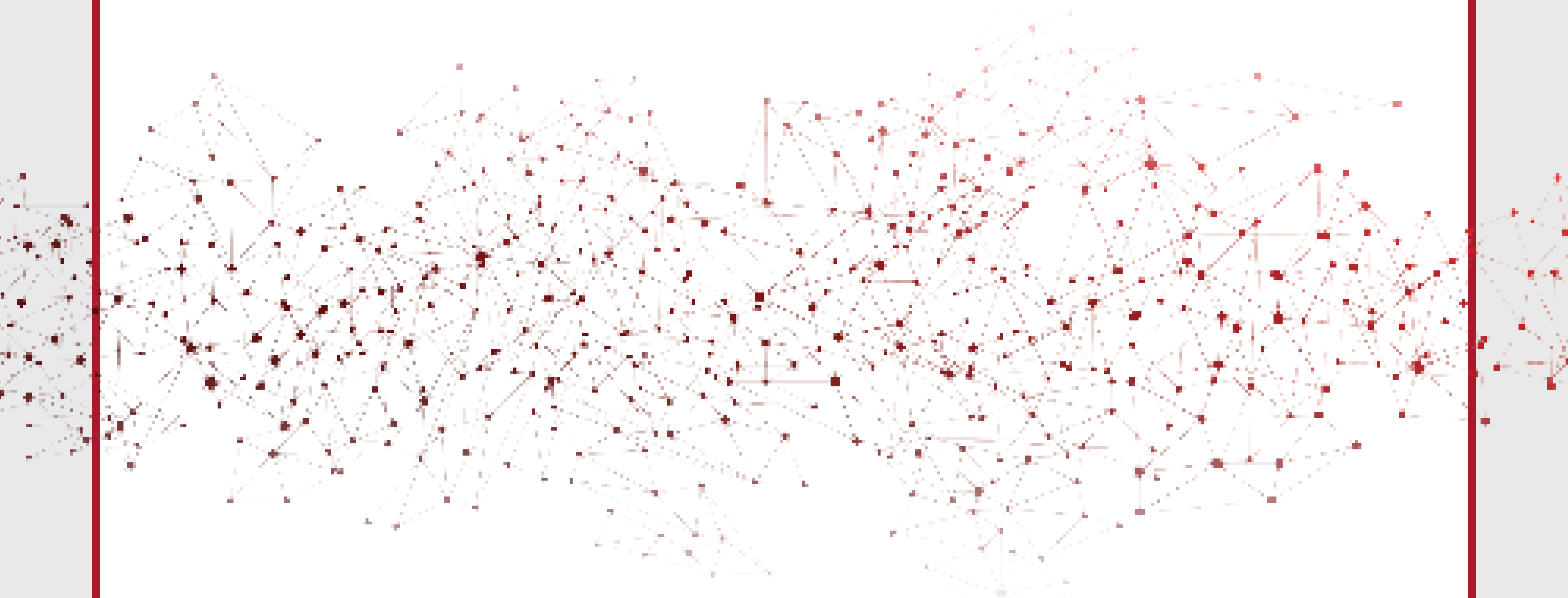
TECHNOLOGY PRIMERS FOR POLICYMAKERS

Direct Air Capture



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The Technology Primers for Policymakers Series was designed to provide a brief overview of a technology and related policy considerations. These papers are not meant to be exhaustive.

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Executive Summary

Direct air capture (DAC) is a type of technology that captures carbon dioxide directly from the air.[1] The captured carbon can either be permanently sequestered in the ground – thus achieving carbon dioxide removal (CDR) – or reused in several beneficial applications. Along with other carbon management technologies, DAC is often discussed in the context of decarbonization and the green energy transition. As the negative impacts of climate change become ever more apparent, governments and private industries have funneled increasing support toward DAC as a critical pathway toward achieving a net-zero future. The market for DAC has also expanded, with many emerging companies developing and commercializing innovative approaches to DAC technology.

Although a promising technology, wide-scale deployment of DAC faces several significant challenges. Resource limitations – including DAC's high energy requirements – and the high economic costs of developing DAC systems are ongoing constraints. While gaining prominence, DAC is still in its infancy, with few operating plants worldwide. DAC is also significantly more expensive than other commercially available carbon dioxide removal models, and some in the scientific community doubt that we could bring down the resource and material costs of DAC enough to make it a viable negative emissions technology. Furthermore, the DAC process itself comes with its own carbon costs, not to mention the reuse applications of the captured carbon, which on the whole might potentially outweigh the positive environmental benefits of the technology.

Public purpose considerations for DAC include ensuring that the technology actually yields net carbon removal over its full life cycle; protecting the political rights of local communities situated around DAC facilities; balancing investments in DAC infrastructure and green energy with consumer welfare; and making sure that the jobs generated by DAC are equitably distributed. Policymakers have so far focused most of their attention on funding Research and Development (R&D) in DAC and other carbon capture technologies, but effectively and responsibly scaling up DAC will require further developing and enforcing the regulatory framework around these and related technologies.

1 While techniques like afforestation also capture carbon dioxide directly from the air, this primer deals only with technology-based methods of DAC.

PART 1: Technology

According to the International Energy Agency (IEA), "Direct air capture (DAC) technologies extract CO_2 directly from the atmosphere. The CO_2 can be permanently stored in deep geological formations (thereby achieving negative emissions or carbon removal) or it can be used, for example in food processing or combined with hydrogen to produce synthetic fuels."[2]

When combined with long-term carbon storage, DAC is a subcategory of Carbon Dioxide Removal (CDR) technologies. CDR technologies remove carbon dioxide directly from the air and are distinct from Carbon Capture and Storage (CCS) or Carbon Capture and Utilization (CCU) technologies that capture CO_2 at specific points where it is more concentrated than in open air – for example, flue gas at power plants. The increased concentration of CO_2 at these locations typically makes CCS or CCU technologies less costly than DAC due to lower energy and air processing requirements.[3] However, one advantage of DAC over CCS or CCU technologies is that it is not coupled with new sources of carbon emissions and can theoretically be used to capture historic emissions.

DAC is also often discussed as a Negative Emissions Technology (NET). NETs, also known as Greenhouse Gas Removal Technologies, remove greenhouse gasses, usually CO_2, from the atmosphere.[4] NETs only apply to processes that, over their entire life cycles, yield net greenhouse gas removal (i.e., the amount captured minus the amount re-emitted). As implied by the IEA definition, DAC is not inherently a benefit to the environment, as DAC is not inherently a NET. DAC can only be considered negative emissions technology if more CO_2 is permanently sequestered than is generated by the DAC process or through reuse applications.[5]

DAC is often discussed in terms of the carbon budget: The carbon budget is the maximum amount of net emissions that the atmosphere can accommodate while limiting climate change to a certain level. For example, in 2018 the Intergovernmental Panel on Climate Change (IPCC) estimated that to have a 50% chance to limit climate change to 1.5°C, the estimated carbon budget is 495 Gigatonnes (Gt) of emissions.[6] According to a 2021 IPCC report, if no reductions are made, the global carbon budget will run out in the 2030s.[7] DAC can help manage overshoot scenarios, bridging the gap to net-zero and reducing the period of time we will exceed the carbon budget. DAC can also help offset emissions from sectors like shipping that cannot be fully transitioned to carbon-neutral form factors.

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2 Sara Budinis, "Direct Air Capture," International Energy Agency (IEA), accessed June 18, 2022, https://www.iea.org/reports/direct-air-capture.

3 Ibid.

4 William Nicolle, "Four Negative Emission Technologies (NETs) that Could Get Us to Net Zero," Policy Exchange, December 3, 2020, https://policy-exchange.org.uk/four-negative-emission-technologies-nets-that-could-get-us-to-net-zero/.

5 Ibid.

6 Axel Dalman, "Carbon Budgets: Where Are We Now?," Carbon Tracker Initiative, May 11, 2020, https://carbontracker.org/carbon-budgets-where-are-we-now/.

