, areas with an average subsurface temperature of 100°C or higher at a 3-kilometer depth were given the highest score.

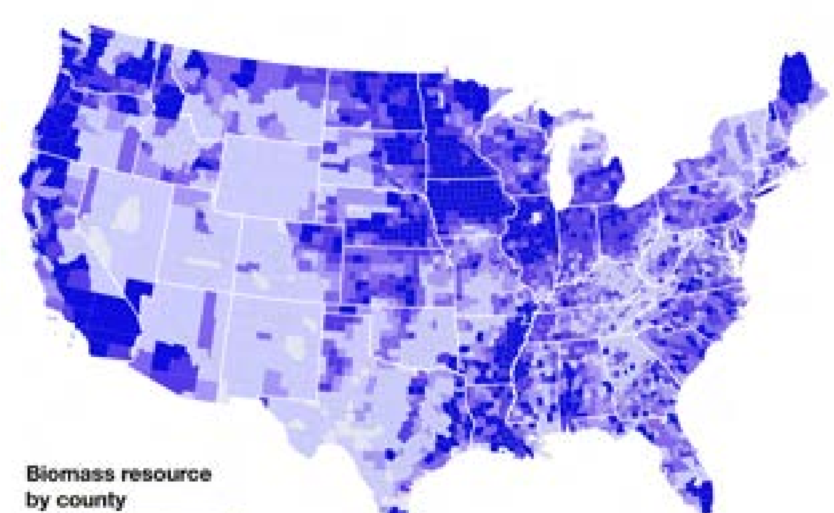
Geothermal Resources



Solar Resources



Biomass Resources



Figures authored by Carbon Solutions (2023) based on Carbon Solutions modeling; Bielecki et al. (October 2015); NREL National Solar Radiation Data Base (June 2018); NREL BioPower Atlas (October 30, 2014).

Sources of Low-Carbon Heat: Geothermal, Biomass, and Solar

Biomass

Biomass can be an important feedstock for low-carbon heat production. In some cases, biomass can even be a net-negative energy source through biomass with CCS. Data on biomass potential was obtained from a National Renewable Energy Laboratory analysis of solid biomass resources.[32] Hexagon grid cells with greater biomass availability received a higher score.

Concentrated solar heat

Concentrated solar power systems use mirrors to concentrate solar energy into a receiver and harness the resulting heat. Data on concentrated solar potential was obtained from the National Renewable Energy Laboratory's National Solar Radiation Database.[33] Hexagon grid cells with a high solar irradiance represent locations with high potential for concentrated solar power and received high scores.

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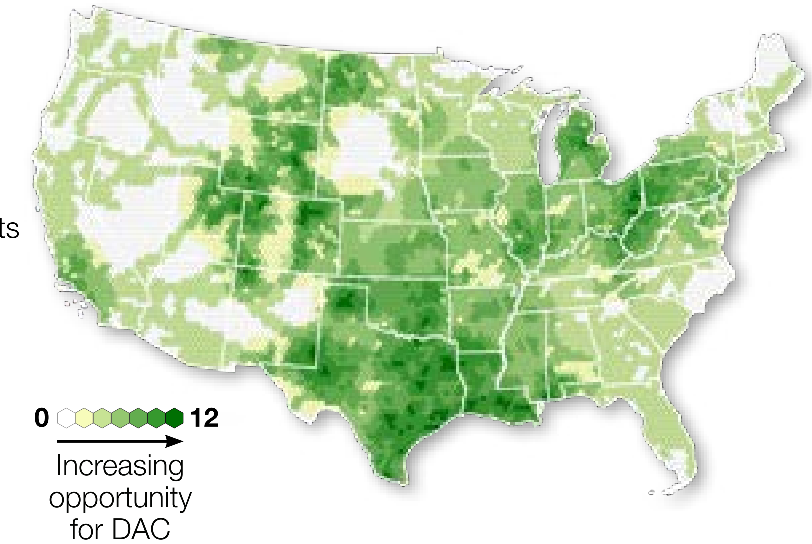
Natural Gas with Carbon Capture: Electricity and Heat Cogeneration

DAC suitability score
Natural gas and fuel supply

Scoring factors:
- NG processing plants
- NG pipelines
- Power plant carbon capture candidates



DAC facilities could be supplied with low-carbon thermal energy from natural gas power plants as long as those power plants are coupled with carbon capture and storage (CCS). In the long term, ideal locations for regional DAC hubs would take advantage of favorable conditions for renewable heat sources discussed on the previous pages. In the short term, if DAC facilities are supplied with thermal energy from natural gas, then a regional hub could be situated where natural gas facilities and pipelines are located.

For this analysis, hexagon grid cells close to natural gas processing plants, natural gas pipelines, or power plant CCS candidates were scored higher than cells not near any of those features.

Data on natural gas processing facilities comes from the US EIA and the Environmental Protection Agency (EPA) Facility Level Information on GreenHouse Gases Tool.[34] Data on natural gas pipelines comes from the Energy Information Administration.[35] Data on power plant CCS candidates is a result of analysis by the Regional Deployment Initiative, Rhodium Group, and Carbon Solutions.[36]

