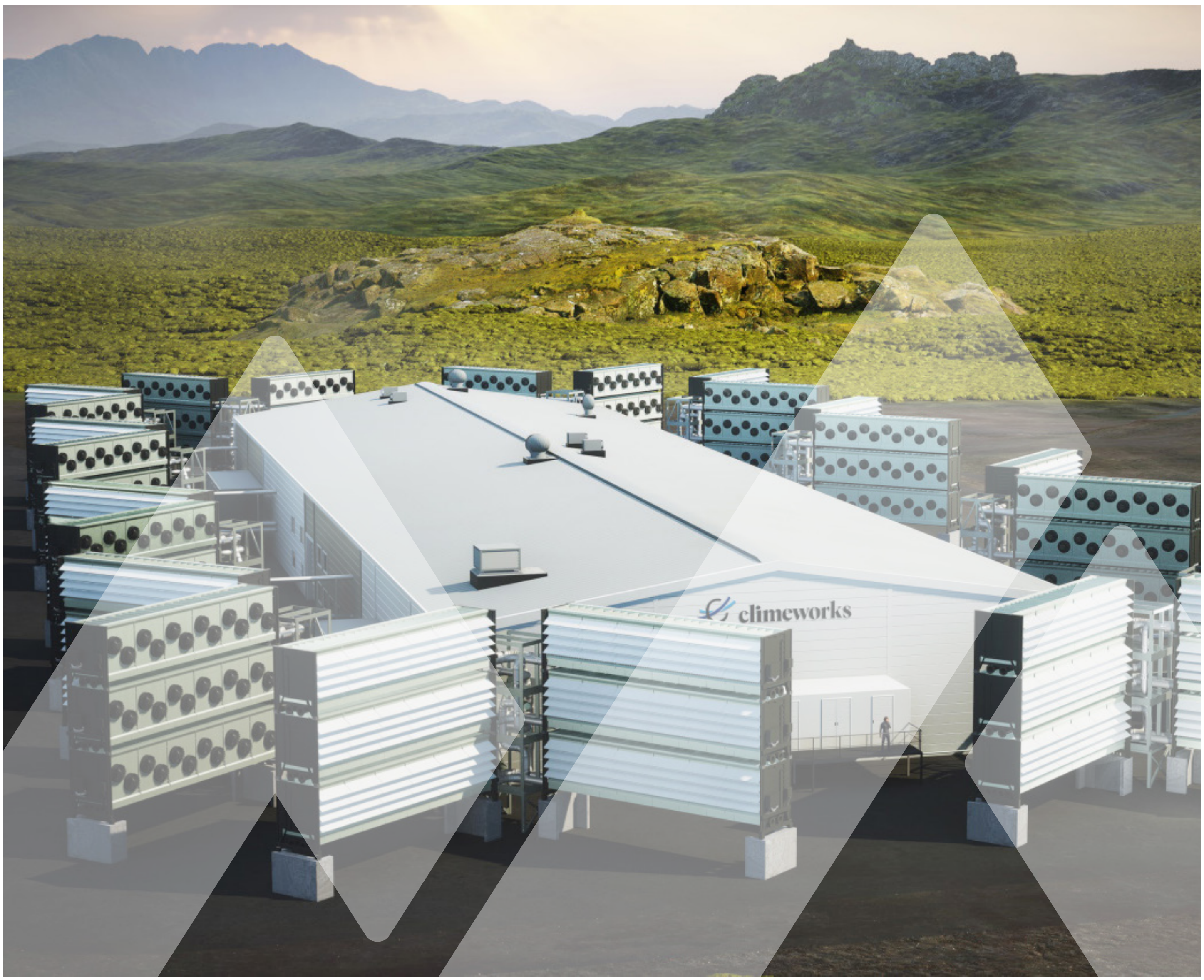
Direct Air Capture and the Energy Transition

Putting Potential Opportunity Costs in Perspective



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About RMI

RMI is an independent nonprofit founded in 1982 that transforms global energy systems through market-driven solutions to align with a 1.5°C future and secure a clean, prosperous, zero-carbon future for all. We work in the world's most critical geographies and engage businesses, policymakers, communities, and nongovernmental organizations (NGOs) to identify and scale energy system interventions that will cut greenhouse gas emissions at least 50 percent by 2030. RMI has offices in Basalt and Boulder, Colorado; New York City; Oakland, California; Washington, D.C.; and Beijing.

About Third Derivative

Founded by RMI and New Energy Nexus in 2020, Third Derivative (D3) is an open, collaborative climate tech ecosystem that accelerates startups and moves markets.

By guiding and supporting climate tech entrepreneurs who are bringing new ideas and innovation to market, D3 is accelerating the clean future worldwide. Through a vast global network of deep experts, corporate partners, and investors, D3 helps startups go to market faster with their breakthrough ideas, create real impact, and transform markets.

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Executive Summary

Attention to carbon dioxide removal (CDR), including both nature-based and engineered solutions, is rapidly growing as governments, corporations, and philanthropists explore its potential role in achieving net-zero emissions. The Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report's Working Group III contribution (WG3 Report), released in April 2022, reinforced this momentum, concluding that large-scale CDR deployment (> 1 $GtCO_2$/y) will be needed by 2050 to counterbalance residual emissions from harder-to-abate sectors and geographies.[1] Others cite the need for CDR to compensate for Earth's emissions triggered by climate change itself and the opportunity for high-ambition actors to address the legacy of past emissions by removing CO_2 already built up in the atmosphere.[2]

Although diverse natural and engineered CDR solutions are in development, interest in direct air carbon capture and storage (DACCS) is accelerating due to potential, but not yet fully proven, advantages over nature-based solutions in terms of permanence, water and land use requirements, and ease of measurement and verification. In earlier insight briefs in this series,[3] RMI and Third Derivative (D3) built upon existing comparisons of CDR technologies to assess the case for de-risking DACCS and analyzed possible innovation pathways for reducing costs and improving performance of this technology from now to 2030.[4] This increased attention, however, raises legitimate concerns about the potential unintended consequences and opportunity costs of DACCS relative to the speed of the underlying clean energy transition, particularly when we are already underinvesting in lower-cost, proven mitigation solutions.

As concluded in our last brief,[5] public and private investment is needed to test technology pathways, drive down costs, and validate system configurations and business models adapted to different conditions before the potential long-term role of DACCS can be more fully assessed. But we can look ahead to consider the relationship between DACCS and other climate change mitigation efforts based on a range of possible costs and resource requirements for these technologies. To help frame these issues, we assessed the potential energy transition implications of gigaton-per-year-scale deployment of one type of DACCS (low-temperature, solid-amine DAC [S-DAC]) in terms of energy, materials, investment, natural capital, and key social and political issues.

Our analysis suggests that rapidly scaling DACCS from 2030 (>1 $GtCO_2$/y capacities from 2040 to 2050) could risk incurring significant energy-transition opportunity costs in terms of economic inputs and political capital. Although a wide range of uncertainties surrounds these conclusions, the pace of DACCS's required technological improvement in all cases is ambitious. The notion of a one-for-one trade-off between DACCS and the speed of the energy transition oversimplifies a complex and nuanced issue, but policymakers must nonetheless consider how to prioritize public investments and structure market mechanisms to ensure a level playing field and deliver the greatest mitigation impact. This paper puts the potential scale and timing of these costs in perspective and recommends priority areas for research, innovation, messaging, and policy to better understand and mitigate these issues.

Developing innovative CDR options, including DACCS, to expand our portfolio of climate change solutions is not an either-or proposition. We need to continue accelerating the adoption of proven, low-cost mitigation solutions while investing in removal solutions that might backstop potential carbon budget overshoot and other long-term reductions in atmospheric greenhouse gas concentrations.

Rising Tensions between DACCS and the Energy Transition

Although the underlying goal of the energy transition remains focused on rapidly decarbonizing every sector of the global economy, energy and economic experts increasingly warn that even our best efforts may fall short. Some degree of nature-based or engineered CDR solutions are now widely (though not universally) seen as necessary for removing residual emissions. For engineered solutions such as direct air capture, however, there is a growing tension between support for DACCS and a realistic skepticism about a costly and energy-intensive technology that is yet unproven at scale. These tensions are further exacerbated by competing demands among different mitigation and removal solutions, including funding, access to clean energy sources to run DACCS equipment, targeted policy support, and optimal allocation of talent, capital, and attention.