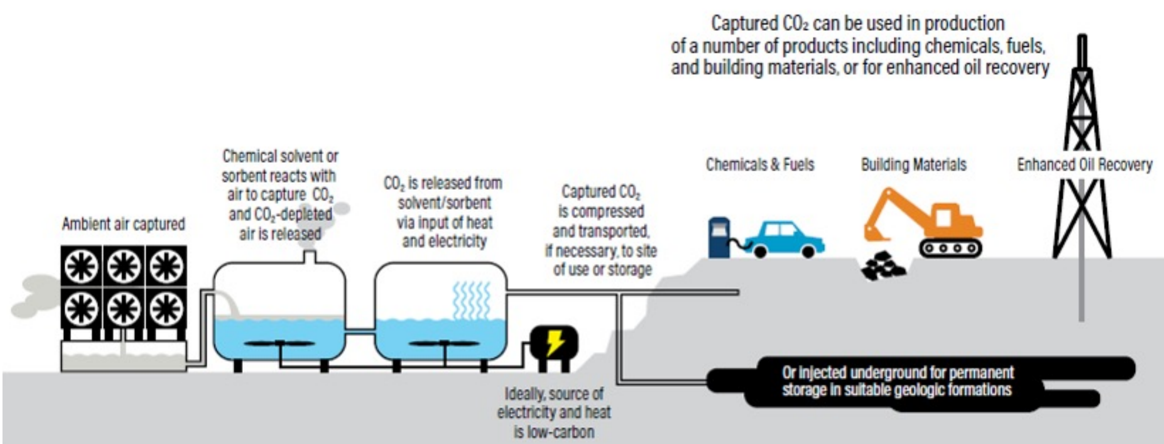
7 "The Global CO_2 Budget Runs Out in 8 Years," Carbon Independent, accessed November 15, 2022, https://www.carbonindependent.org/54.html.

How Does Direct Air Capture Work?

Most DAC plants function by sucking in ambient air using fans that draw the air over or through a selective capture media. "Passive" DAC techniques, which take advantage of natural ambient air flows, have been proposed but are not yet widely available.[8] CO_2 binds chemically (and in some newer sorbents, physically) to the media resulting in a CO_2-lean exhaust stream. Plants mainly use solid sorbents or liquid solvents to perform these reactions.

Once the CO_2 is bonded, the DAC plant releases it from the solvent/sorbent by applying heat. Liquid solvent systems typically require higher heat (900°C) to release the captured carbon.[9] Solid sorbent systems require lower heat (80 - 120°C), which allows plants to utilize other energy sources (like waste heat from other plants) to operate. The solvents/sorbents are then reused for a new cycle of air capture while the pure CO_2 is captured for either reuse in new products or permanent storage (sequestration).

Figure 1.



Note: While solid sorbent and liquid solvent direct air capture facilities are somewhat different, this illustration offers a general representation of both technologies. In liquid solvent systems there are two simultaneous cycles—one for absorption and one for regeneration, while in solid sorbent systems, these happen together, one after the other. Additionally, liquid solvent systems require a higher level of heat input for regeneration.

Sources: Adapted from NAS 2018a; Gunther 2011.

Reprinted from Katie Liebling, "Could Direct Air Capture of CO_2 Work? If so, We Have to Invest in Carbon Capture Tech NOW," Red, Green, and Blue (blog), June 11, 2020, http://redgreenandblue.org/2020/06/11/direct-air-capture-co2-work-invest-carbon-capture-tech-now/.

Regardless of the type of system used, DAC technology has several distinguishing features which separate it from other carbon capture technologies and potential NETs:

8 "MechanicalTreeTM," Carbon Collect (blog), April 2020, https://mechanicaltrees.com/mechanicaltrees/.

9 Soheil Shayegh, Valentina Bosetti, and Massimo Tavoni, "Future Prospects of Direct Air Capture Technologies: Insights from an Expert Elicitation Survey," *Frontiers in Climate* 3 (May 2021), https://doi.org/10.3389/fclim.2021.630893.

High energy costs: Carbon is captured when it comes into contact with either a liquid solvent or solid sorbent and is then released via the application of heat. This heating/release step dominates the energy requirements of a DAC facility. Additional energy costs are accrued when either sequestering or compressing the CO_2 for other uses.[10] The IEA estimates that capturing 1GtCO_2 from the air through DAC will require six exajoules of energy, equivalent to around 6.5% of US primary energy consumption today.[11] Given DAC's substantial energy consumption, ensuring net carbon removal will require pairing DAC with low-carbon energy sources.

Physical footprint: DAC requires many large plants to meaningfully cut carbon emissions. DAC's land requirements are not insignificant, and vary depending on the process type, source of energy, and carbon transfer and storage options.[12] However, DAC requires significantly less land than some other negative emissions techniques like Bio-Energy with Carbon Capture and Storage (BECCS) or reforestation.[13] The World Resources Institute estimates that a DAC plant would need 0.4 to 66 km2 in total to capture one million tons of CO_2, while forests capturing a similar amount would require around 862 km2.[14] Moreover, DAC does not require arable land, which gives it more siting flexibility than technologies like BECCS. DAC plants' relatively small physical footprint means that they can be strategically placed where there is access to both green energy sources and easier movement and storage of the captured CO_2.

10 Committee on Developing a Research Agenda for Carbon Dioxide Removal and Reliable Sequestration National Academies of Sciences, Engineering, and Medicine et al. *Negative Emissions Technologies and Reliable Sequestration: A Research Agenda*" (Washington, DC: National Academies Press), https://doi.org/10.17226/25259.

11 IEA, *Direct Air Capture: A Key Technology for Net Zero* (Paris: Organisation for Economic Cooperation and Development [OECD], 2022), https://doi.org/10.1787/bbd20707-en; Statistical Review of World Energy 2022, 71st edition (London: British Petroleum, 2022).

12 Mihrimah Ozkan et al., "Current Status and Pillars of Direct Air Capture Technologies." *IScience* 25, no. 4 (2022), https://doi.org/10.1016/j.isci.2022.103990.

13 Kelly Levin, "How Effective Is Land at Removing Carbon Pollution? The IPCC Weighs In," *Insights*, World Resources Institute, August 8, 2019, https://www.wri.org/insights/how-effective-land-removing-carbon-pollution-ipcc-weighs.

14 Katie Lebling et al., "6 Things to Know About Direct Air Capture," *Insights*, May 2, 2022, https://www.wri.org/insights/direct-air-capture-resource-considerations-and-costs-carbon-removal.

PART 2: Applications and Market Overview

Applications of Direct Air Capture

There are **six common applications** of DAC separated into **two categories**, sequestration and reuse. Sequestration permanently or semi-permanently stores the CO_2, effectively reducing the carbon levels in the atmosphere.

Carbon Sequestration:

The most common way that carbon is sequestered is by injecting it into deep geological formations. In Iceland, two companies (Climeworks and CarbFix) are injecting their captured carbon into basalt rock formations. This process results in the mineralization of the carbon, transforming it from a liquid to a rock, trapping the carbon permanently.[15] Deep saline aquifers have the greatest long-term storage potential, with the US Department of Energy (DOE) estimating that deep saline formations in the United States could potentially store more than 12,000 billion tons of CO_2.[16]

Reuse Applications:

Enhanced oil recovery (EOR): This is a technique where CO_2 is injected into oil wells to extract oil that cannot be collected using traditional methods. The CO_2 displaces the oil at the bottom of the wells, pushing it toward the surface and allowing it to be extracted. A portion of the injected carbon remains stored underground.EOR can also be performed using chemicals other than CO_2 or using thermal energy to thin the oil.[17]

EOR is currently the largest industrial use of CO_2. Proponents of EOR argue that since oil will continue to be a major resource during the energy transition, EOR (particularly paired with DAC technology) can lower the carbon footprint of oil production as opposed to conventional methods. One study concluded that, depending on operational design, CO_2-EOR could reduce greenhouse gas emissions.[18] Per the DOE,

15 Budinis, "Direct Air Capture."

16 "Carbon Storage R&D," U.S. Department of Energy, accessed September 5, 2022, https://www.energy.gov/fecm/science-innovation/carbon-capture-and-storage-research/carbon-storage-rd.

17 "Enhanced Oil Recovery," U.S. Department of Energy, accessed August 29, 2022, https://www.energy.gov/fecm/science-innovation/oil-gas-research/enhanced-oil-recovery.