Natural Gas Heat Supply

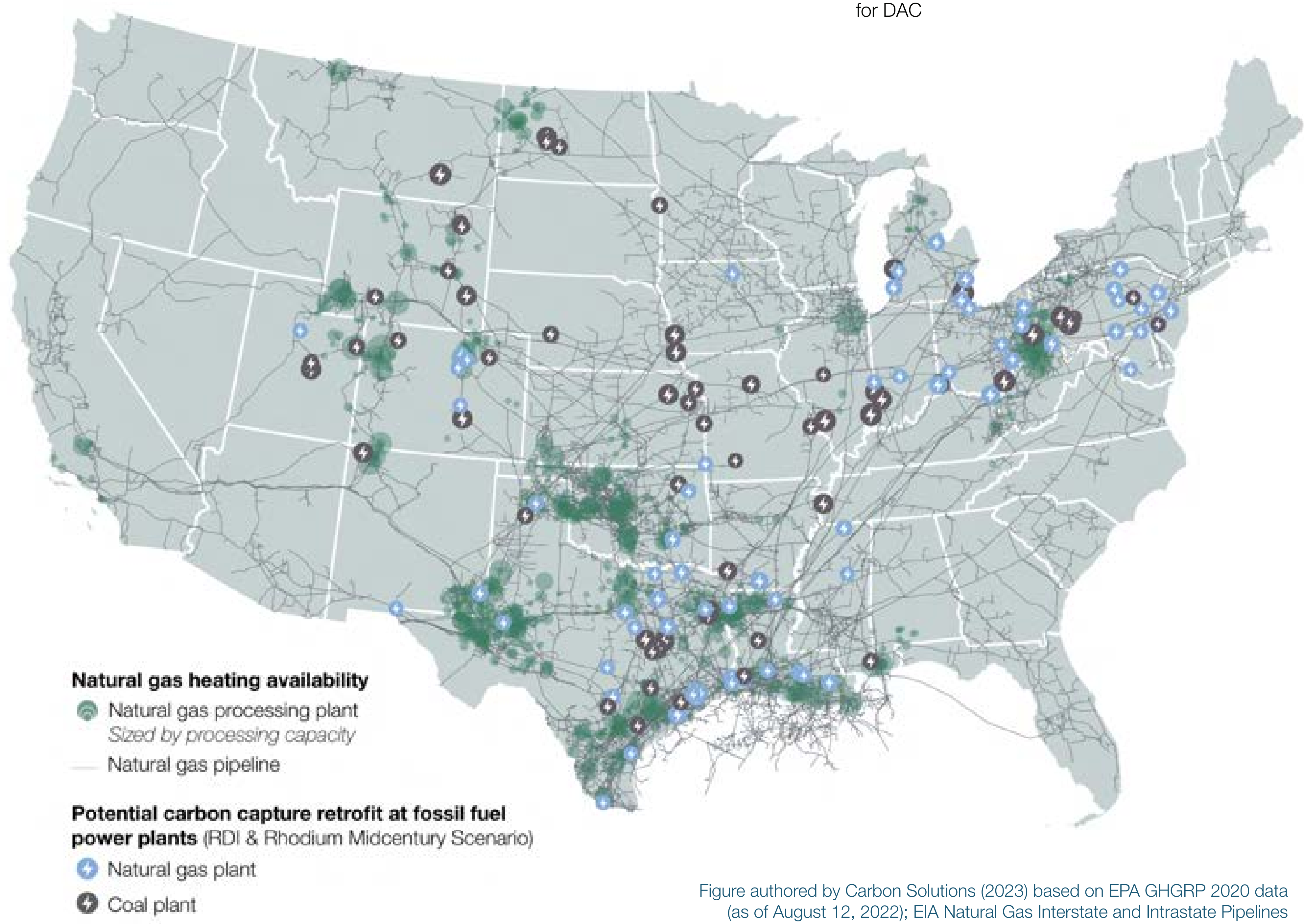


Figure authored by Carbon Solutions (2023) based on EPA GHGRP 2020 data (as of August 12, 2022); EIA Natural Gas Interstate and Intrastate Pipelines (April 28, 2020); EIA US Natural Gas Processing Plants (January 13, 2020).

Sources of Low-Carbon Heat: Waste Heat and Combined Heat and Power

To serve the thermal energy load needed to operate DAC systems, energy that is currently wasted at industrial facilities throughout the US could be used for low-carbon heat. When burning fuels for process heat or chemical reactions, thermal energy is often released and left uncaptured. More than half of the energy generated from fuel combustion is lost to heat.[37]

Combined heat and power (CHP) systems or waste heat recovery (WHR) methods capture this lost energy and deliver it to new processes or energy generation, resulting in increased efficiency and reduced carbon intensity.

An Oak Ridge National Laboratory study identified 12 industrial sectors as being good targets for WHR technologies due to their demand for large quantities of high heat ranging from 400°F-2000°F (205°C-1100°C).[38] The study reports that petroleum and coal producers have the largest potential of any industrial sector. In the US, this sector produces more than 650 trillion Btu of waste heat (between 450°F-1200°F) available for recovery and utilization. Chemical manufacturers and primary metals manufacturers also generate large amounts of waste heat, producing 108.3 trillion Btu and 7.2 trillion Btu of waste heat between 450°F-1200°F (230°C-650°C), respectively. While primary metal manufacturers had less usable waste heat below 1200°F, they produced 87.2 trillion Btu of waste heat above 1200°F, the largest of any industrial sector.