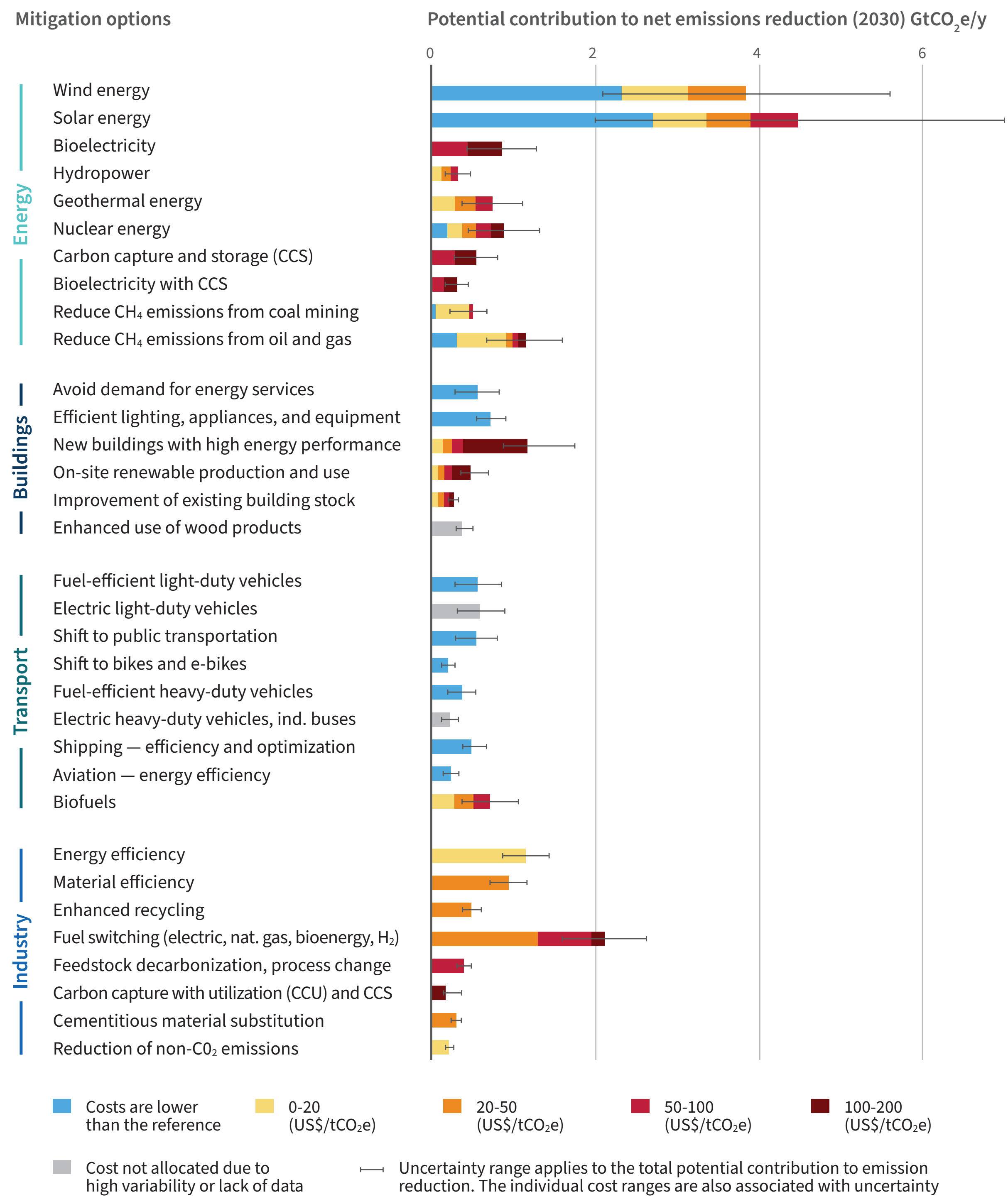
We are underinvesting in the most cost-effective, prompt, and certain path to 1.5°C

Efficient end-use of energy and materials, efficient electrification, and renewables are the most cost-effective ways to mitigate most carbon dioxide emissions. The Intergovernmental Panel on Climate Change Sixth Assessment Report's Working Group III (IPCC AR6 WG3) report reinforces this message with its high-confidence conclusion that mitigation options costing less than \$100/tCO_2eq could reduce global greenhouse gas (GHG) emissions by at least half of the 2019 level by 2030. The IPCC further notes that options with mitigation costs lower than \$20 per ton of CO_2 equivalent (tCO_2e) make up more than half of this potential and are available for all sectors. By comparison, DACCS costs in 2022 are tens of times higher (Exhibit 1). Even if, as some experts suggest, the cost of DACCS comes down to under \$100/tCO_2 by 2030, it will still cost considerably more than many other mitigation solutions whose costs are also continuing to decline.[6] Therefore, the potential for DACCS to be mischaracterized as a substitute for abatement is a key concern: Every missed opportunity to cost-effectively reduce emissions in the near term leads to increased future dependence on more costly and less certain removal solutions.

Despite the availability of low-cost, mature solutions and a sufficiently large global finance system, only a small portion of global funds are invested in efficiency and renewable energy efforts. In 2021, global energy transition investments broke a new record, growing by 25% from 2020 to reach \$755 billion total, according to a Bloomberg NEF report.[7] About half of these funds flowed into renewable energy and electrified transport solutions. Unfortunately, even these levels of investment fall far short of what is needed — BNEF estimates that \$2.1 trillion per annum on average is required for 2022 to 2025 to achieve even a 1.75°C target. A lack of enabling policies and regulations is a key contributor to this slow pace, as nationally determined contributions, pledges, and announced targets submitted by countries party to the Paris Climate Agreement remain inadequate to direct funding toward high-priority mitigation strategies.[8]

Exhibit 1 Estimated global GHG abatement costs

Many options available now in all sectors are estimated to offer substantial potential to reduce net emissions by 2030. Relative potentials and costs will vary across countries and in the longer term compared with 2030.



Source: Adapted from IPCC AR6 WG3

But the case for developing engineered CDR extends beyond harder-to-abate emissions

Although DACCS is currently one of the costliest climate solutions, it may play a role where policies and markets fail to support a least-cost emissions mitigation approach or in those limited cases where near-term abatement options are too challenging or expensive. For example, smaller amounts (<1 GtCO_2/y) of CDR could balance out emissions from harder-to-abate sectors such as heavy industry and long-haul aviation. Similarly, some economies may take longer to reduce GHG emissions in the context of their development goals and various policy, financial, and technology constraints.

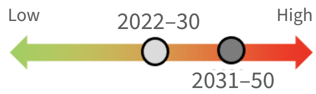
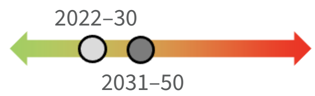
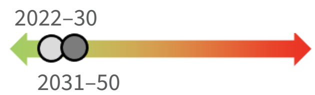
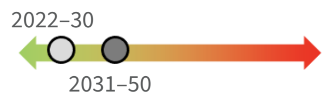
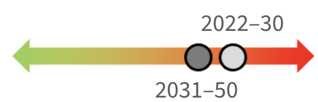
The higher costs for CDR solutions like DACCS must also be weighed against the potentially catastrophic costs of worsening climate change. In the longer term, CDR will be necessary if we have any hope of addressing carbon budget overshoot, earlier-than-expected Earth-systems tipping points (which may in fact be irreversible), or removing historical emissions already accumulated in the atmosphere. In its November 2021 guidance on CDR, the World Economic Forum considers each of these objectives to be "appropriate" uses of removals in organizations' climate strategies.[9]

How might scaling DACCS undermine a rapid energy transition?