18 Vanessa Núñez-López, Ramón Gil-Egui, and Seyyed A. Hosseini, "Environmental and Operational Performance of CO_2-EOR as a CCUS Technology: A Cranfield Example with Dynamic LCA Considerations," *Energies* 12, no. 3 (January 2019): 448, https://doi.org/10.3390/en12030448.

EOR is considered a beneficial reuse application. Large-scale EOR could help scale up and commercialize DAC technologies, especially since it deals with the problem of CO_2 sequestration/storage.[19]

However, experts disagree as to the net carbon impact of EOR. Life cycle analyses of EOR are dependent on unknown factors such as how effectively EOR oil will replace conventional oil and the energy requirements of the DAC technology (i.e., supplied by conventional energy or renewables).[20] Criticism of EOR centers around the environment (such as the potential effects of EOR on groundwater) and environmental justice, as well as reluctance to prolong fossil fuel production over supporting proven CDR techniques like permanent sequestration in the midst of a climate emergency.[21]

EOR operators pay a price for CO_2 generally linked to the price of oil. Although companies employing EOR do not make the price of CO_2 publicly available, the literature estimates that operators pay around \$20 to \$40 per ton of CO_2.[22] While the use of captured carbon is not uncommon in the EOR industry, CO_2 sourced from natural reservoirs has always been dominant.[23] In 2019, Occidental Petroleum partnered with Carbon Engineering to draw half a million tons of CO_2 out of the air each year for EOR. This project is still in development.[24]

Synthetic Fuel: CO_2 captured from the air is combined with hydrogen to create hydrocarbons for synthetic fuels like diesel, gasoline, and jet fuel.[25] Synthetic fuel could be a low-carbon source of power for industries such as shipping that cannot completely end their reliance on traditional hydrocarbon fuels in the near term. The lifespan of large shipping vessels is 25-30 years, preventing full replacement of the fleet for greener ships for decades. Using DAC-generated low-carbon synthetic fuels would be a stopgap measure to minimize the industry's carbon footprint in the interim.[26]

Producing synthetic fuels is significantly more expensive than traditional methods – in 2019, Carbon Engineering estimated that its Air to Fuels (A2F) process cost around \$4 a gallon, compared to the average \$2.70 a gallon retail price of conventional gas in the United States.[27] However, public interest

19 David Roberts, "Could Squeezing More Oil out of the Ground Help Fight Climate Change?," *Vox*, October 2, 2019, https://www.vox.com/energy-and-environment/2019/10/2/20838646/climate-change-carbon-capture-enhanced-oil-recovery-eor.

20 Ibid.

21 Ibid.

22 Vanessa Núñez-López and Emily Moskal. "Potential of CO_2-EOR for Near-Term Decarbonization," *Frontiers in Climate* 1 (September 2019), https://doi.org/10.3389/fclim.2019.00005; Ryan W. J. Edwards and Michael A. Celia, "Infrastructure to Enable Deployment of Carbon Capture, Utilization, and Storage in the United States," *Proceedings of the National Academy of Sciences* 115, no. 38 (2018), https://doi.org/10.1073/pnas.1806504115.

23 Ibid.

24 James Mulligan and Dan Lashof, "A CO_2 Direct Air Capture Plant Will Help Extract Oil in Texas. Could This Actually Be Good for the Climate?," *Insights*, July 31, 2019, https://www.wri.org/insights/co2-direct-air-capture-plant-will-help-extract-oil-texas-could-actually-be-good-climate.

25 Robert F. Service, "Cost Plunges for Capturing Carbon Dioxide from the Air," *Science*, June 7, 2018. https://www.science.org/content/article/cost-plunges-capturing-carbon-dioxide-air.

26 "The Case for Direct Air Capture: De-Fossilising Long-Distance Shipping," Carbon Infinity, December 1, 2021, https://www.carboninfinity.com/news/the-case-for-direct-air-capture-de-fossilising-long-distance-shipping.

27 Clifford Krauss, "Blamed for Climate Change, Oil Companies Invest in Carbon Removal," *New York Times*, April 7, 2019, https://www.nytimes.

in synthetic fuels has grown, and policymakers have recently introduced regulations and policies that would support the production and uptake of synthetic fuels. US lawmakers have introduced bills like the Sustainable Aviation Fuel Act and the Aviation Emissions Reduction Opportunity Act, which would support aviation fuels produced using carbon sourced from DAC.[28] The European Commission has also proposed the ReFuelEU aviation and FuelEU maritime initiatives, which aim to increase the uptake of sustainable fuels (and particularly synthetic fuels) in the aviation and maritime industries by, among other proposals, mandating that fuel supplied to EU airports contains a minimum share of synthetic fuel.[29]

Bioplastic is another potential application for DAC. Newlight Technologies in California invented and patented a bioplastic called "AirCarbon" made from captured methane and CO_2. Newlight runs a production facility with a multimillion-pounds per year production capacity and has agreements to supply millions of pounds of AirCarbon.[30]

Concrete: The concrete industry generates 8% of global carbon emissions, but DAC offers a potential pathway to reduction.[31] CO_2 captured from the air can be used to cure concrete instead of water. CO_2 can also be mixed into liquid concrete during production to create low-cost and stronger concrete products.[32] Companies like Solidia Technologies and Carbon Cure Technologies are incorporating this application and working with major concrete producers to scale green concrete production.

Food processing: In 2019, Climeworks partnered with a Coca-Cola subsidiary to use DAC technology to capture and develop food-grade CO_2. Dubbed CAPDrinks, the project resulted in the release of bottled water carbonated with captured carbon.[33]

The Limitations of Direct Air Capture

While DAC has great potential, several limitations make its adoption and scaling a challenge. If these limitations are not mitigated, DAC will struggle to find a long-term, viable market with a path to future growth. Specifically, DAC must overcome three primary **limitations**: high energy costs, high economic

com/2019/04/07/business/energy-environment/climate-change-carbon-engineering.html.

28 "Carbon Removal Policy Tracker," Carbon180, accessed August 2, 2022, https://carbon180.org/policy-tracker.

29 "Infographic–Fit for 55: Increasing the Uptake of Greener Fuels in the Aviation and Maritime Sectors," Council of the European Union, accessed September 11, 2022, https://www.consilium.europa.eu/en/infographics/fit-for-55-refueleu-and-fueleu/.

30 "Case Studies: Real-world Companies that Are Pioneering Direct Air Capture Technology and Market Applications of Carbon Dioxide," Bipartisan Policy Center, June 2021, https://bipartisanpolicy.org/download/?file=/wp-content/uploads/2021/02/Bipartisan_Energy-DAC-Fact-Sheet-Part-3_R01_2.5.2021edits-2.pdf.

31 Johanna Lehne and Felix Preston, "Making Concrete Change: Innovation in Low-Carbon Cement and Concrete," Chatham House, June 13, 2018, https://www.chathamhouse.org/2018/06/making-concrete-change-innovation-low-carbon-cement-and-concrete.

32 Ibid.

33 Gregory Heilers, "Coca-Cola Bottler Experiments with Turning Emissions into Effervescence," *GreenBiz*, May 6, 2019, https://www.greenbiz.com/article/coca-cola-bottler-experiments-turning-emissions-effervescence.

costs, and risks to carbon storage and transport. These limitations are interrelated and progress in one area may impact the other two areas.