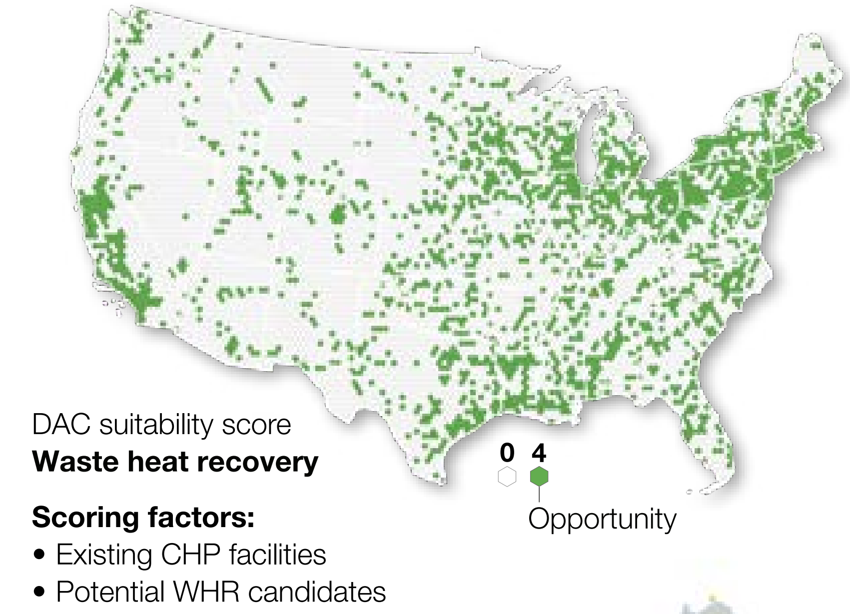
There are also opportunities for WHR beyond industrial facilities and units. Few dedicated power generation facilities currently recover heat from exhaust gases or via conductive methods for utilization.[39] Waste heat from electricity generation is one of the largest reservoirs of usable heat and can be applied to a wide range of processes, such as district heating and amine regeneration in carbon capture units, among other uses. Utilization of these untapped waste heat sources presents an excellent opportunity to optimize DAC and reduce the amount of heat and electricity demanded by each DAC system.

Candidate unit types for waste heat capture by industrial sector

Sector	Unit Type	Exchange Method
Petroleum & coal products	Calciners, thermal crackers, fractionators, catalytic processes, treatment processes, etc.	Exhaust
Chemical manufacturing	Petrochemical units, industrial gases, alkalis & chlorine, cyclic crudes and intermediates, agricultural chemicals/ammonia, etc.	Exhaust
Cement & lime	Rotary kilns	Exhaust
Flat glass & container glass	Melting furnaces, annealing ovens, tempering furnaces	Exhaust
Iron & steel mills	Coke ovens, blast furnaces, basic oxygen furnaces, electric arc furnaces, etc.	Exhaust
Aluminum production	Hall-Heroult cells, secondary melters, etc.	Exhaust & conductive
Silicon/non-ferrous production	Electric arc melters, continuous charge furnaces	Exhaust
Ferrous & non-ferrous foundries	Ladle preheating, core baking, cast metal cooling, heat treating, quenching, reverberatory furnaces, melting furnaces, etc.	Exhaust & conductive
Fabricated metals	Pre-heaters, heat treatment, cleaning, drying, furnace heating	Exhaust & conductive
Natural gas compressor stations	Internal combustion engines or turbines	Exhaust
Landfill gas	Internal combustion engines/turbines, flares	Exhaust
Flare gas in oil & gas production	Flares	Exhaust
Steam pressure reduction	Steam pressure reducing valves	Physical & Exhaust

Source: Elson, Tidball, and Hampson, *Waste Heat to Power Market Assessment*.

Sources of Low-Carbon Heat:
Waste Heat and Combined Heat and Power



This analysis positively scored grid cells that contained an existing or potential WHR or CHP facility. Grid cells where no existing or potential CHP or WHR facilities were present received a score of zero.

Data on facilities with existing WHR and CHP systems comes from the US DOE's Combined Heat and Power and Microgrid Installation Databases.[40] These databases are likely an underrepresentation of facilities that use CHP and WHR systems as they are collected via a self-reported survey. Additional potential candidates for WHR were identified through separate Carbon Solutions analysis.