In our previous insight brief we estimate a plausible potential for DACCS to provide up to approximately 3 GtCO_2/y by 2050 if the technology were successfully developed and scaled rapidly from today's levels.[10] In this insight brief we describe the potential intersections and opportunity costs of simultaneously accelerating known emissions abatement options while de-risking and potentially scaling DACCS as a carbon removal solution. We characterize these potential intersections across each of the five dimensions outlined in Exhibit 2, including their relative levels of concern for each of DACCS's initial de-risking phase (to 2030) and a potential subsequent scale-up phase (2031–2050). The remainder of this paper presents our characterization of the potential opportunity costs associated with each dimension, followed with recommendations for how policymakers and businesses can reduce their likelihood and impact on the underlying energy transition.

> **"The higher costs for CDR solutions like DACCS must also be weighed against the potentially catastrophic costs of worsening climate change. In the longer term, CDR will be necessary if we have any hope of addressing carbon budget overshoot, earlier-than-expected Earth-systems tipping points (which may in fact be irreversible), or removing historical emissions already accumulated in the atmosphere."**

Exhibit 2 **Key dimensions for DACCS potential impact on the energy transition**

Dimension	Description	Potential Opportunity Costs	Potential Conflicts and Considerations
1. Clean Energy	Zero-emissions energy to run DACCS processes		• Diverting low-carbon energy away from clean electrification of existing end uses
2. Capital	Financial investment to build DACCS infrastructure		• Competition for public and private investment versus options with higher mitigation benefit
3. Material Inputs	Steel, concrete, and chemicals to build and operate DACCS facilities		• Consuming material inputs that themselves require significant energy inputs
4. Natural Capital	Carbon storage, water, and land use implications		• Opportunity cost of land with high resource potential for wind and solar power • Incremental water demand • Lack of permitted geological storage
5. Political and Societal Factors	Considerations around political focus, public acceptance, and equity		• Public and political distraction from lower-cost mitigation efforts • Lack of public acceptance on need, siting, etc. • Questions of equity (geographic, generational)

Note: 2050 risk assessment assumes >1 GtCO_2/y capacity.

Source: RMI Analysis

DACCS deployment scenarios

We evaluated potential economic input and natural capital impacts using four deployment scenarios, summarized in Exhibit 3.

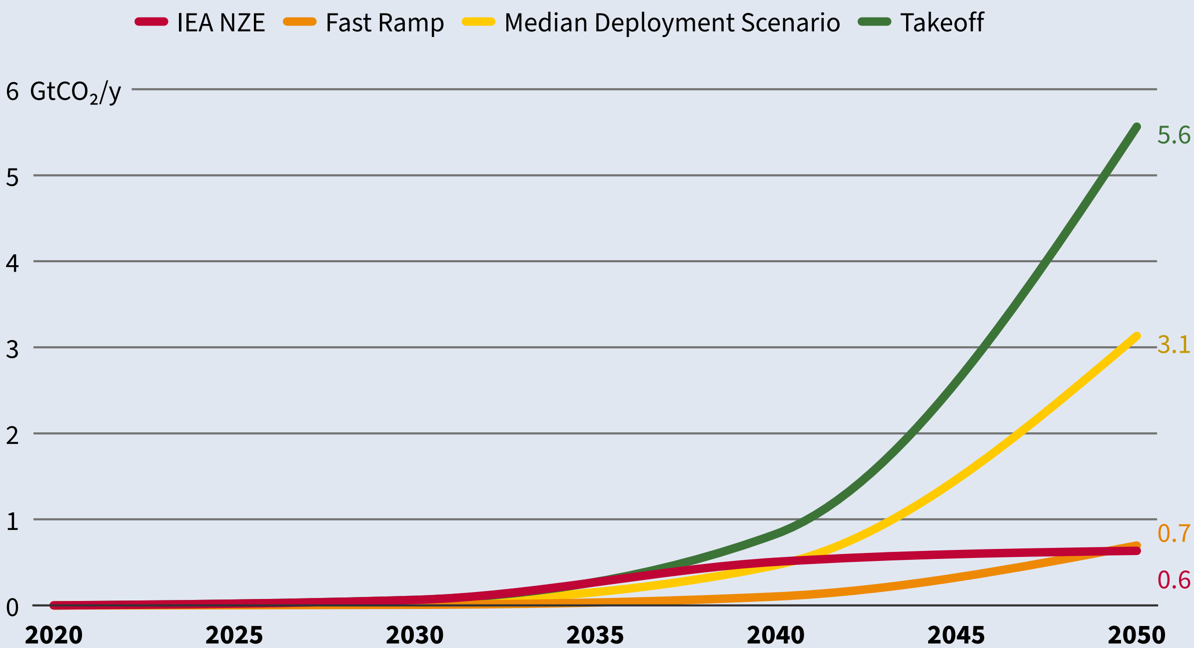
Three illustrative DACCS deployment scenarios are baselined against the IEA's 1.5°C-aligned Net Zero by 2050 scenario (IEA NZE). Although it is just one potential roadmap to net zero, IEA NZE represents what RMI considers an appropriate response to the climate challenge. Additional key considerations include:

- **We focus our analysis on low-temperature, solid-amine (S-DAC) technologies**, both for simplicity and our assessment that S-DAC's lower-temperature requirement currently presents a clearer path to reliance on low-cost, emissions-free power (e.g., electricity-based heat from renewable energy) than higher-temperature liquid-absorbent DAC (e.g., run off of abated natural gas, hydrogen, or biomethane).

- **We assume that captured CO_2 is sequestered underground in long-term geological storage.** We did not consider carbon capture and utilization pathways such as CO_2-derived fuels or enhanced oil recovery, the potential scalability, economics, and net climate benefits of which are unclear.

- **Electricity, heat, and investment analyses include sensitivity ranges** based on varying rates of technology and cost improvements from 2020 to 2050 (noted in each graph).

Exhibit 3 S-DAC deployment scenarios used to analyze potential constraints



Scenarios	Description	Rationale
IEA NZE	Based on IEA NZE DACCS deployment assumptions	Baseline capacity deployment trajectory for comparison
Fast Ramp	Yearly doubling DACCS capacity to 2030, followed by 20% annual growth to 2050	Alternative deployment projection to IEA NZE while reaching a similar capacity by 2050
Median Deployment Scenario	Median deployment scenario analysis output	Bullish but possible DACCS deployment with associated learning-effect cost reductions
Takeoff	Diverge from IEA NZE at 2030 to grow at 20% annually to 2050	S-curve type exponential growth

Source: RMI analysis; see ***Scoping the Need for Direct Air Capture*** for details

Scaling DACCS Will Require a Lot of Low-Carbon Energy

The additional demand that DACCS will create for low-carbon electricity is an oft-cited area of perceived trade-off between engineered CDR and a faster energy transition.[11] A primary justification for CDR stems from the need to abate emissions from slower-to-transition sectors (e.g., heavy industry) and potential carbon budget overshoot. Until we achieve anything close to net zero in regions where DACCS may scale up, however, one can reasonably argue that a megawatt (MW) of solar or wind is better deployed to more quickly and cheaply decarbonize the electric grid and decarbonize currently unelectrified fossil-fueled uses (directly, as in road vehicles, or via green molecules). Our analysis reveals that the energy needs for large-scale DAC deployment (>1 GtCO_2/y) from 2040 to 2050 are in fact significant, but that the notion of a one-for-one trade-off with the speed of the energy transition oversimplifies the issue.

Today's DAC plants use energy in two primary ways: electricity to drive the collector or air contactor systems and heat to regenerate the carbon-capturing sorbent for reuse. This analysis focuses on solid-amine DAC (S-DAC), which requires lower-temperature heat (80°C–120°C) for regeneration than liquid-solvent (L-DAC) approaches (900°C).[i] The resulting analysis of energy requirements under our different DACCS deployment scenarios appears in Exhibit 4. Notably, the incremental energy needs from now until 2030 in all four scenarios are relatively small, about 0.2% each of projected global electricity demand and projected global final heat demand in the *Median Deployment* scenario — an acceptable trade-off to support the de-risking and future optionality of DACCS technologies.