Energy requirements: DAC requires high levels of energy, including to create the materials (like the sorbents) as well as to release the captured carbon from the sorbents for sequestration. Estimates about the long-term energy requirements of DAC based on current technology range from around 1,200 kWh/ tCO_2 to 2,000 kWh/tCO_2.[34] One study finds that a "massive" DAC scale-up to achieve stringent climate targets (at a rate of 1.5 $GtCO_2$/year) would require up to 300 EJ of annual energy input by the end of 2100, *equal to a quarter of global energy demand*.[35]

This energy usage comes with a carbon impact. DAC plants powered using fossil fuels will have a significantly higher carbon footprint than those powered using other energy sources like nuclear, solar, or geothermal.[36] Solvent-based DAC systems require much higher heat to function, preventing them from utilizing geothermal energy.[37] DAC companies must balance the need for a low-cost power source with the carbon impact of power generation. This issue is particularly acute in the short term because as green energy sources scale they will become a more accessible and viable low-cost energy source. Some analyses have suggested that the demand for low-carbon heat and electricity from DAC will incentivize the expansion of greener energy sources like nuclear power. However, this assumes that individual DAC plant capabilities have scaled enough to capture 360,000 tons of CO_2/year, substantially higher than current capabilities.[38]

Industry model/costs: In 2017, Climeworks, the world's leading commercial DAC company, indicated that its DAC process cost around $600 per ton of CO_2 captured.[39] Analyses done by the American Physical Society and scientists at Carbon Engineering estimate that, depending on the technology choice, energy source, and scale of deployment, DAC costs could range from around $90 to $600 per ton of CO_2 if implemented commercially.[40,41] While the variability is high, the preponderance of the literature suggests that the costs must decrease to approximately $100 per ton for the technology to directly

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34 Michelle Ma, "Direct Air Capture's Hidden Energy Cost," *Protocol*, October 21, 2022, https://www.protocol.com/bulletins/direct-air-capture-energy-use;Christoph Beuttler, Louise Charles, and Jan Wurzbacher, "The Role of Direct Air Capture in Mitigation of Anthropogenic Greenhouse Gas Emissions," *Frontiers in Climate* 1 (November 2019), https://doi.org/10.3389/fclim.2019.00010.

35 Giulia Realmonte et al., "An Inter-Model Assessment of the Role of Direct Air Capture in Deep Mitigation Pathways," *Nature Communications* 10, no. 1 (2019): 3277, https://doi.org/10.1038/s41467-019-10842-5.

36 Committee on Developing a Research Agenda, *Negative Emissions Technologies*; Mihrimah Ozkan et al., "Current Status and Pillars.".

37 Yang Qiu et al., "Environmental Trade-Offs of Direct Air Capture Technologies in Climate Change Mitigation toward 2100," *Nature Communications* 13, no. 3635 (2022), https://doi.org/10.1038/s41467-022-31146-1.

38 Slesinski, Daniel, and Scott Litzelman. "How Low-Carbon Heat Requirements for Direct Air Capture of CO_2 Can Enable the Expansion of Firm Low-Carbon Electricity Generation Resources." *Frontiers in Climate* 3 (September 7, 2021): 728719. https://doi.org/10.3389/fclim.2021.728719.

39 Rosamund Pearce, "The Swiss Company Hoping to Capture 1% of Global CO_2 Emissions by 2025," Carbon Brief, June 22, 2017, https://www.carbonbrief.org/swiss-company-hoping-capture-1-global-co2-emissions-2025/.

40 Lebling et al., "6 Things to Know."; Jeff Tollefson, "Sucking Carbon Dioxide from Air Is Cheaper than Scientists Thought," *Nature* 558, no. 7709 (2018): 173, https://doi.org/10.1038/d41586-018-05357-w.

41 David W. Keith et al., "A Process for Capturing CO_2 from the Atmosphere," *Joule* 2, no. 8 (2018): 1573–94, https://doi.org/10.1016/j.joule.2018.05.006.

compete with CO_2 capture technologies already commercially available.[42] This number is also the target of the DOE's Carbon Negative Shot program to stimulate DAC development.

While Climeworks hopes to reduce commercial DAC costs to $200 to $300 per ton by 2030, and to $200 to $100 per ton by the middle of the decade, some experts doubt that DAC could ever become economically viable in the near term, if ever.[43] One analysis finds that, assuming that DAC has the same learning curve as solar energy, lowering the cost of DAC to $100 per ton would require federal investment and subsidies of up to $2 billion to bridge the gap between actual costs and market commodity rates.[44] While $2 billion is significant, the United States provides approximately $20 billion in annual subsidies to the fossil fuel industry.[45] One analysis has suggested that an investment of several hundred million dollars would spur enough technological maturation that the prices per ton of CO_2 would become much more competitive.[46] However, there remains a substantial risk that the technology does not scale enough to be comparably priced to other carbon capture techniques.

Climeworks offers carbon offsets that currently cost between $600 to $1,200 per ton of CO_2 removed.[47] The cost of other carbon offsets is much lower, as low as $10/ton, but are often not as durable or high quality as DAC sequestration.[48] The current carbon offset model is purely market-driven, and keeps prices low because of a large supply of carbon offset instruments. However, many of those offsets function not by actively reducing carbon levels, but by preventing future emissions. There are also quality concerns in the offset industry regarding overestimation of carbon captured, lack of permanent sequestration, and lack of additionality (e.g., selling carbon offsets on activities that would have happened regardless). Carbon sequestered via DAC is relatively easily verified and permanently stored, which addresses some of the concerns typically associated with carbon offsets. The permanence of DAC sequestration and its lower environmental impact and sustainability may allow DAC technology to command a premium over other offset instruments.[49] The predicted increase in demand (and therefore price) of carbon offsets in the next 30 years also abates the competitiveness concerns to a degree.[50]

42 Mihrimah Ozkan et al., "Current Status and Pillars."

43 Ragnhildur Sigurdardottir and Akshat Rathi, "World's Largest Carbon-Sucking Plant Starts Making Tiny Dent in Emissions," *Bloomberg*, September 8, 2021, https://www.bloomberg.com/news/features/2021-09-08/inside-the-world-s-largest-direct-carbon-capture-plant.

44 James Temple, "What It Will Take to Achieve Affordable Carbon Removal," *MIT Technology Review*, June 24, 2021, https://www.technologyreview.com/2021/06/24/1027083/what-it-will-take-to-achieve-affordable-carbon-removal/.

45 Clayton Coleman and Emma Dietz, "Fossil Fuel Subsidies: A Closer Look at Tax Breaks and Societal Costs," Environmental and Energy Study Institute, July 29, 2019, https://www.eesi.org/papers/view/fact-sheet-fossil-fuel-subsidies-a-closer-look-at-tax-breaks-and-societal-costs.

46 Klaus S. Lackner and Habib Azarabadi, "Buying Down the Cost of Direct Air Capture," *Industrial & Engineering Chemistry Research* 60, no. 22 (2021): 8196–8208, https://doi.org/10.1021/acs.iecr.0c04839.

47 Emily Pontecorvo, "Climeworks Is Building a Bigger Carbon Removal Plant—and Getting Some New Competition," Grist, June 29, 2022, https://grist.org/climate-energy/climeworks-is-building-a-bigger-carbon-removal-plant-and-getting-some-new-competition/.

48 "Live Carbon Prices Today," Carbon Credits, accessed August 31, 2022, https://carboncredits.com/carbon-prices-today/.

49 Office of Fossil Energy and Carbon Management, "Carbon Negative Shot," U.S. Department of Energy, accessed November 9, 2022, https://www.energy.gov/fecm/carbon-negative-shot.

50 Veronika Henze, "Carbon Offset Prices Could Increase Fifty-Fold by 2050," *BloombergNEF* (blog), January 10, 2022, https://about.bnef.com/blog/carbon-offset-prices-could-increase-fifty-fold-by-2050/.

DAC costs projections at this juncture are highly variable due to the limited nature of DAC deployments. Most cost estimates at the $100 per ton range justify the estimate by assuming that costs will lower as the technology scales. Research comparing the validity of these cost projections has raised numerous concerns regarding the quality of their inputs and ability to make accurate estimates.[51] Existing cost estimates for DAC in a fully deployed and scaled modality are limited by the current data. It is nearly impossible to accurately assess the cost of a fully scaled technology when it is still in a pilot stage. As DAC continues to develop these estimates will be revised into more accurate assessments.