Waste Heat Supply

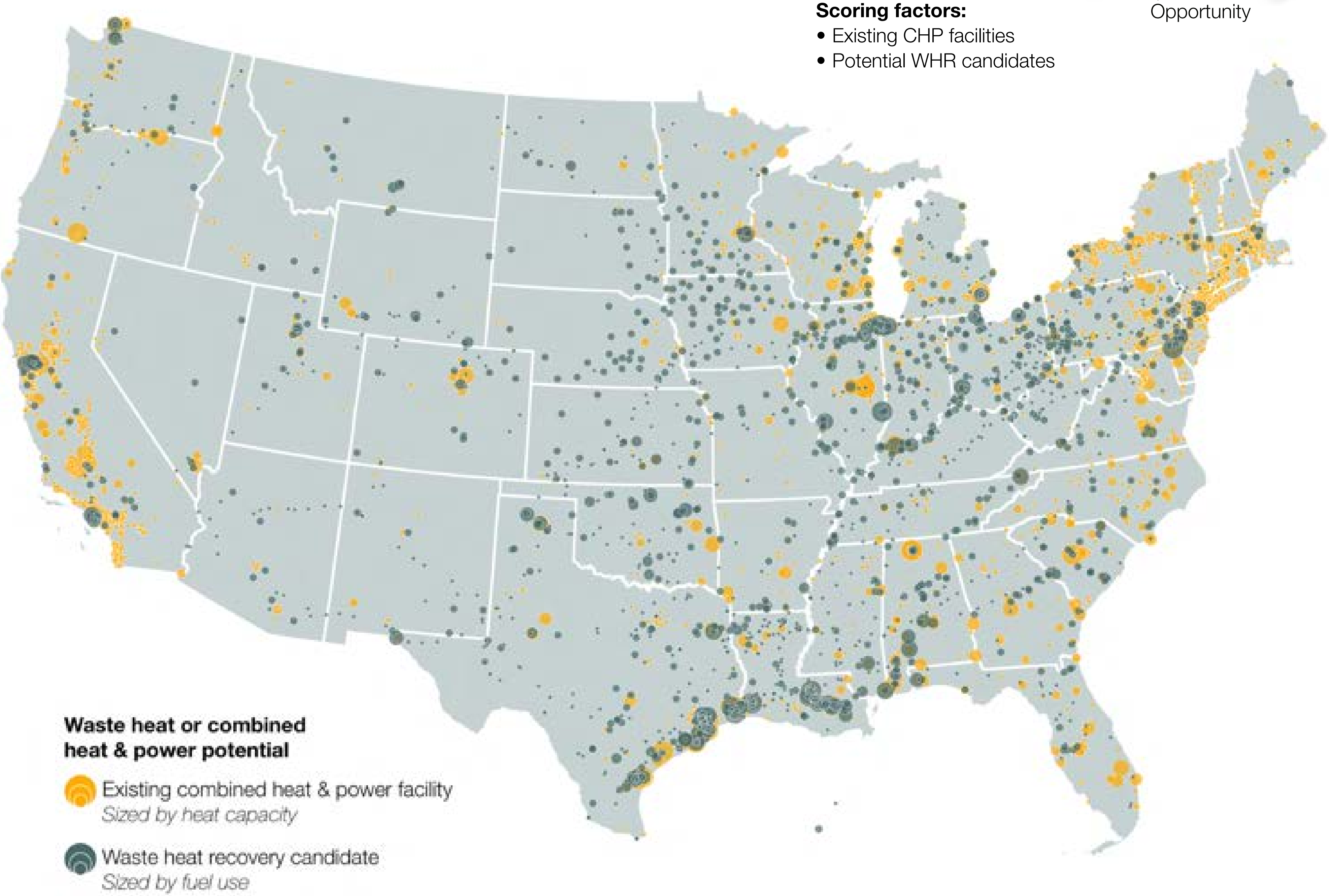
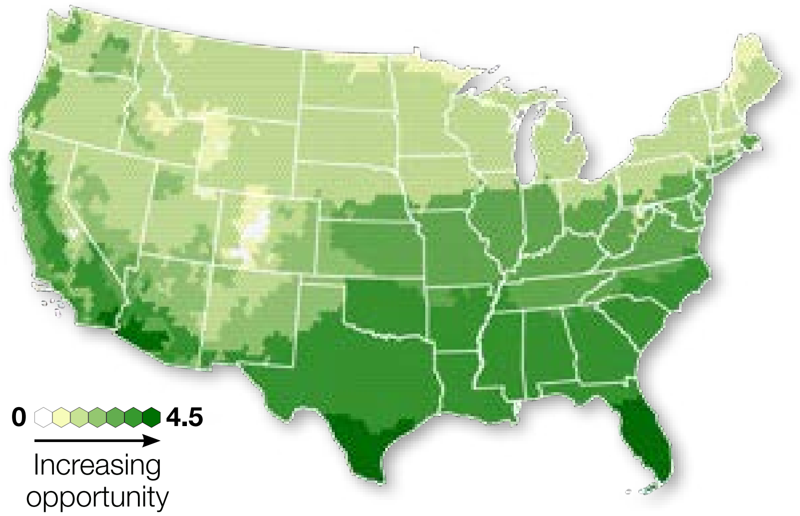


Figure authored by Carbon Solutions (2023) based on EPA GHGRP 2020 data (as of August 12, 2022); US DOE Combined Heat and Power and Microgrid Installation Databases (October 2022).

Atmospheric Suitability: Air Temperature and Humidity



The performance of DAC systems is sensitive to ambient atmospheric conditions around the facility. A modeling study of a liquid solvent, high-temperature DAC system found that DAC achieves better performance at high ambient temperature and high relative humidity.[41] The study did not address low-temperature, solid sorbent DAC systems. The study's results indicated that temperature had a substantially greater effect on performance than humidity across the likely ranges of these values. The effect of temperature is estimated to be about eight times larger, on average, across the range of temperatures and relative humidity studied. However, the exact relationship depends on the values.

Air temperature and relative humidity data layers are obtained from the Climatic Research Unit at the University of East Anglia via The Nelson Institute Center for Sustainability and the Global Environment, University of Wisconsin-Madison.[42]

Hexagon grid cells containing areas with high air temperature and humidity received the highest scores. The relative humidity layer received a 1/8 weight in the final overall map score, representing its lesser effect compared to temperature.