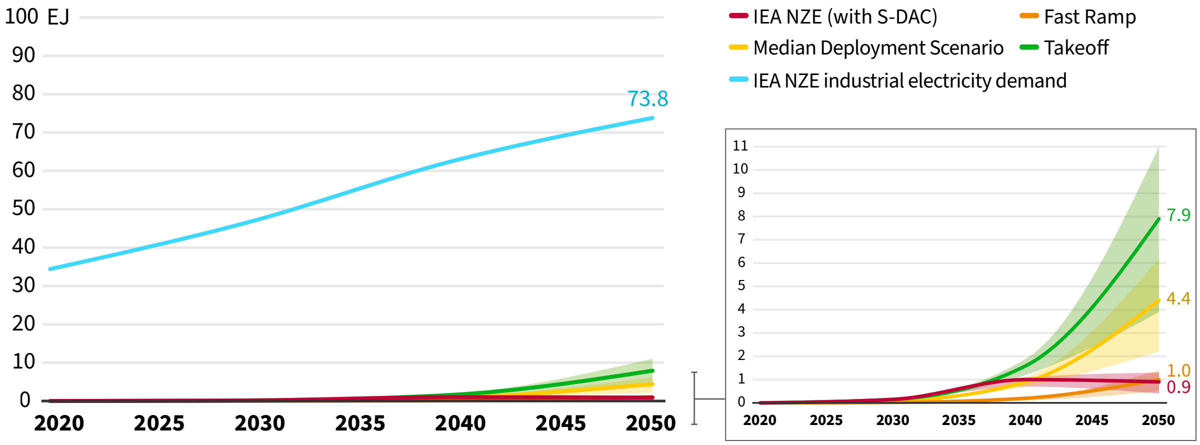
Competition for clean energy could slow the underlying transition

Potential concerns arise, however, when considering the potential energy requirements to significantly scale DACCS beyond about 1 GtCO_2/y. Our *Median Deployment* scenario, which achieves 3.1 GtCO_2/y of global removals in 2050, represents a highly ambitious but plausible path for DACCS development and scale-up. Under this scenario, we estimate that DACCS's demand for low-carbon electricity (excluding any that is used for regeneration heat, addressed below) would reach 0.9 exajoules (EJ) in 2040 and 4.4 EJ (range of 2.2–6.2 EJ) by 2050, an amount greater than Japan's 2020 total final electricity demand of 3.5 EJ.[12] This is equivalent to about 5% of *total* global electricity consumption in 2020 (81.8 EJ) and would represent a 6% increase over the 73.8 EJ of industrial-sector electricity demand that IEA NZE assumes for 2050. In our most aggressive *Takeoff* scenario, 2050 electricity demand for DACCS reaches 7.9 EJ (3.9–11 EJ), a 10.6% increase over NZE's industrial-sector electricity demand. Incremental electricity demand in 2050 for the two lower scenarios is estimated at ~1.0 EJ.

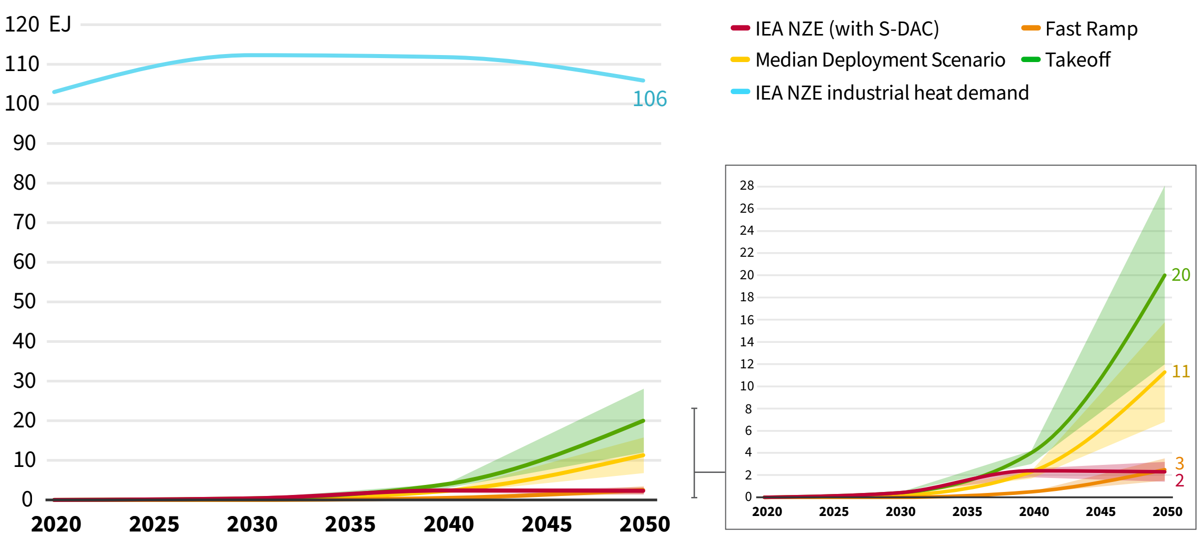
i See *DACCS deployment scenarios* section above. High-temperature, liquid-sorbent DAC (L-DAC) and other emerging technologies may present significant energy, cost, and other resource-related opportunities and trade-offs.

Exhibit 4 Estimated incremental final energy demand for S-DAC in illustrative DACCS deployment scenarios

4A: Global Final Electricity Demand



4B: Global Final Heat Demand



Note: Error bands represent sensitivities to the degree of S-DAC process improvement between 2020 and 2050: upper limit = 30% improvement, middle = 50%, lower limit = 75%. Also see footnote ii.

Source: RMI analysis, IEA NZE S-DAC adapted from IEA NZE

The situation for incremental heat demand is more complex. In the *Median Deployment* scenario, incremental heat demand for DACCS grows to around 2.3 EJ by 2040 and 11.3 EJ (6.8–15.8 EJ) by 2050, while the *Takeoff* scenario would require up to an additional 20 EJ (12–28 EJ).[ii] By comparison, the global cement industry's 2019 total final energy consumption was approximately 12 EJ. These values are large,

ii These values equate to 3.6 EJ heat/GtCO_2 removed, which is slightly lower than the 5 EJ heat/GtCO_2 removed in the IEA's 2022 DACs report. The difference is due to focusing our analysis only on low-temperature S-DAC and assuming 50% reduction in heating energy requirements by 2050. Note also that our analysis only includes DACCS, whereas the IEA's report also includes CCUS.

representing an increase of 10%–20% in 2050 industrial final heat demand relative to the IEA NZE baseline, even assuming 50% reduction in DACCS energy requirements per ton of CO_2 removed from 2020 to 2050.[iii]

What is unclear, however, is from where this heat will come. Low-temperature, solid-amine DAC has the advantage of requiring heat at temperatures around 100°C for its sorbent regeneration process. This heat could come from renewable electricity (via resistance heating or heat pumps), geothermal energy, or waste heat from co-located industrial or thermal electricity generation facilities. IEA NZE estimates that 65% of low- and medium-temperature heat (up to 400°C) for light industry use would come from electricity by 2050. However, addressing DAC's incremental heat demand with electricity could further increase competition for renewable energy capacity and electricity storage that might otherwise contribute to grid decarbonization.

Whole-systems approaches could reduce energy requirements

Reducing energy requirements should be a top priority for S-DAC research and development efforts, including those outlined in Third Derivative's earlier brief on DAC innovation pathways.[13] In parallel, however, researchers and industry players should continue to evaluate the most cost-effective low-carbon ways to power future DAC facilities, particularly where they may lessen the risk of slowing grid decarbonization efforts.