Carbon storage/transport: Carbon captured using DAC will need to be compressed and transported using an extensive network of pipelines. CO_2 pipelines have a good safety record, with failure and accident rates similar to oil and gas pipelines.[52] However, CO_2 storage and transport does pose risks – pipelines can leak or rupture, and compressed CO_2 can be highly hazardous and lead to asphyxiation.[53] Underground storage of carbon can also pose environmental risks, including potential leakage, contamination of drinking water, and stimulation of seismic activity.[54]

Market Landscape of Direct Air Capture

There are currently 18 DAC facilities operating in Canada, Europe, and the United States. Most of the plants are small and sell the captured CO_2 for use. The largest plant, commissioned in Iceland in 2021, captures 4,000 tCO_2 per year for storage. The first large-scale DAC plant is being developed in the United States and could be operational as soon as 2024. It is designed to have the capacity to capture 500,000 tCO_2 per year when finished, with the ability to scale up to one $MtCO_2$.[55] Following the passage of the Inflation Reduction Act in August 2022, which increased the 45Q federal tax credit for DAC projects, Los Angeles-based CarbonCapture and Frontier Carbon Solutions announced the start of a large-scale DAC project in Wyoming that aims to capture and sequester five $MtCO_2$ by the year 2030.[56]

Climeworks, Carbon Engineering, and Global Thermostat were early leaders in the DAC market. Climeworks and Carbon Engineering have received significant public and private funding in recent years

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51 Howard Herzog, "Direct Air Capture," in *Greenhouse Gas Removal Technologies*, edited by Mai Bui and Niall Mac Dowell, (Cambridge, UK: Royal Society of Chemistry, 2022), https://doi.org/10.1039/9781839165245.

52 Richard Doctor and Andrew Palmer, coords., "Chapter 4: Transport of CO_2," in *Carbon dioxide Capture and Storage*, IPCC Special Report, edited by Bert Metz et al. (New York: Cambridge University Press, 2005), https://www.ipcc.ch/site/assets/uploads/2018/03/srccs_chapter4-1.pdf

53 Ibid.

54 "Carbon Capture and Storage," Center for International Environmental Law, accessed July 28, 2022, https://www.ciel.org/issue/carbon-capture-and-storage/.

55 Occidental Petroleum, "Occidental, 1PointFive to Begin Construction of World's Largest Direct Air Capture Plant in the Texas Permian Basin," *GlobeNewswire*, August 25, 2022, https://www.globenewswire.com/news-release/2022/08/25/2504560/0/en/Occidental-1PointFive-to-Begin-Construction-of-World-s-Largest-Direct-Air-Capture-Plant-in-the-Texas-Permian-Basin.html.

56 Valerie Volcovici, "Exclusive New Law Helps U.S. Firm Launch Wyoming Direct Air Carbon Capture Project," *Reuters*, September 8, 2022, https://www.reuters.com/markets/carbon/exclusive-new-law-helps-us-firm-launch-wyoming-direct-air-carbon-capture-project-2022-09-08/.

and are currently developing new DAC plants.[57] The market is expanding, with a number of smaller companies in the United States and worldwide developing novel DAC technologies. These include the aforementioned CarbonCapture, headed by the former CEO of Carbon Engineering; Carbon Collect, which is working with Arizona State University to commercialize a passive direct air capture technology known as the "mechanical tree"; and Avnos and Verdox, which have patented DAC technologies with lower heat requirements.[58,59]

57 Leslie Kaufman and Akshat Rathi, "A Carbon-Sucking Startup Has Been Paralyzed by Its CEO," *Bloomberg*, April 9, 2021, https://www.bloomberg.com/news/features/2021-04-09/inside-america-s-race-to-scale-carbon-capture-technology.

58 Zayna Syed, "Can a Mechanical 'Tree' Help Slow Climate Change? An ASU Researcher Built One to Find Out," *Arizona Republic*, April 22, 2022, https://www.azcentral.com/story/news/local/arizona-environment/2022/04/22/asu-researcher-builds-mechanical-tree-capture-carbon-dioxide/7398671001/.

59 "XPRIZE and the Musk Foundation Award $15m to Prize Milestone," *XPRIZE*, April 22, 2022, https://www.xprize.org/prizes/elonmusk/articles/xprize-and-the-musk-foundation-award-15m-to-prize-milestone-winners-in-100m-carbon-removal-competition.

PART 3: Support and Regulation

Government Support: Funding and Strategies

Regulations and policies have tended to focus on carbon capture, storage, and utilization (CCUS) technologies broadly, rather than specific technologies. **DAC is a Carbon Dioxide Removal (CDR) technology, a subset of CCUS technology.** In the following section we discuss support and regulation of DAC in the context of CCUS, but acknowledge its place within the set of CDR technologies. Most DAC projects (and most CCUS projects more broadly) are located in the United States and the European Union, both of which have made a concerted effort in recent years to invest in carbon capture technologies as a way to meet emissions targets and spur the green energy transition. While other nations like China also provide support for CCUS and CDR more broadly, China lags behind in the deployment of DAC specifically. While there exist private efforts to stimulate carbon removal like XPRIZE's $100 million global competition, the following section is primarily focused on public sector support and regulation.[60]

United States

One of the main mechanisms to support DAC in the United States is the **45Q tax credit**. Introduced in 2008 and expanded in 2018 and 2022 (with the passage of the **Inflation Reduction Act (IRA)**) the tax credit provides $130 per ton of CO_2 from DAC used in EOR and other beneficial reuse and $180 per ton of CO_2 captured from DAC and stored in saline geological formations. The credit is available for DAC only if the capture capacity of the plant is above 1,000 tCO_2/year, a decrease from the previous requirement of 100,000 tCO_2/year.[61] The IRA includes a number of other 45Q tax credit changes, such as extending the deadline for carbon capture projects to qualify and higher credit values for carbon captured from the industrial and power sectors.[62]

The **2022 Consolidated Appropriations Act** included funding for DAC technologies, as did the **Infrastructure Investment and Jobs Act**, which provided almost $12 billion in CCUS support. This included $3.5 billion in funding to establish four DAC hubs and related transport and storage infrastructure. DAC projects are also eligible for additional CCUS funding support of around $500 million. A DAC Prize program was also fully funded by the infrastructure package, with $100 million for

60 "$100m Prize for Carbon Removal," XPRIZE, accessed February 8, 2023, https://www.xprize.org/prizes/carbonremoval.

61 "Carbon Capture Provisions in the Inflation Reduction Act of 2022," Clean Air Taskforce, https://cdn.catf.us/wp-content/uploads/2022/08/19102026/carbon-capture-provisions-ira.pdf

62 David Iaconangelo et al, "How Manchin-Schumer Would Change Energy, from Oil to Solar," *E&E News*, July 29, 2022, https://www.eenews.net/articles/how-manchin-schumer-would-change-energy-from-oil-to-solar/.

commercial-scale projects and $15 million for pre-commercial projects.[63]

There is other proposed legislation pending in the US Congress that would also impact DAC. These include the Removing Emissions to Mend Our Vulnerable Earth Act of 2022 (REMOVE Act), the Federal Carbon Dioxide Removal Leadership Act of 2022, the DOE's Science for the Future Act of 2022, the Aviation Emissions Reduction Opportunity Act, and the NET Zero Act of 2021.[64]

The DOE has announced multiple funding programs for DAC, including investing $14 million in five front-end engineering design (FEED) studies that will connect DAC projects to existing geothermal, nuclear, or industrial facilities.[65] Previous funding programs included $14.5 million announced in October 2021; $24 million in March 2021; $15 million in January 2021; and $22 million in March 2020.[66] The DOE is also leading the **Carbon Negative Shot**, a call for innovation in carbon removal technologies and approaches that will capture and store carbon for less than $100/net metric ton of CO_2.[67]

Notable State-level Support: California has enacted the **California Low-Carbon Fuel Standard**, which places life-cycle carbon intensity targets on all transportation fuels sold in California and provides credits to direct air capture projects worldwide provided they meet the requirements of the Carbon Capture and Sequestration Protocol (including 100 years of storage monitoring).[68] Eligible storage sites under the CCS Protocol include saline reservoirs, depleted oil and gas reservoirs, and reservoirs used for CO_2-enhanced oil recovery.[69] In 2020, the Low Carbon Fuel Standard credits traded at an average of around $200/t$CO_2$.[70]

European Union

The European Commission has funded DAC projects, among others, through **Horizon Europe** and the **Innovation Fund**. Horizon Europe is the main EU funding program for research and innovation, with a total budget across all EU areas of EUR 95.5 billion (around $113 billion). The Innovation Fund (EUR 10 billion, or $11.8 billion) was launched in 2020 to support low-carbon technologies and processes.[71] The EU's **Just Transition Fund** provides support to territories facing serious socioeconomic challenges arising from the transition toward climate neutrality and also provides support for CCUS technologies.