Air temperature

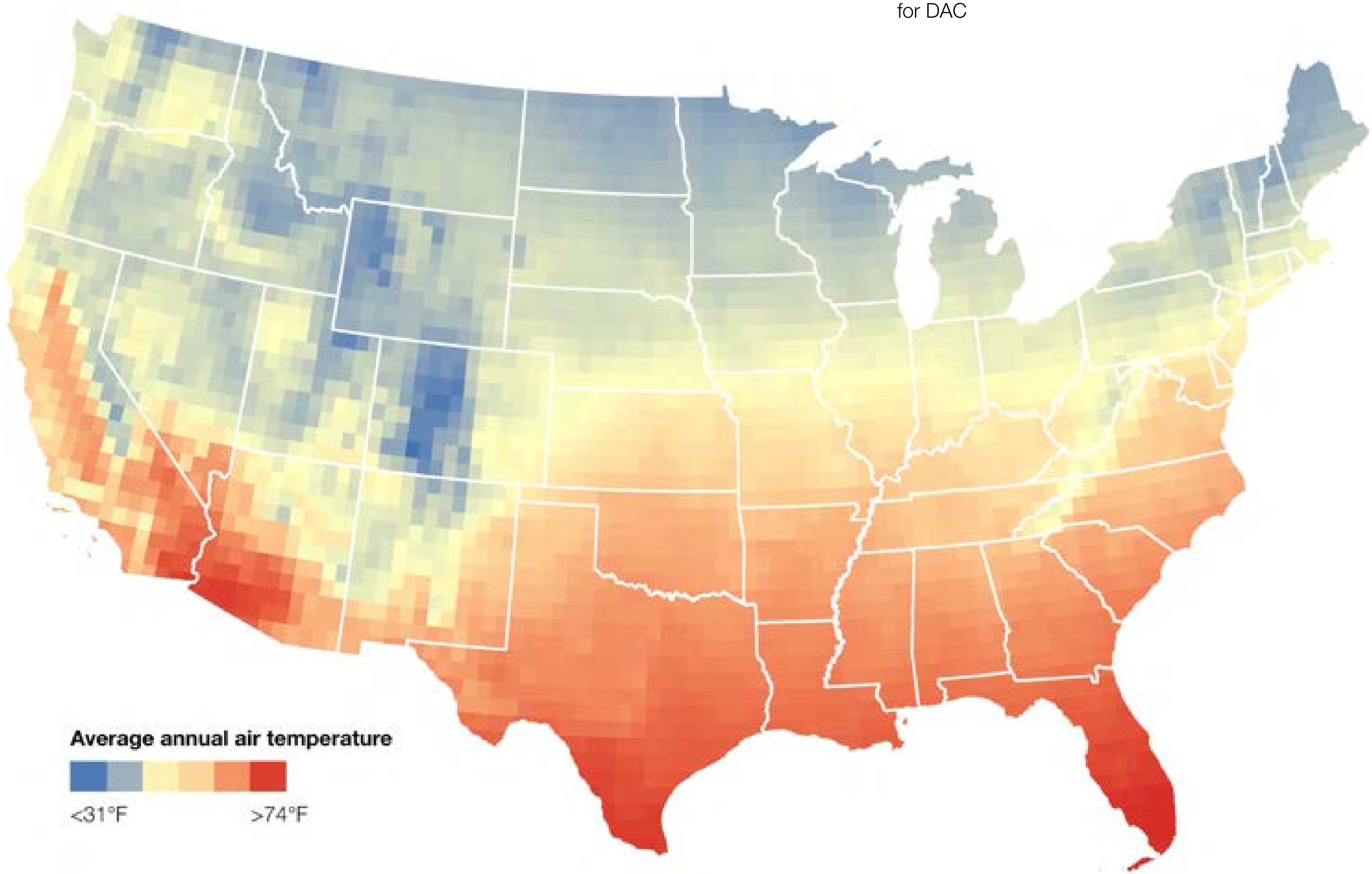


Figure authored by Carbon Solutions (2023) based on University of East Anglia (June 2022).

The Landscape of Opportunity for DAC

This analysis assessed suitability for siting of regional DAC hubs, using 17 key metrics across six categories as described previously in this atlas. The resulting map, aggregating scores along all categories, is shown at the right. There is broad geographic distribution among regions that emerge as prime candidates for DAC hub development. Each identified region has unique advantages that could anchor the development of a thriving industrial ecosystem for DAC facilities and supportive infrastructure and activities.

There is broad scientific consensus that DAC is likely to become an important component of the global effort to reach net-zero emissions and restore current atmospheric conditions to safe and stable levels. The DOE's regional DAC hubs program provides an exciting opportunity to jumpstart the development of this industry in the US. Continued and expanded investment will be required to scale DAC to likely necessary levels. The regional opportunities laid out in this analysis provide a road map for where to begin.

Overall DAC suitability scores: Regional strengths, advantages, opportunities for DAC hub development