Exhibit 5 — Different S-DAC energy supply configurations may factor significantly into the levelized cost of CO_2 capture

Considerations for Meeting Energy Requirements	Islanded On-Site Generation	Grid-Tied On-Site Generation	Grid Dependent
No interconnection cost or dependence on grid access	✓	–	–
Additional capital costs for on-site generation	✓	✓	–
Self-generated power at cost	✓	✓	–
Resilient against grid outages	✓	✓	–
Resilient against on-site generation outage	–	✓	✓
Access to capacity and demand response markets	–	✓	(Some)
Potential to leverage renewable energy power purchase agreements or curtailed wind/solar	–	✓	✓
Co-located power (e.g., solar, wind, natural gas + CCS) entails land use and permitting considerations	✓	✓	–

Source: RMI analysis

iii As IEA NZE does not provide detailed total final heat demand or industry final heat demand, we calculated an illustrative baseline that assumes total final consumption of heat accounts for **50% of global final energy demand** and around **two-thirds of total final energy demand in industry**. Under IEA NZE, these proportions may be much lower given the scenario's degree of electrification and the higher efficiency of electricity-based heat versus fossil-based heat. In that case, the incremental heat demand for DACCS would represent an even larger increase against the IEA NZE baseline.

Reliance on solar or wind power would provide a low-cost option for high carbon-removal efficiencies. But the assumption that every marginal MW needed for DACCS should come from incremental solar and wind capacity oversimplifies the solution set, especially in a rapidly evolving energy system. Energy sources could include other renewable energy sources (with geothermal, solar thermal, or electrical heat) paired with electricity storage; nuclear energy (potentially including small modular reactors); on-site thermal generation (e.g., biomass or natural gas with CCS) with waste heat used for regeneration; or co-location with other industrial facilities with shared power and heat requirements. Similarly, different combinations of on-site versus grid-based power could dramatically alter the economics of an individual DACCS facility based on local energy market dynamics (Exhibit 5).

For example, a DACCS facility with grid-tied, on-site energy would have the option of selling excess capacity onto the grid, participating in demand response events, or even opting to sell power instead of capturing carbon if the economics dictate it. In addition to optimizing its own operations for carbon and power markets, such facilities could provide additional grid flexibility to ease the incorporation of variable renewables elsewhere on the grid. Developing a set of common approaches for DACCS energy demand and supply would provide the basis for a more complete accounting of potential energy costs and benefits, as well as potential impacts on clean energy supply chains.

Scaling DACCS Will Increase Climate-Related Investment Requirements

Financial market structures, as well as CDR's complementary role to emissions abatement efforts, make it challenging to claim that direct trade-offs exist between DACCS-related public or private investment and increased spending on the energy transition. Although there is some degree of competition among climate mitigation solutions for philanthropic and corporate attention and investment, both public or private capital can theoretically flow as easily into markets for energy efficiency and clean energy as they can into those for high-quality greenhouse gas removals. Therefore, much of the potential opportunity cost associated with capital requirements quickly turns to political and regulatory decisions to prioritize public investments and structure market mechanisms to deliver desired outcomes (see *Political and Societal Factors*).

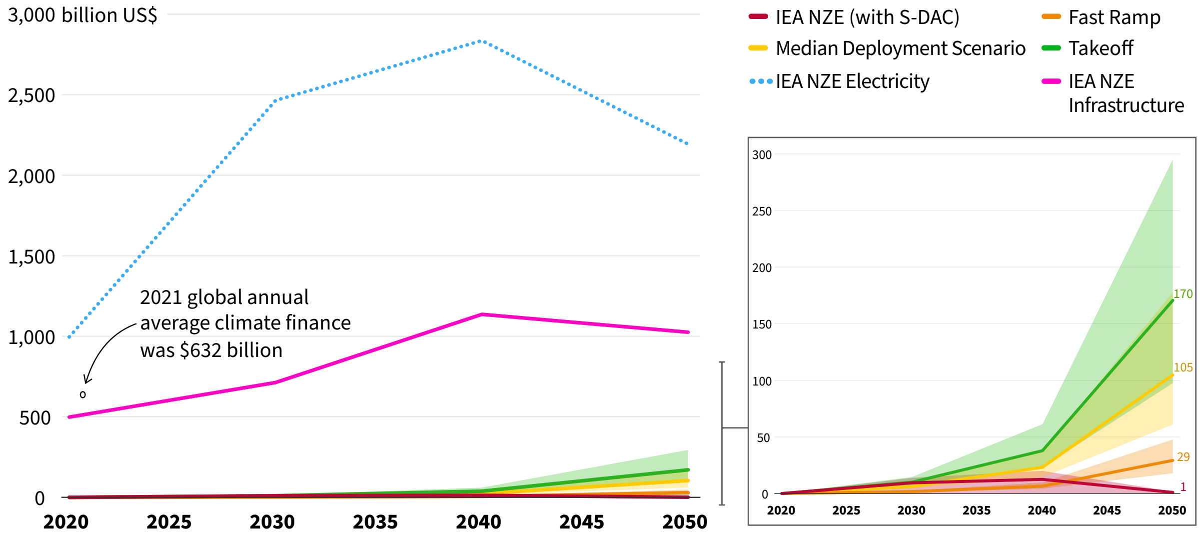
Instead, the more critical concern is the persistent gap in the overall pace of investment in climate change mitigation. According to the Climate Policy Initiative (CPI), the $632 billion/y invested globally in climate finance from 2019 to 2020 would need to be increased by 590% to meet internationally agreed upon climate objectives by 2030 and to avoid the most dangerous impacts of climate change.[14] This gap in funding cost-effective mitigation strategies must be closed alongside any new investment in technologies such as DACCS, whose promise remains so uncertain.

The near-term investment requirements for de-risking DACCS through 2030 are relatively modest compared with these overall levels of investment required for climate change mitigation. In the *Median Deployment* scenario, the estimated annual capital investment for DACCS is $6.2 billion/y ($4.3–$8.9 billion/y) in 2030. By comparison, the 2021 Infrastructure Investment and Jobs Act in the United States allocated $10 billion over five years primarily toward DAC and carbon storage research, development, and deployment.[15]

Beyond 2030, however, the prospect of scaling DACCS to multi-gigaton levels raises more meaningful questions about the pace of public and private investment across mitigation solutions. IEA NZE estimates that about $1 trillion/y will need to be invested in energy transition-related infrastructure from 2035 to 2050 to meet the 1.5°C goal, with another $2.2 trillion/y to $2.8 trillion/y required for new electricity generation (Exhibit 6).[iv] In the *Median Deployment* scenario, the incremental costs of scaling DACCS to 3.1 $GtCO_2$/y by 2050 would require an additional $105 billion/y ($61 billion/y to $178 billion/y depending on assumed learning rates) in that year above and beyond these investments, equal to a 10% increase in required annual energy-transition infrastructure spending. In the *Takeoff* scenario (5.2 $GtCO_2$/y by 2050), that number jumps to $170 billion/y ($98 billion/y to $295 billion/y), up to a 29% increase in annual infrastructure spending with an assumed 8% learning rate. This estimate includes capital for required transportation and storage infrastructure but excludes any incremental costs for clean energy capacity or grid infrastructure required to support that DACCS capacity.

iv Per IEA NZE, infrastructure includes "electricity networks, public EV charging, CO_2 pipelines and storage facilities, direct air capture and storage facilities, hydrogen refueling stations, and import and export terminals for hydrogen, fossil fuels pipelines and terminals."

Exhibit 6 Estimated average annual DACCS capital investment for illustrative S-DAC deployment scenarios



Note: Error bands represent sensitivities to the degree of S-DAC cost improvement from 2020 to 2050 based on different learning rates of 8%, 10%, and 12%. See sidebar *The Risks of Assuming Learning Rates* for *Emerging Technologies*.

Source: RMI analysis, IEA NZE, Climate Policy Initiative, **https://www.climatepolicyinitiative.org/publication/global-landscape-of-climate-finance-2021/**

The risks of assuming learning rates for emerging technologies

Great care and caution should be taken when using learning curves to project future costs for any emerging technology, including DACCS. Extensive studies of learning effects have shown that the costs for a given technology tend to decrease at a constant percentage with every doubling in cumulative production.[16] As described in the second brief in this series, some analysts propose that the cost to capture CO_2 using DACCS (including operating costs and levelized capital costs) will follow this trend, predicting 10%–15% as plausible learning rates.[17] But learning curves are often applied in an oversimplified manner when used in forward-looking technology analyses, particularly for an early-state technology such as DACCS where it is difficult to predict a long-term learning rate.

