Where democracy
gets to work

Navigating the Stages of Commercialization to Deploy Direct Air Capture at Scale

A REPORT BY THE BIPARTISAN POLICY CENTER'S
DIRECT AIR CAPTURE ADVISORY COUNCIL

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Bipartisan Policy Center

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Introduction

Achieving national and international climate goals will require significantly scaling up efforts to remove carbon dioxide from the atmosphere.[1] This reality presents commercial opportunities as well as challenges for carbon dioxide removal (CDR) technologies. This report focuses on direct air capture (DAC), a CDR technology that is poised for success.

In the United States, the Biden administration has set an ambitious goal of reducing economy-wide greenhouse gas (GHG) emissions 50%–52% below 2005 levels by 2030 and achieving net-zero GHG emissions by 2050.[2] The successful commercialization of cost-effective CDR technologies, including DAC, is critical to meet these goals. Based on the representative scenarios presented in a recent 2021 administration report[3] on strategies for meeting the nation's commitments under the United Nations Framework Convention on Climate Change, the United States will need roughly 500 million metric tons per year (TPY) of CO_2 removal capacity to be operative by mid-century. To date, however, CDR technologies remain expensive and have not yet been demonstrated at scale.

Achieving domestic goals for DAC deployment will require meeting the companies in this nascent industry where they are and crafting effective policies to complement private sector investment. This report provides a status update on the commercial landscape for DAC technologies and makes the case for designing Department of Energy programs to meet the unique near- and medium-term needs of DAC companies today.

RECENT POLICY ACHIEVEMENTS IN THE UNITED STATES

The United States has long been a leader in technology innovation, and the field of CDR is no exception. In the last two years, Congress has provided the Biden administration with significant tools to help drive down costs for DAC by supporting innovation and deployment. Table 1 provides an overview of related program efforts across the federal government.

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[1] H. Lee et al. "IPCC, AR6 Synthesis Report," IPCC, 2023. Available at: https://www.ipcc.ch/report/ar6/syr/

[2] From "The Long-Term Strategy of the United States, Pathways to Net-Zero Greenhouse Gas Emissions by 2050," November 2021. Available at: https://unfccc.int/sites/default/files/resource/US-LongTermStrategy-2021.pdf

[3] The Long-Term Strategy of the United States: Pathways to Net-Zero Greenhouse Gas Emissions by 2050," U.S. Department of State, U.S. Executive Office of the President, 2021. Available at: https://www.whitehouse.gov/wp-content/uploads/2021/10/US-Long-Term-Strategy.pdf