63 Ibid.

64 "Carbon Removal Policy Tracker," Carbon180.

65 "DOE Announces $14.5 Million Supporting Direct Air Capture and Storage Coupled to Low Carbon Energy Sources," press release, U.S. Department of Energy, October 26, 2021, https://www.energy.gov/articles/doe-announces-145-million-supporting-direct-air-capture-and-storage-coupled-low-carbon.

66 IEA, *Direct Air Capture.*

67 Office of Fossil Energy and Carbon Management, "Carbon Negative Shot."

68 "Carbon Capture and Sequestration Project Eligibility FAQ," California Air Resources Board, October 2022, https://ww2.arb.ca.gov/resources/fact-sheets/carbon-capture-and-sequestration-project-eligibility-faq.

69 Ibid.

70 Office of Fossil Energy and Carbon Management, "Carbon Negative Shot."

71 IEA, *Direct Air Capture.*

The **Recovery and Resilience Facility** aims to mitigate the economic and social impact of the coronavirus pandemic through investments in flagship areas such as clean technologies and renewables, for example, CCUS. The **Connecting Europe Facility** also provides funding for cross-border CO_2 networks.[72] Member States can also support carbon capture, storage, and/or utilization technologies using state aid according to conditions specified in its **Guidelines for State aid for climate, environmental protection and energy 2022**.[73]

To encourage the energy transition, the European Union has passed the **Renewable Energy Directive**, which includes provisions on the use of fuels produced by carbon capture technologies. This directive was strengthened in the legislative package for the European Green Deal, a package of proposals to ensure that greenhouse gas emissions are reduced by 55% by 2030, compared to 1990 levels. As part of its Fit for 55 package, which seeks to reduce the EU's carbon emissions by 55 percent by 2030, the European Commission has proposed the **ReFuelEU Aviation Initiative** and the **FuelEU Maritime Initiative**, which seeks to increase the uptake of sustainable fuels (including synthetic low-carbon fuels) in the aviation and maritime industries.[74] In December 2021, the Commission published the **"Sustainable Carbon Cycles" Communication**, which sets out an action plan to develop sustainable solutions to increase carbon removal.[75]

China

As public interest in DAC grows, the IEA estimates that other regions like China and the Middle East could become some of the least-cost locations for DAC deployment.[76] The Chinese government has supported CCUS pilot projects for many years – the **2019 Roadmap for Development of CCUS Technology** in China set goals for reducing the cost and energy consumption of carbon capture and called for the deployment of multiple CCUS hubs throughout the country while 2021 **14th Five Year Plan** highlighted the role of CCUS in China's low-carbon development.[77] However, although China has 38 operational CCUS projects and several hubs in the pipeline, only two demonstration-level pilots utilize DAC technology.[78] As such, China currently is not a leader in this technology like the United States or Europe, nor is it a regulatory leader – although the government has issued 52 policy documents mentioning CCUS, China has no specific laws governing CCUS and many regulatory measures have yet to be detailed.[79]

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72 "Carbon Capture, Use and Storage," Climate Action, European Commission, accessed July 29, 2022, https://ec.europa.eu/clima/eu-action/carbon-capture-use-and-storage_en.

73 "Carbon Capture, Storage and Utilisation," Energy, European Commission, accessed February 8, 2023, https://energy.ec.europa.eu/topics/oil-gas-and-coal/carbon-capture-storage-and-utilisation_en.

74 Ibid.

75 Ibid.

76 Budinis, *Direct Air Capture.*

77 "US-China Roundtable on Carbon Capture, Utilization and Storage," Center on Global Energy Policy, Columbia University, accessed November 9, 2022, https://www.energypolicy.columbia.edu/research/global-energy-dialogue/us-china-roundtable-carbon-capture-utilization-and-storage#_edn16.

78 "The DAC MAPP," Carbon180, accessed November 9, 2022, https://carbon180.org/work-resources-1/6pem7olk4b1d9zgevatdux0xyukk5h.

79 Kai Jiang et al., "China's Carbon Capture, Utilization and Storage (CCUS) Policy: A Critical Review," *Renewable and Sustainable Energy Reviews* 119

Regulation

Along with providing significant funding support, U.S. and EU policymakers have begun tackling regulatory issues such as carbon quality, safe storage and transport, and environmental standards. As DAC technologies become increasingly commercially available, policymakers will need to develop a robust regulatory framework to govern the construction and management of DAC facilities and related infrastructure.

United States

CCUS technologies, including DAC, do not fit neatly within current governance frameworks in the United States. There are no federal policies or regulations that are specific to DAC projects or associated infrastructure and states carry much regulatory responsibility. The Council on Environmental Quality recently released the **Carbon Capture, Utilization, and Sequestration Guidance** to provide guidance at the federal level for CCUS technologies.[80] However, there are several existing federal laws and regulations that enable federal agencies to regulate CCUS projects, including DAC:

Underground Injection Control Program (under the Safe Drinking Water Act): Underground carbon sequestration is regulated by the US Environmental Protection Agency (EPA), under established rules stemming from the Safe Drinking Water Act to protect underground sources of drinking water. The Underground Injection Control (UIC) program sets rules for the operation of underground injection wells, including for liquid byproducts from EOR (Class II wells) or geological storage of CO_2 (Class VI wells). The EPA has delegated primary regulatory authority to some states to administer the UIC program, and others are in the process of acquiring primary regulatory authority.[81]

National Environmental Policy Act (NEPA): NEPA dictates how environmental review and permitting work at the federal level. CCUS projects, including those in the private sector, can fall under NEPA purview if they have a federal nexus – for example, if the project involves federal land, federal funding, federally managed infrastructure, or is associated with another NEPA-connected project. DOE usually takes the lead because of its significant role in funding CCUS projects.[82]

Clean Water Act: If a CCUS project or pipeline crosses water or wetlands, it may require a permit under

(March 2020), https://doi.org/10.1016/j.rser.2019.109601.

80 The White House, "CEQ Issues New Guidance to Responsibly Develop Carbon Capture, Utilization, and Sequestration," press release, February 15, 2022, https://www.whitehouse.gov/ceq/news-updates/2022/02/15/ceq-issues-new-guidance-to-responsibly-develop-carbon-capture-utilization-and-sequestration/.

81 Seth Kerschner and Taylor Pullins, "How US Environmental Laws and Regulations Affect Carbon Capture and Storage," White & Case, January 29, 2021, https://www.whitecase.com/publications/insight/carbon-capture/how-us-environmental-laws-and-regulations-affect.

82 Ibid.

the Clean Water Act. The Army Corps of Engineers issues permits under Section 404 to dredge or fill materials.[83] If a CCUS system results in a discharge of wastewater, it will require a permit under the National Pollutant Discharge Elimination System, administered by the EPA for states that do not have delegated authority.[84]

National Historic Conservation Act (NHPA): If a CCUS project impacts a federally recognized historic or cultural property, it may require federal review under the NHPA. US federal agencies are required to seek counsel with the Advisory Council on Historic Preservation.[85]

Endangered Species Act, the Migratory Bird Treaty Act, and the Bald and Golden Eagle Protection Act: CCUS projects may require review if they have the potential to impact threatened or listed species under habitat protection and mitigation requirements. Federal laws such as those listed here prohibit developers from activities that are likely to result in a "take" of a protected species. Purview would fall to the EPA and the Fish and Wildlife Service.[86]

Greenhouse Gas Reporting Program (GHGRP): The GHGRP requires reporting of data from large GHG emission sources, fuel, and industrial gas suppliers, and CO_2 injection sites in the United States. Regulations governing CO_2 suppliers apply to facilities that capture CO_2 from industrial sources or extract it from natural CO_2-bearing formations for supply into the economy. Regulations governing the underground injection of CO_2 apply to facilities that inject CO_2 underground for any other purpose other than geologic sequestration, such as EOR. Regulations governing the geologic sequestration of CO_2 apply to facilities conducting geologic sequestration and provide a mechanism for such facilities to monitor their own activities and report to the EPA about the amounts of CO_2 they sequester.[87]

Pipeline and Hazardous Materials Safety Administration (PHMSA): The PHMSA's Office of Pipeline Safety regulates the design, construction, operation, maintenance, and spill response planning for pipelines. The PHMSA establishes minimum safety standards for interstate pipelines and has largely preempted states from establishing their own standards. However, states may regulate the safety of their CO_2 pipelines to varying degrees under delegation of authority from the Hazardous Liquid Pipeline Act. The regulations only apply to CO_2 transported in a liquid state (which is the majority of CO_2 transported).[88]

83 Ibid.

84 Council on Environmental Quality, *Council on Environmental Quality Report to Congress on Carbon Capture, Utilization, and Sequestration* (Washington, DC: U.S. Executive Office, 2021), https://www.whitehouse.gov/wp-content/uploads/2021/06/CEQ-CCUS-Permitting-Report.pdf.