To help demonstrate the risks and sensitivities embedded in learning curve analysis, we modeled a range of learning rates while assessing the potential future capital investment required to de-risk and scale DACCS (Exhibit 7). We applied these learning rates against the capacity deployed in each scenario, starting from a 2021 capital cost estimate of $2,500/ton-y. This is equivalent to the low end of Climeworks' published estimates for its Orca facility in Iceland and in the range of estimated capital costs for a large solid-amine facility per a 2019 National Academies of Science CDR study.[18] The variation in resulting capital cost estimates is striking, particularly when applied to the larger *Median* and *Takeoff* deployment scenarios assessed for this brief.

Exhibit 7 **Average S-DAC capital costs modeled in each scenario based on assumed learning rates ($/ton-y)**

Scenarios	Learning Rate	2030	2040	2050
Fast Ramp	8%	768	517	402
	10%	563	341	249
	12%	409	223	152
IEA NZE (Assuming S-DAC)	8%	600	417	365
	10%	412	260	219
	12%	280	161	131
Median Deployment	8%	642	431	336
	10%	449	272	198
	12%	311	169	115
Takeoff	8%	599	403	313
	10%	411	249	181
	12%	280	152	104

Note: Assumes $2,500/ton capital cost in 2021 and a scaling unit of 1,000 ton/y.

Source: RMI Analysis

Putting cost improvement needs in perspective

The usefulness of DACCS to help address harder-to-abate emissions is predicated on steep cost declines and technology improvements. Earlier insights describe key opportunities for reducing DACCS costs to the levels assumed in this analysis, including reducing air collector and contactor costs, passive air contactor solutions, and novel sorbent and regeneration approaches.[19] Government and private-sector funding should continue to target these critical areas to ensure that resource requirements for DACCS solutions are minimized.

We must also continue to develop a more holistic accounting for DACCS's potential costs and benefits in helping to achieve net zero. This should include different siting and clean energy supply configurations such as those discussed above, as well as a shared understanding of potential approaches to both long-term storage and carbon utilization (e.g., carbon-derived fuels). A set of common, peer-reviewed assumptions about potential costs, revenues, and other considerations (e.g., net energy and emissions balances) could help provide a better basis for qualifying the scope and scale of DACCS's potential role in a net-zero economy.

Finally, we must also better incorporate the economic risks and societal costs of a changing climate into any analysis of decarbonization options. As the financial industry develops shared frameworks for evaluating climate risk, the increasing costs of inaction will become ever clearer.[20]

Materials Inputs Are Unlikely to Constrain DACCS Potential

Three materials — steel, cement, and sorbents — are commonly invoked in discussions questioning the viability or impact of large-scale DACCS, including potential competing demand for steel and cement to support the fast-growing renewable energy market. They are unlikely to significantly limit the scale of future DACCS deployment or cause incrementally larger concerns for the speed of the energy transition.

Steel and cement are addressable inputs

Our analysis of the potential steel and cement requirements for DAC facilities across our four deployment scenarios indicates that none would represent a meaningful increase in demand for either material. For example, IEA NZE assumes that 2050 global demand reaches 2,000 million tons per year (Mt/y) for steel and 4,000 Mt/y for cement. Additional demand for steel and cement in our most aggressive scenario is only 0.06% and 0.05% of these estimates, respectively. Although our analysis did not model the potential incremental demand from associated pipelines, storage facilities, or clean energy capacity, other studies have found that large-scale DACCS deployment would require less than 0.1% of the global annual demand for concrete, steel, stainless steel, aluminum, copper, and plastics.[21]

Sorbent demand would require rapid but not unprecedented scale up

Ultimately, the specific types of sorbents required for a future DACCS industry will be determined based on the research, development, and demonstrations conducted over the next decade. For the sake of evaluating potential constraints, we estimated the potential annual demand for solid amine sorbent across our four deployment scenarios using sensitivity parameters similar to what we used with our energy use requirements. This included improvements in the amount of sorbent consumed per unit of CO_2 removed on an annual basis (assuming that solid amine sorbent must be replaced every 12 months) of 30%, 50%, and 75% between 2020 and 2050.

Global amine production was 1.9 Mt in 2020, used mostly for crop protection, surfactants, water treatment, personal care products, and natural gas treatment. In our *Median Deployment* scenario, sorbent demand would grow to an estimated 11.7 Mt/y by 2050, a more than six-fold increase. For comparison, global nitrogen fertilizer production increased by greater than five-fold between 1960 (12 Mt) and 1980 (63 Mt).[22] Other recent life-cycle assessments of DAC published in 2021 similarly concluded that input requirements for chemical absorbents will not limit DACCS scaling potential.[23] Attention should be paid to the potential disposal requirements of spent sorbents, but at this point no research has indicated any associated constraints.

Natural Capital Considerations

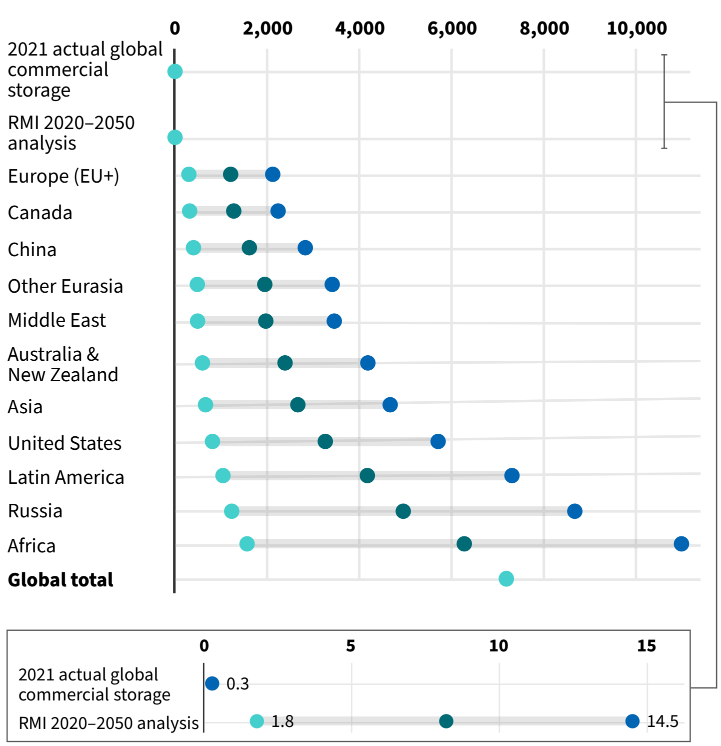
As with any technology-based climate solution, DACCS both requires inputs from the environment and imposes impacts on it. Here we assess DACCS impacts in terms of geological storage, land use, and water usage, with a particular focus on land-use opportunity costs for the energy transition.

Geological storage is abundant but undeveloped

One of the most attractive qualities of DACCS is its long-term CO_2 storage potential. Although the demand for storage seems large, the estimated total global storage potential is far larger. Academic and industry analyses suggest that there are millions of gigatons of storage potential worldwide, both on land and in deep-sea sedimentary and other reactive rock formations.[24] Our largest deployment scenario requires only 14.5 $GtCO_2$ cumulative storage capacity from 2020 to 2050, a volume that could conceivably be stored in any region on Earth.

Exhibit 8

Estimated practical geological storage capacity by region, onshore and offshore ($GtCO_2$)



Regions	Lower	Upper	Average
2021 actual global commercial storage	0.3		
RMI 2020–2050 DACCS demand	1.8	14.5	8.2
Europe (EU+)	302	2,120	1,211
Canada	318	2,236	1,277
China	403	2,830	1,616
Other Eurasia	485	3,410	1,948
Middle East	492	3,454	1,973
Australia & New Zealand	595	4,184	2,390
Asia	665	4,670	2,667
United States	812	5,708	3,260
Latin America	1,040	7,310	4,175
Russia	1,234	8,673	4,954
Africa	1,563	10,986	6,275
Global total	**7,190**	**55,581**	**31,745**

Source: Kearns et al. (2017); RMI Analysis; OGCI - CO_2 Storage Resource Catalogue (2021)

Despite this vast storage potential, only around 0.3 $GtCO_2$ of geological storage sites are currently operational and questions remain about how quickly additional capacity can be verified and brought online.[25] The IEA notes that storage site development can take up to 10 years in some cases.[26] Further, most global estimates of capacity are not physically or economically validated but are derived from general geological surveys and numerical simulations. Commercial development of storage capacity to support DACCS scaling would require detailed investigations, drilling for site preparation, and a robust monitoring and permitting framework to manage environmental impacts.