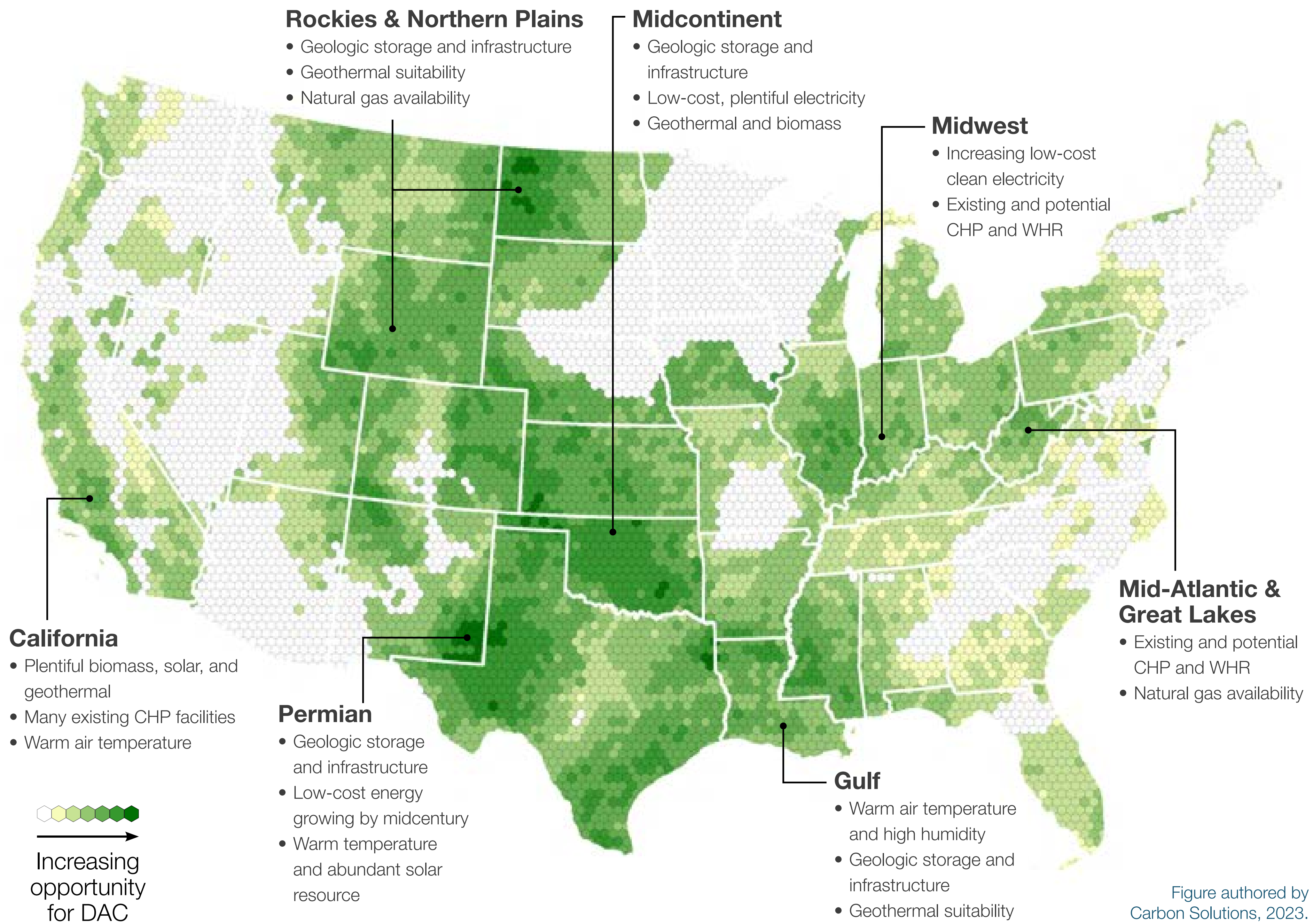


Figure authored by Carbon Solutions, 2023.

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2 IPCC “Summary for Policymakers” (2018), 17; IEA, *Net Zero by 2050*, 55.

3 Global Carbon Project, *Supplemental data of Global Carbon Budget 2022* (Version 1.0) (2022), https://www.icos-cp.eu/science-and-impact/global-carbon-budget/2022; Global Carbon Project, “Global Carbon Budget 2022,” November 11, 2022, https://www.globalcarbonproject.org/carbonbudget/22/presentation.htm.

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The photos of the earth at night and an industrial landscape on page 1 are from iStock. The photo of an industrial landscape on page 10 is from iStock. All other photos are from Envato Elements.

Appendix | Detailed Cell Scoring Methodology

Siting Consideration	Scores	Scoring Methodology
Geologic carbon storage and transport infrastructure		
Saline formation storage	0, 2, 4	0 if no overlap with a saline formation; 2 if overlap with NATCARB dataset saline formation only; 4 if overlap with SCO_2T^{PRO} dataset saline formation
Oil/gas reservoir storage	0, 2, 4	0 if no overlap with an oil/gas reservoir; 2 if overlap with HIFLD dataset reservoir only; 4 if overlap with NATCARB dataset reservoir
Potential EOR site	0, 1, 2, 3, 4	0 if nearest potential EOR site located >100 miles away; 1 if site within 50 to 100 miles; 2 if within 25 to 50 miles; 3 if within 10 to 25 miles; 4 if within 10 miles
Existing CO_2 pipeline	0, 2	0 if existing CO_2 pipeline >20 miles away; 2 if within 20 miles
Electric energy grid factors		
Availability of excess energy, 2030 & 2050	0, 1, 2, 3, 4	Scores of 0 to 3 for positive values (areas without excess electricity), divided by quartiles; 4 if net load is negative (areas with excess electricity score highest)
Electric carbon intensity, 2030 & 2050	0, 1, 2, 3, 4	0 if carbon intensity >200 (CO_2e/MWh); 1 if between 150-200; 2 if between 100-150; 3 if between 50-100; 4 if <50 (lowest carbon intensity scores highest)
Price of electricity, 2030 & 2050	0, 1, 2, 3, 4	Divided by quintiles. 0 if in highest quintile (highest-cost electricity); 4 if in lowest quintile (lowest-cost electricity scores highest)
Regional resources for low-carbon heat		
Hydrothermal or enhanced geothermal	0, 1, 4	0 if subsurface temperature <80°C; 1 if between 80°C and 100°C; 4 if above 100°C
Sedimentary basin geothermal	0, 1, 2, 3, 4	0 if temperature <100°C; cells with temperature of at least 100°C divided into quintiles. 1 if in lowest quintile; 4 if in highest quintile
Biomass	0, 1, 2, 3, 4	Divided by quintiles. 0 if in lowest quintile (least biomass availability); 4 if in highest quintile (most biomass availability)
Solar	0, 1, 4	Divided by quintiles. 0 if in lowest three quintiles; 1 if in second-highest quintile; 4 if in highest quintile (highest solar irradiance scores highest)
Natural gas availability for heat (with CCS)		
Near-term power plant CCS candidate	0, 1, 2, 3, 4	0 if nearest candidate located >100 miles away; 1 if site within 50 to 100 miles; 2 if within 25 to 50 miles; 3 if within 10 to 25 miles; 4 if within 10 miles
Natural gas processing plant	0, 1, 2, 3, 4	0 if nearest plant located >100 miles away; 1 if site within 50 to 100 miles; 2 if within 25 to 50 miles; 3 if within 10 to 25 miles; 4 if within 10 miles
Natural gas pipeline	0, 4	0 if existing natural gas pipeline >20 miles away; 4 if within 20 miles
Electric power and industrial facilities with waste heat supply or combined heat and power (CHP)		
Existing or potential CHP facility	0, 4	0 if cell does not contain an existing or potential CHP/waste heat recovery facility; 4 if cell does contain such a facility
Atmospheric conditions		
Air temperature	0, 1, 2, 3, 4	Divided into equal intervals. 0 if in lowest interval (lowest heat); 4 if in highest interval (highest heat)
Humidity	0, 1, 2, 3, 4	Divided into equal intervals. 0 if in lowest interval (lowest humidity); 4 if in highest interval (highest humidity). All scores given a 1/8 weight to reflect lesser effect as compared to temperature.