85 Ibid.

86 Ibid.

87 Ibid.

88 Ibid.

European Union

The European Commission is preparing to propose a regulatory EU framework for the certification of carbon removals by the end of 2022. The certification framework, if passed, seeks to ensure transparent monitoring, reporting, and verification of carbon removals.[89] The European Commission has adopted a number of directives related to carbon capture, storage, and utilization projects in Europe, including the **Carbon Capture and Storage Directive (2009/31/EC)** which provides a regulatory framework for the safe transport and geological storage of CO_2.[90] As part of the CCS Directive, the European Commission has published three implementation reports (the latest in October 2019) as well four guidance documents providing a framework for CO_2 storage life-cycle risk management, site characterization, monitoring and collective measures, and financial mechanisms and security.[91]

Existing EU environmental legislation such as the **Environmental Impact Assessment (EIA) Directive** or the **Industrial Emissions Directive** also help regulate carbon capture projects. Before carbon projects in the EU receive any construction and operation permits, they are required to conduct an EIA addressing all environmental concerns and providing a detailed site selection assessment as well as a monitoring plan for possible leakage risks.[92] The revised **Emissions Trading System (ETS) Directive**, which governs the world's largest "cap and trade" carbon market, explicitly includes capture, storage, and transport installations and considers carbon that is captured and safely stored as "not emitted."[93] In case of leakage, the ETS helps ensure that operators need to surrender allowances for any resulting emissions.[94] The **Directive on Environmental Liability** deals with local damage to the environment while EU Member States regulate liability for damage to health and property.[95]

Self Regulation

While the leading DAC companies have not published DAC principles, trade groups, nonprofit organizations, and other companies interested and/or involved in the DAC space have developed best practices for DAC technologies specifically, or carbon capture and storage technologies more broadly.

89 "Sustainable Carbon Cycles," Climate Action, European Commission, accessed July 29, 2022, https://ec.europa.eu/clima/eu-action/forests-and-agriculture/sustainable-carbon-cycles_en.

90 "A Legal Framework for the Safe Geological Storage of Carbon Dioxide," Climate Action, European Commission, accessed February 8, 2023, https://climate.ec.europa.eu/eu-action/carbon-capture-use-and-storage/legal-framework-safe-geological-storage-carbon-dioxide_en.

91 "Implementation of the CCS Directive," Climate Action, European Commission, accessed July 29, 2022, https://ec.europa.eu/clima/eu-action/carbon-capture-use-and-storage/implementation-ccs-directive_en.

92 "Carbon Capture, Use and Storage," European Commission.

93 Ibid.

94 "A Legal Framework for the Safe, " European Commission.

95 Ibid.

These include Carbon Direct and Microsoft's **Criteria for High-Quality Carbon Dioxide Removal**[96], which covers carbon quality, environmental justice, societal harms and benefits, carbon accounting, durability, and monitoring; Science Based Targets' **Corporate Net-Zero** Standard, which sets criteria for businesses to set near- and long-term targets to get to net-zero emissions that are science-based and take into account beyond value chain mitigation; the International Standard Organization's **Standards for Carbon Capture and Storage**, which covers transportation, geological storage, EOR storage, capture systems, quantification and verification, life-cycle risk management; the Society of Petroleum Engineers' **CO_2 Storage Resources and Management System**, covering CO_2 storage; and the American Petroleum Institute's **Standard 1104 (Welding Pipelines and Related Facilities)**, which covers CO_2 pipeline development.

96 Carbon Direct, *Criteria For-Quality Carbon Removal* (Redmond, WA: Microsoft, 2022), https://d13en5kcqwfled.cloudfront.net/files/Criteria-Doc_FY23_April-2022.pdf.

PART 4: Public Purpose Considerations

Considerations By Sector

Environment: DAC technology is currently pulling thousands of tons of CO_2 out of the atmosphere, and has the potential to capture gigatons in the coming decades for sequestration or reuse. This gives some hope that DAC could play a key role in green transitions, buying more time for industries with long lead times to adopt carbon-neutral footprints.

However, DAC firms must overcome multiple scaling challenges to achieve a tangible positive effect on the environment. **First, there is a risk that DAC will not scale to the point of being cost-effective for most applications.** Government agencies and cost estimates are targeting $100/ton for long-term pricing of DAC CO_2.[97] **This is a substantial decrease from reported costs today, and some scholars doubt DAC's ability to achieve economic viability in the long run.**

At the same time, governments assessing the costs of potential DAC policies and regulation should consider the social cost of carbon, which measures the economic damages that result from one additional ton of CO_2 in the atmosphere.[98] While the US Interagency Working on Social Cost of Greenhouse Gases currently puts the price tag at $51 per ton, a recent multi-year study by researchers from Resources for the Future and Univeristy of California Berkeley put the figure at $185 per ton.[99] The EPA has also proposed increasing the federal estimate to $190 per ton.[100] Even if the price of DAC cannot be lowered to $100/ton, some experts argue that pursuing DAC expansion might still be worthwhile if the total social cost of running a DAC facility was less than the social cost of carbon.

Second, there is a risk that the energy powering the DAC plants substantially reduces their net carbon removal potential. DAC companies must identify energy sources with low-carbon intensities to power their facilities. Climeworks' Orca plant in Iceland is a prominent example of DAC-powered using geothermal energy.

An additional challenge is that DAC firms could emphasize carbon reuse rather than sequestration. Synthetic fuel is a potentially lucrative reuse of carbon but will result in the captured carbon being

97 Office of Fossil Energy and Carbon Management, "Carbon Negative Shot," accessed August 3, 2022, U.S. Department of Energy, https://www.energy.gov/fecm/carbon-negative-shot.

98 "Social Cost of Carbon More Than Triple the Current Federal Estimate, New Study Finds," press release, Resources for the Future, September 1, 2022, https://www.rff.org/news/press-releases/social-cost-of-carbon-more-than-triple-the-current-federal-estimate-new-study-finds/.

99 Ibid.

100 Niina H. Farah and Lesley Clark, "EPA Floats Sharply Increased Social Cost of Carbon," E&E News, November 21, 2022, https://www.eenews.net/articles/epa-floats-sharply-increased-social-cost-of-carbon/.

re-released into the atmosphere. **Reuse applications' impact on emissions varies. Some applications (CO_2 storage in concrete) reduce emissions and remove carbon, some applications only reduce emissions, and other applications do neither. As discussed in this document, reuse applications can play a valuable role in green transitions, but sequestration is imperative for decarbonization.** Governments should incentivize the DAC industry to emphasize sequestration rather than reuse applications to maximize the DAC's environmental impact.

A current policy weakness is that 45Q tax credits do not require a net reduction in carbon, only that the carbon is stored in order to claim the credit.[101] Companies that store carbon can claim the credit even if more carbon was released into the atmosphere than was stored. A useful policy change would be to base these credits on net tons of carbon sequestered. While requiring more thorough oversight by the Internal Revenue Service in partnership with EPA, this would encourage DAC companies to develop form factors that are true NETs.

While DAC is an attractive technology there are real economic and energy challenges to scaling it. DAC is not a solution to our climate problems, but only one tool of many that must be used to create a comprehensive climate strategy. Investment in DAC should be supplementary to investment in other priorities like the clean energy transition.