As land-use requirements will vary substantially, energy transition impacts are challenging to predict

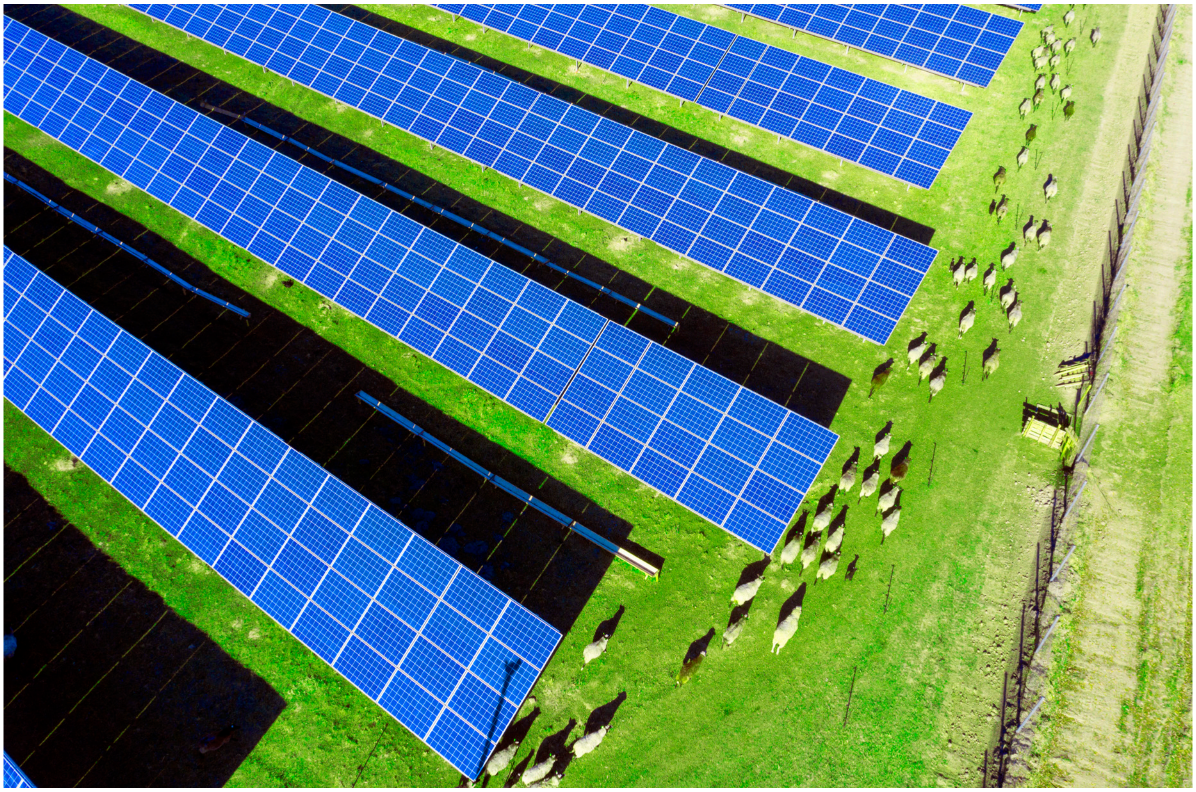
Direct air capture facilities are expected to have much lower land requirements than other CDR solutions.[27] For example, the Climeworks Orca plant in Iceland removes 4,000 tCO_2/y and occupies only ~1,000 m^2 (about one-quarter of an acre). Larger facilities are expected to require incrementally less land per unit of carbon removal, and DACCS can be sited on non-arable land, mitigating potential conflicts with agricultural uses. However, land use to supply energy to DACCS plants can be considerable. For S-DAC plants supplied with renewable electricity from solar and wind, for example, the indirect land use requirements for electricity generation are 70–130 times larger than the direct requirements for DACCS plants, with the caveat that the land between turbines or surrounding modules remains open and accessible for other productive uses (potentially including modularized DAC units).

In any case, facility siting for DACCS must still be deliberate, with ideal locations being in close proximity to: (1) operational (i.e., "injection ready") geological storage, (2) an abundant and affordable low-carbon energy source, and (3) land with clear property rights. Three areas of uncertainty in assessing DACCS land use that deserve additional study and consideration as technologies are developed and evaluated include:

- **Energy supply:** Overall land-use implications for DACCS will ultimately depend on the energy source. Recent work from IEA and others underscores the potential benefits and limitations to co-locating DACCS facilities with areas of strong renewable energy resource potential or existing nuclear energy capacity.[28] As noted earlier, however, other potential cost-effective, low-carbon energy sources warrant consideration in an evolving energy system.

- **Sequestration:** The land-use requirements for carbon transport and sequestration infrastructure depend on plant (or multi-plant hub) configurations. In some cases, such as at the Climeworks Orca plant, DACCS facilities built close to sequestration sites will minimize these impacts, but this cannot be assumed to be the case for large-scale deployment. Construction of new pipeline networks would significantly increase land use unless they can be co-located with or repurpose existing infrastructure and rights-of-way.

- **DAC plant configuration:** Particularly for solid-amine DAC, the optimal spacing of air collectors and CO_2 collection and storage units is still unknown and likely to evolve. As with wind turbines, significant spacing may be required to achieve optimal capture efficiencies, safety, and operating costs.



Water requirements

The net water use of a DACCS facility depends on the type of system and method of sequestration. The solid-amine process, for example, consumes no water and even produces water from the CO_2 capture process, raising the possibility of additional value streams.[29] By contrast, high-temperature liquid-solvent DAC, such as that used by Carbon Engineering, can require up to 50 tons of water per ton of CO_2 captured. These estimates will vary based on the local climate conditions and technologies used. Companies have only recently begun to evaluate or consider ways to optimize water use against other performance metrics.

Water consumption for the sequestration phase can also vary significantly depending on the process used. Injection of CO_2 directly into subsurface media such as saline formations or depleted gas reservoirs requires no water but can be energy intensive. However, other methods of sequestration, such as the Carbfix process used at the Climeworks facility, require about 27 tons of water to sequester 1 ton of CO_2.[30] By comparison, other CDR solutions, such as bioenergy with carbon capture and storage (BECCS) and afforestation, can require hundreds of tons of water per tCO_2/y.[31]

Global water stress already affects the lives of one-quarter of the world's population and must be considered when assessing the merits of these technologies relative to alternatives and evaluating possible deployment sites.[32] Similarly, more research is needed to better understand the potential likelihood and ways in which geological storage of CO_2 could affect groundwater quality in order to inform regulators and the public about potential impacts and safety measures.[33]

Political and Societal Factors: Where Does DACCS Fit?

Direct air capture has not yet attained broad public awareness. As DACCS technology development accelerates, politicians, policymakers, and citizens will increasingly engage in public conversation about whether and how these technologies should be deployed and at what scale. Ultimately, policymakers must consider how to prioritize public investments and structure market mechanisms to ensure a level playing field and deliver the greatest mitigation impact while also considering the potential long-term need for cost-effective carbon removals. But de-risking DACCS is not just a matter of improving performance and cost. Key questions will include who will pay, where to deploy, who is liable for post-sequestration monitoring or potential leakage, what role public and private institutions will play, and how to evaluate trade-offs between these and other solutions.