Note: All individual scores were summed to calculate each cell's overall DAC suitability score. If a cell received a score of zero on every siting consideration within the geologic carbon storage and transport infrastructure category, the cell's overall suitability score was set to zero, reflecting the importance of proximity to CO_2 storage and utilization opportunities.

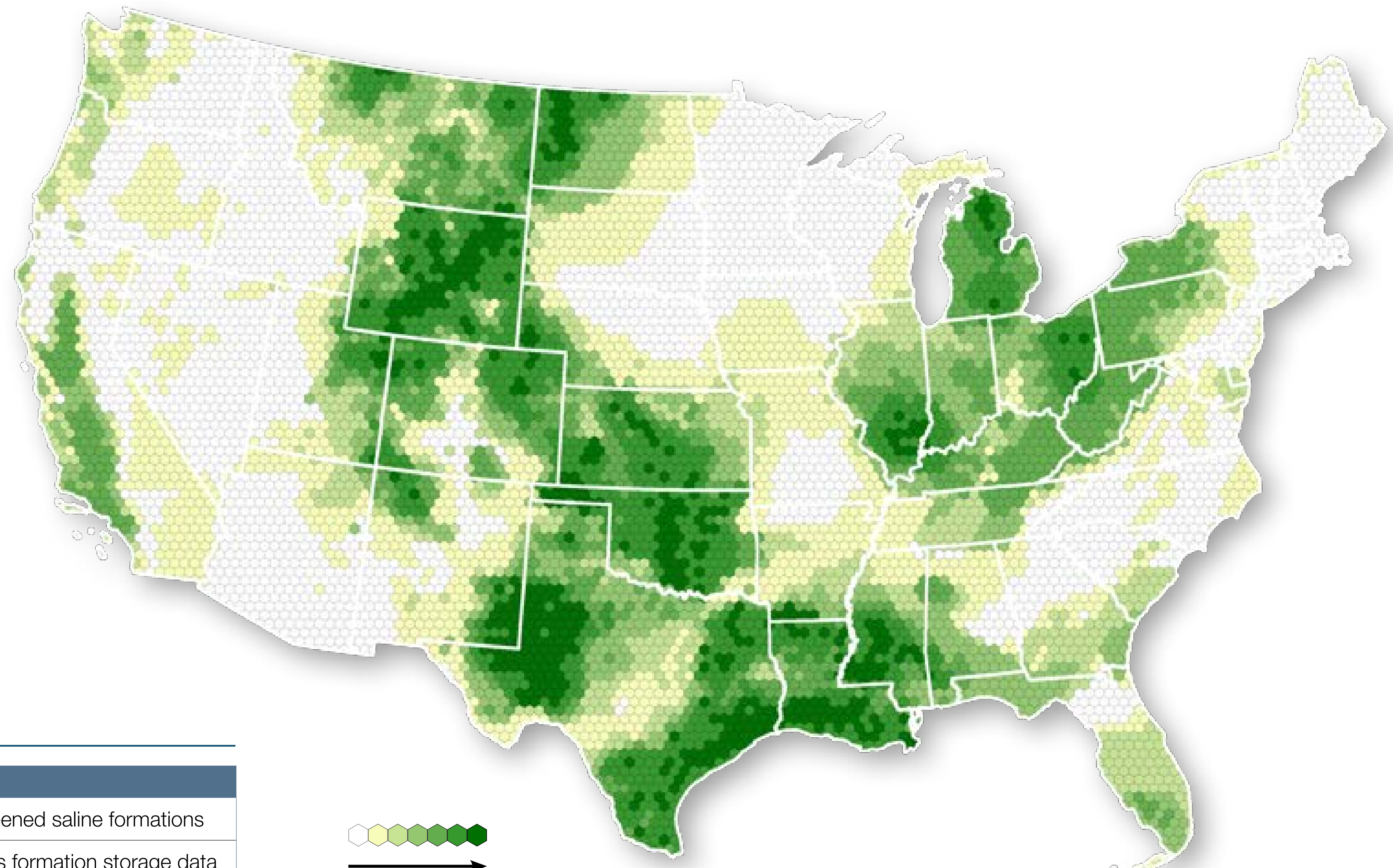
UNITED STATES ATLAS OF DIRECT AIR CAPTURE

Appendix | Opportunities for Geologic Carbon Storage

Access to geologic carbon storage opportunities is a key siting consideration for DAC facilities. Geologic carbon storage is achieved when carbon dioxide (CO_2) collected from a DAC facility is injected deep underground into formations or reservoirs with suitable physical characteristics. Locating DAC facilities in areas with plentiful geologic carbon storage capacity can minimize costs and logistic hurdles associated with developing CO_2 transport infrastructure. Co-locating DAC facilities with permanent CO_2 storage sites can also support the growth of a local ecosystem of associated industry and infrastructure.