Environmental Justice and Political Rights: While climate change affects everyone, the groups that feel the effects earliest and most severely are typically those without access to power or resources. The rapid expansion of DAC poses risks and the government must make an effort to ensure that any negative consequences are not borne by marginalized communities.

DAC facilities need to be constructed close to a large energy source. Additionally, carbon sequestration requires pumping large quantities of CO_2 into geologic formations. Those sites are likely to be chosen in relatively rural areas where land is inexpensive. This may cause certain communities to disproportionately bear any burdens resulting from DAC plant construction and carbon storage. Many effects of DAC facilities (local air quality, pollution, etc.) are unexplored and it is therefore impossible for communities to make informed decisions about them.[102] DAC will require moving large quantities of captured carbon, usually involving pipelines. This carries an inherent risk of rupture/spillage. For these reasons, some environmental justice groups strongly oppose the construction of DAC facilities.

Public input and influence of site selection for DAC facilities and subsequent infrastructure (pipelines,

101 Angela Jones and Molly Sherlock. "The Tax Credit for Carbon Sequestration (Section 45Q)," In Focus, Congressional Research Service, June 8, 2021, https://sgp.fas.org/crs/misc/IF11455.pdf.

102 Maya Batres et al., "Environmental and Climate Justice and Technological Carbon Removal," *Electricity Journal* 34, no. 7 (2021), https://doi.org/10.1016/j.tej.2021.107002.

geologic sequestration sites) are crucial since this infrastructure can have substantial impacts on a community. There is a political risk that corporations with a vested interest in developing an economically profitable facility may have more influence than a local community that does not want a site nearby. It will be crucial to ensure that the existing regulatory framework governing the construction and operation of DAC infrastructure is utilized to balance the benefits of the technology against the risks to the people who live in geographical proximity to the plant.

The Council of Environmental Quality released guidance on how to select and evaluate these sites, including prioritizing community outreach and engagement.[103] NEPA and other existing environmental laws (Clean Air Act, Clean Water Act, etc.) largely govern the regulations surrounding DAC construction. EPA will act as the federal regulatory stakeholder with other agencies, like the Bureau of Land Management also involved.

Consumer Welfare and Employment: DAC can reduce the carbon impact of relatively dirty supply chains by creating carbon-neutral synthetic fuels and building materials, providing more time to transition from legacy energy sources. The green energy transition will require trillions of dollars in new infrastructure and capital investment, likely leading to increased costs of goods while the technology scales and impacts consumers.[104] Consider the shipping industry, where the cost of transitioning to a smaller carbon footprint will require whole fleets of new ships to be built, costs which will be borne in part by consumers. Increasing the carbon budget may reduce consumer price shock somewhat by lengthening the timeline for transition.

DAC as an industry has substantial job creation potential. A single 1-megaton plant generates an estimated 3,000 jobs. However, most of these would be temporary roles. As this technology scales, the positive employment impacts will increase. Some estimates indicate that this industry can bring up to 300,000 jobs by 2050.[105] DAC could aid in facilitating a just transition for disadvantaged groups in the workforce who will be negatively impacted by the green energy transition, such as those currently employed in the fossil fuel industry.

Public Health: DAC public health benefits are driven by carbon emission/impact reductions at scale. These reductions have positive public health effects associated with cleaner air and reduced pollution. **However, DAC plants must utilize sustainable energy sources to maximize their net carbon removal potential and achieve greater public health benefits.**[106]

103 "Carbon Capture, Utilization, and Sequestration Guidance," Council on Environmental Quality, Federal Register, vol. 87, no. 32, February 16, 2022, https://www.federalregister.gov/documents/2022/02/16/2022-03205/carbon-capture-utilization-and-sequestration-guidance.

104 Mekala Krishnan et al., *The Net-zero Transition: What it Would Cost, What it Could Bring* (Sydney: McKinsey Global Institute, 2022), https://www.mckinsey.com/capabilities/sustainability/our-insights/the-net-zero-transition-what-it-would-cost-what-it-could-bring.

105 Ugbaad Kosar, "Creating Jobs and Meeting Climate Goals: The Evolving Case for Direct Air Capture," Carbon180, Medium (blog), January 30, 2020, https://carbon180.medium.com/creating-jobs-and-meeting-climate-goals-the-evolving-case-for-direct-air-capture-428a853223d3.

106 Mark Z. Jacobson, "The Health and Climate Impacts of Carbon Capture and Direct Air Capture," *Energy & Environmental Science* 12, no. 12 (2019): 3567–74, https://doi.org/10.1039/C9EE02709B.

Selected Readings and Additional Resources

The list below highlights some of the citations in this document or comprehensive documents on specific topics and is not meant to be exhaustive.

On the Technology

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- Yang Qiu et al., "Environmental Trade-Offs of Direct Air Capture Technologies in Climate Change Mitigation toward 2100," *Nature Communications* 13, no. 3635 (2022), https://doi.org/10.1038/s41467-022-31146-1.

On Applications and Market Overview

- Colin McCormick, "Who Pays for DAC? The Market and Policy Landscape for Advancing Direct Air Capture," *Bridge on Frontiers and Engineering* 51, no. 4 (2021), https://www.nae.edu/266376/Who-Pays-for-DAC-The-Market-and-Policy-Landscape-for-Advancing-Direct-Air-Capture.

- Vanessa Núñez-López, and Emily Moskal. "Potential of CO_2-EOR for Near-Term Decarbonization." *Frontiers in Climate* 1 (September 2019), https://doi.org/10.3389/fclim.2019.00005.

- Ryan W. J. Edwards, and Michael A. Celia. "Infrastructure to Enable Deployment of Carbon Capture, Utilization, and Storage in the United States," *Proceedings of the National Academy of Sciences* 115, no. 38 (2018): E8815–E8824, https://doi.org/10.1073/pnas.1806504115.

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- Council on Environmental Quality, *Council on Environmental Quality Report to Congress on Carbon Capture, Utilization, and Sequestration*, (Washington, DC: US Executive Office, 2021), https://www.whitehouse.gov/wp-content/uploads/2021/06/CEQ-CCUS-Permitting-Report.pdf

- "The Case for Federal Support to Advance Direct Air Capture," Bipartisan Policy Center, June 2021, https://bipartisanpolicy.org/download/?file=/wp-content/uploads/2021/06/BPC_FederalCaseForDAC-final.pdf.

- US Government Accountability Office (GAO) *Decarbonization: Status, Challenges, and Policy Options for Carbon Capture, Utilization, and Storage* (Washington, DC: GAO, 2022), https://www.gao.gov/assets/gao-22-105274.pdf.

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- Rudy Kahsar, Guy Wohl, Charlie Bloch, and James Newcomb, "Direct Air Capture and the Energy Transition," Rocky Mountain Institute, July 18, 2022, https://rmi.org/direct-air-capture-and-the-energy-transition/.

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About the Technology and Public Purpose (TAPP) Project

The arc of innovative progress has reached an inflection point. It is our responsibility to ensure it bends toward public good.

Technological change has brought immeasurable benefits to billions through improved health, productivity, and convenience. Yet as recent events have shown, unless we actively manage their risks to society, new technologies may also bring unforeseen destructive consequences.

Making technological change positive for all is the critical challenge of our time. We ourselves - not only the logic of discovery and market forces - must manage it. To create a future where technology serves humanity as a whole and where public purpose drives innovation, we need a new approach.

Found by former U.S. Secretary of Defense Ash Carter, the TAPP Project works to ensure that emerging technologies are developed and managed in ways that serve the overall public good.

TAPP Project Principles:

1. Technology's advance is inevitable, and it often brings with it much progress for some. Yet, progress for all is not guaranteed. We have an obligation to foresee the dilemmas presented by emerging technology and to generate solutions to them.

2. There is no silver bullet; effective solutions to technology-induced public dilemmas require a mix of government regulation and tech-sector self-governance. The right mix can only result from strong and trusted linkages between the tech sector and government.

3. Ensuring a future where public purpose drives innovation requires the next generation of tech leaders to act; we must train and inspire them to implement sustainable solutions and carry the torch.

For more information, visit: www.belfercenter.org/TAPP