> **“Direct air capture technologies aim to create a global public service and, at the same time, their deployment has local and regional consequences tied to a complex system of actors, infrastructure, and regulation. Environmental and climate justice experts note that public concerns go beyond the technology itself and are rooted in past experiences with government or corporate behavior.”**

All of this will be made more difficult by the complexity and uncertainty surrounding DACCS and other CDR options. Part of the challenge lies in the nuanced message about the role of CDR and DACCS that the IPCC, IEA, and other leading institutions are trying to convey. Specifically, they argue that although CDR will be needed to compensate for harder-to-abate emissions, it is not an alternative to sharply reducing the use of fossil fuels. Despite what could be a simple and unifying message about investing in CDR alongside continued acceleration of emissions reduction efforts, distrust and a misplaced sense of competition could stifle progress on DACCS if divisions persist or deepen.

Public education and engagement will be critical

A 2019 study found that the level of public support for CDR solutions is inversely related to perceptions of how much a given strategy interferes with nature.[34] Further, an increase in information about a CDR strategy's trade-offs generally leads to decreased acceptance. As a result, developers and policymakers will need to be mindful of public understanding of these technologies and their combination of local and global consequences. Direct air capture technologies aim to create a global public service and, at the same time, their deployment has local and regional consequences tied to a complex system of actors, infrastructure, and regulation. Environmental and climate justice experts note that public concerns go beyond the technology itself and are rooted in past experiences with government or corporate behavior. This is especially the case when DACCS developers or investors include oil and gas companies whose operations are at the center of the climate crisis.

Policymakers, corporations, civil society, and investors interested in DACCS can and should ensure that a successful deployment of DACCS be net beneficial to the stakeholders most affected by it, from local communities near the plants to global society, while also taking into consideration implications for future generations. In a recently published article leading civil society and academic experts offered a helpful framework for considering environmental justice in the context of engineered CDR (Exhibit 9).[35] It rightly suggests that entities interested in investing or deploying DACCS should engage with the public early on to understand each community's needs and concerns.

Exhibit 9 **Framework for considering the environmental justice aspect of engineered CDR**

	Local Communities	Global	Intergenerational
Addressing the knowledge gap	Early engagement with local communities is key to: • Thoroughly assess and educate around possible environmental and health risks. • Clearly understand the community's needs, values, and development priorities, to identify possible conflicts or synergies with the DACCS project.	• Identify which polluting stakeholders are most responsible to remove historic CO_2 pollution. • Identify who has the most capacity to support deployment of DACCS.	• Consider how current policies and projects will affect future generations. • Determine the possible impacts of DACCS technologies for future generations.
Fair and equitable decision-making process	• Invite and empower the local communities into the decision-making process. • Assess and resolve public and private roles around the technology.	• Identify and address possible global implications and opportunities for technology transfer.	–

Source: Adapted from M. Batres et al., "Environmental and Climate Justice and Technological Carbon Removal," https://doi.org/10.1016/j.tej.2021.107002

Conclusions and Recommendations

Scientists now broadly agree that large-scale nature-based or engineered CDR will be required to counterbalance residual emissions from harder-to-abate sectors, and in the longer term to draw down historical emissions, if we are to avoid the worst impacts of climate change. Direct air capture is a promising potential component of the portfolio of CDR solutions that requires our attention and investment if it is to become a viable option. Although DACCS's current capture costs are high, pathways may exist to drive these costs below that of known mitigation solutions for our hardest-to-address emissions. Further, avoiding the economic costs and social impacts of inadequate action to address climate change will far outweigh the near-term investments in both emissions mitigation and removals.

The levels of clean energy, investment, and other material and natural capital inputs required to attempt to de-risk DACCS by 2030 are unlikely to dramatically disrupt the clean energy transition. The greater near-term risk is that we allow the future potential for cost-effective DACCS to distract policymakers, financial institutions, and corporate climate strategists from the critical work of dramatically reducing emissions now across every sector of the global economy. It cannot be overstated that the scientific consensus for CDR's role is in *addition* to the already unprecedented transformation of our energy, food, and agricultural systems to reduce GHG emissions in line with net zero by 2050.

Should S-DAC deployment ambitions expand beyond 1 GtCO_2/y capacities from 2040 to 2050, the clean energy capacity requirements will likely impact deployment rates and supply chains for renewable energy projects that would otherwise contribute to the underlying energy transition. This is true under even the most ambitious DAC technology and cost improvement assumptions, though the degree of impact may be partially mitigated based on the ultimate clean energy supply configurations that emerge for DACCS. It is therefore critical that we prioritize technology and cost improvements between now and 2030, including better consideration of the whole-system costs and potential synergies between DACCS and other aspects of the energy transition (e.g., grid flexibility).

The following recommendations are intended to help policymakers, researchers, corporations, investors, and philanthropists prioritize near-term investments to de-risk DACCS in ways that will reduce potential competition with the fundamental needs of the underlying energy transition and support public understanding and acceptance of its potential role in a net-zero future.

Keep DACCS's relative role in perspective

Efforts to de-risk DACCS from now to 2030 must be undertaken with recognition of the broader goals, needs, and opportunity costs of different mitigation options, particularly as it relates to the potential to undermine increased focus on and support for accelerating the energy transition and associated emissions reductions.

- **Advance clear messages and frameworks about what constitutes CDR and its appropriate role in climate change mitigation.** Policymakers, goal-setting bodies, and corporations should set clear definitions and boundaries for CDR within national and corporate climate plans.
    - They should reinforce that high-quality carbon credits and removals *must be additional* to a rapid and robust energy transition. They cannot be a substitute for rapidly reducing emissions when viable mitigation options exist, nor justification for investing in new fossil fuel resources.
    - Policymakers and researchers should continue to develop analysis and guidance on the potential long-term role of "net-negative" carbon removals to compensate for Earth's potential emissions triggered by climate change itself and the opportunity to address the legacy of past emissions already built up in the atmosphere.
    - Finally, policymakers and industry actors should continue to differentiate between DACCS (a removal) and point-source CCS (an avoidance) while still acknowledging the need for both approaches.
- **Spend in relation to solutions' costs and expected roles.** Investment in existing, proven, prompt, and cost-effective mitigation solutions is already falling far short of the pace required to meet 1.5°C targets. Climate policies and investment strategies should fund mitigation and removals at levels reflecting their respective cost and speed, and hence their ultimate roles in achieving net zero. This should especially include maximizing cost-effective investments in energy efficiency, which remains the most underutilized mitigation tactic. The IEA NZE provides one helpful resource for estimating the relative need across different aspects of the energy transition.
- **Consider equity implications as a core component of DACCS policy and investment decisions.** Public perceptions and acceptance of DACCS may play a significant role in its ability to rapidly scale. Advocates should continue to prioritize equity considerations alongside other critical success factors. This includes engaging local communities in where and how DACCS facilities should be deployed and giving consideration to the historical geographic inequalities related to development and carbon emissions.

Take a whole-systems approach to prioritizing key cost and value drivers

Few of the cost and technology improvement pathways for DACCS can be considered in isolation from their interactions with and impacts on other cost and impact drivers. Optimal system designs will be location and technology specific and may involve several viable variations.

- **Prioritize near-term DACCS research and development on reducing electricity and heat demand.** Given that electricity and heat requirements remain the largest and most expensive inputs for DACCS, research should focus on reducing these impacts first. This can include both incremental design improvements to known capture approaches as well as emerging novel approaches that represent step changes in capital or operating costs.

- **Develop shared resources to support a whole-systems approach to optimizing plant configurations and siting.** What with differing capture technologies, approaches to clean energy supply, evolving power market dynamics, water needs, and storage and utilization options (among other criteria), there are countless potential configurations for DACCS facilities. Research institutions and industry groups should collaborate to develop open-source data resources and common DACCS configurations to serve as a basis for comparing and improving approaches to reducing both capital costs and energy requirements.

Mitigating climate change and limiting warming to 1.5°C will require contributions across all sectors, technologies, and approaches. If we are to limit warming, we must search widely for potential solutions including in the supply and demand of energy as well as emissions reductions and removals. All sectors will need to make progress as quickly as possible, but investing in technologies at different stages is not a zero-sum game. Climate change is a systems-level problem that will require whole-systems solutions. DACCS should be considered objectively as part of that solution portfolio.

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