The geologic carbon storage siting criteria considered in this analysis are listed in the table below. Given the importance of geologic carbon storage opportunities in DAC siting, any location that scored a zero across all geologic storage layers was given an overall DAC suitability score of zero.

Geologic carbon storage DAC suitability scoring results



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Geologic carbon storage cell scoring considerations

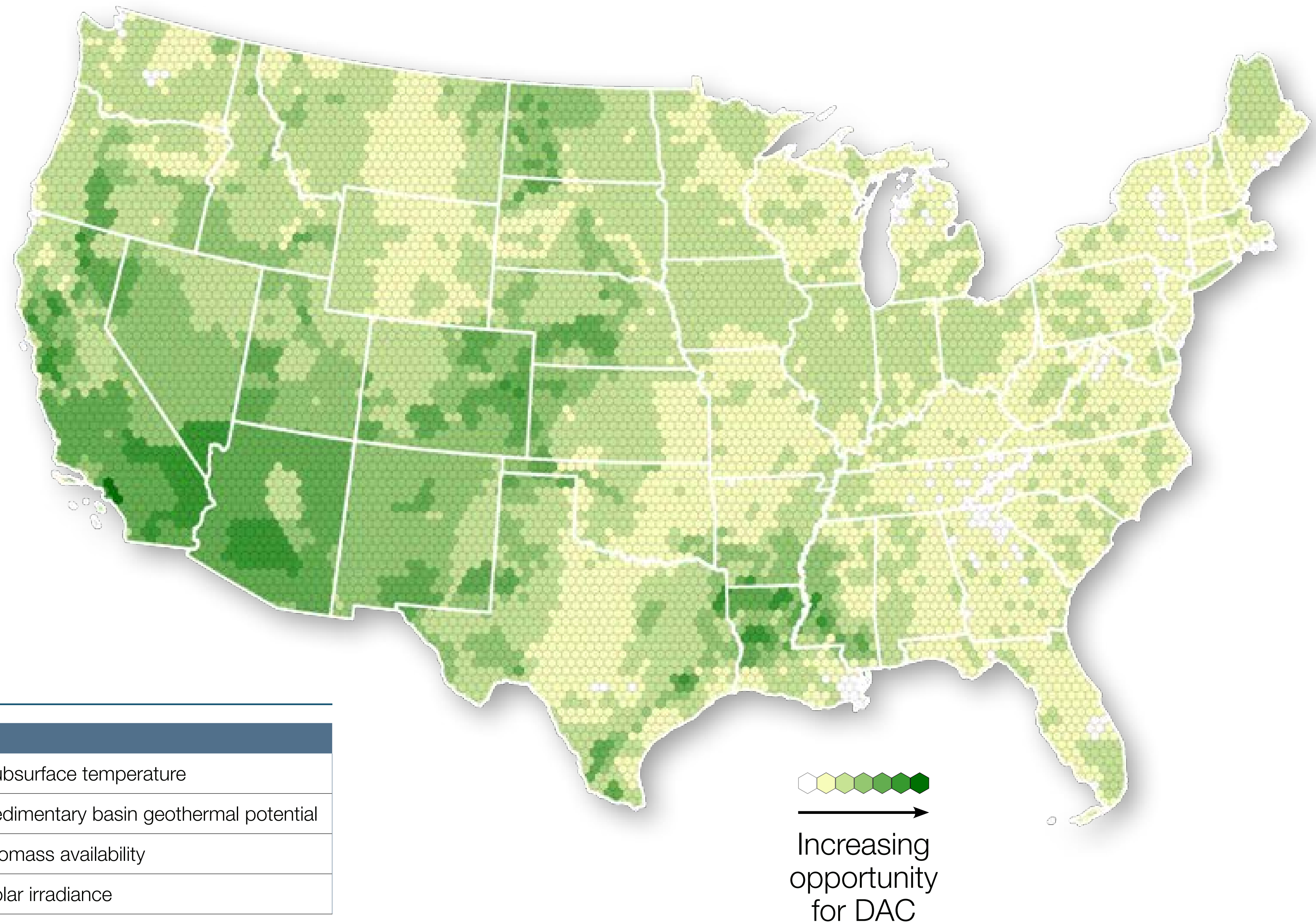
Siting Consideration	Criteria for Highest Score
Saline formation storage	Cell contains SCO_2T^{PRO} model screened saline formations
Oil/gas reservoir storage	Cell contains NATCARB oil and gas formation storage data
Potential EOR site	Cell close to oil field with current or potential EOR activity
Existing CO_2 pipeline	Cell close to existing CO_2 pipeline

Appendix | Sources for Low-Carbon Heat

DAC facilities require low-carbon sources of both heat and electricity (except in the case of an electric-only system) to power facility operations. Low-carbon sources of heat, including geothermal, biomass, and concentrated solar energy, are considered in this analysis. When paired with carbon capture and storage, biomass can even be a net-negative energy source. Non-renewable heat sources, such as natural gas with carbon capture and storage, are considered separately.

The table below summarizes the renewable resources assessed in this analysis. Areas with high geothermal energy potential, biomass availability, and concentrated solar energy were given high scores to reflect their potential as low-carbon energy sources to power DAC facilities.

Regional resources DAC suitability scoring results



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Regional resource cell scoring considerations

Siting Consideration	Criteria for Highest Score
Hydrothermal or enhanced geothermal	Cell contains area with high subsurface temperature
Sedimentary basin geothermal	Cell contains area with high sedimentary basin geothermal potential
Biomass	Cell contains area with high biomass availability
Solar	Cell contains area with high solar irradiance