Table 1: Overview of Federal Programming for DAC

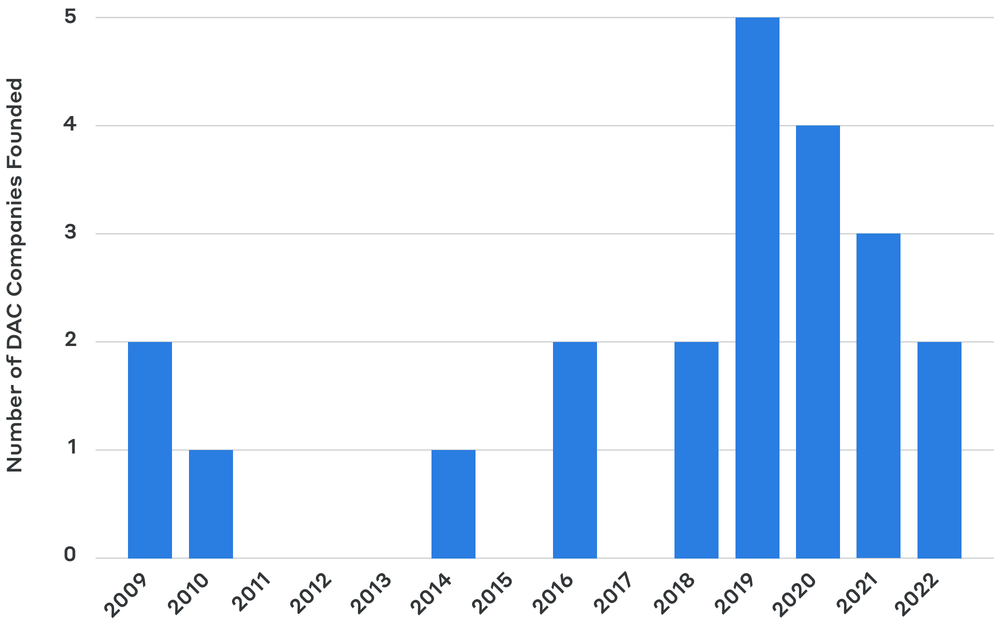
Program		Description	Funding
Regional DAC Hubs Program		Infrastructure Investment and Jobs Act (IIJA) program to launch four regional DAC Hubs. Designed to facilitate the commercial-scale deployment of DAC projects and leverage shared infrastructure.	$3.5 billion from IIJA through fiscal year 2026
DAC Technology Prize Competitions		Authorized by the Energy Act of 2020 and funded by the IIJA, this program sponsors multiple prize competitions to advance RD&D and commercial scale deployment of DAC technologies.	$15 million for a pre-commercial prize competition, $100 million for commercial prize competition
CDR Research, Development, and Demonstration (RD&D) Program		A crosscutting research initiative authorized by the Energy Act of 2020 to test, validate, or improve a wide range of CDR technologies (including DAC) at a large scale. CHIPS and Science Act authorized $1 billion in funding for FY2023-26, but the program receives annual appropriations through the standard appropriations process.	$140 million funded by FY2023 funding omnibus
DAC Test Center		Authorized by the Energy Act of 2020 and funded by the IIJA to conduct research on DAC materials and support large-scale pilot and demonstration efforts.	$25 million from FY2022 funding omnibus
Enabling Infrastructure	Carbon Capture Utilization and Storage (CCUS) Pilots and Demonstration Funding	Authorized by the Energy Act of 2020 and funded by the IIJA to support pilot projects and demonstrate carbon capture equipment beyond the laboratory stage. This program can help reduce risk for CO$_2$ transport and storage infrastructure that is also necessary for DAC.	$3.474 billion from IIJA through FY2025
	Carbon Dioxide Transportation Finance and Innovation (CIFIA) Program and Grants	New loan authority for CO$_2$ pipeline projects, and an accompanying grant program for performing Front End Engineering Design (FEED) studies on CO$_2$ transport infrastructure. This infrastructure enables a carbon managed economy by connecting CO$_2$ capture facilities to the storage and utilization sites necessary for permanent storage.	$2.2 billion from IIJA through FY2026
	New Grants for CO$_2$ Utilization	A new IIJA-created grant program for state and local governments to procure and use products derived from captured CO$_2$.	$307 million from IIJA through FY2026
	Expanded Carbon Storage and Validation Program at DOE	Authorized by the Energy Act of 2020 and funded by the IIJA to support RD&D and large-scale development of CO$_2$ sequestration projects, including funding for the feasibility assessment, site characterization, permitting, and construction stages of project development.	$2.5 billion from IIJA through FY2026
	(EPA) Grants for Class VI Primacy	Grants for states to develop resources for exercising primary authority ("primacy") over the permitting of Class VI wells for geologic storage of CO$_2$.	$50 million from IIJA
	(EPA) Class VI permitting funding	A provision of the IIJA that gives increased resources to EPA's Class VI permitting program to process the backlog of Class VI permits. At the beginning of 2023 there were two operational wells and ∼30 permits under administrative review across the United States.	$25 million over five years by IIJA ($5 million each year), with an additional $5 million provided by the FY2023 omnibus

The Pathway to Commercialization: From Lab to Market

The DAC industry is experiencing a period of rapid growth and company formation. For most of the last decade, the commercial landscape was dominated by the "first wave" of DAC companies: Climeworks (Switzerland), Global Thermostat (United States), and Carbon Engineering (Canada). All three of these private companies were founded between 2009 and 2010.

In recent years, the DAC landscape has expanded significantly. It now includes startup companies, research institutions, and corporations, using technology developed through internal R&D efforts, licensed from private companies or labs, acquired by purchasing companies, or some combination thereof. Over 20 DAC startups have each raised at least $1 million of private capital to date; most of these startups were launched within the last five years (Figure 1).[4] More technology development is underway at research institutions such as Xerox PARC, TDA Research, and GTI, in many cases with the support of significant public grants. So far, however, few of these efforts have resulted in the creation of independent spinoff companies.

Figure 1. DAC startups founded by year (includes private startups that raised at least $1 million from an institutional investor in one funding round)



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[4] Based on BPC review of publicly available announcements and funding data from www.crunchbase.com

The process of bringing a new technology from idea to commercial availability on an industrial scale can take a decade or more of development time and millions of dollars of investment.[5] While the experience of individual DAC companies has varied widely, a typical pathway is to start with lab-scale research while navigating multiple stages of risk on the pathway to commercial-scale deployment. Figure 2 shows the association of different product development stages with four distinct types of risk (note that the association of stages with risk is loose and features significant overlap, both between stages of development and types of risk):

- **Science risk:** the risk that a process proves to be scientifically or physically infeasible.
- **Engineering risk:** the risk that a process cannot be reproduced cost effectively at-scale or under real-world conditions.
- **Commercial risk:** the risk that there is not demand for the product being offered, the product being offered is not competitive in the marketplace, or that a company is not likely to be profitable.
- **Financing risk:** the risk that a company cannot access capital or manage its debt.

Because each product development stage is associated with distinct types of risk, different forms of private-sector funding and access to DOE funding may be appropriate at each stage. Successful emerging technology companies must raise funding from many different sources on their path to commercialization, and these sources may shift as the company and technology matures. Both public and private investors have important roles to play and must take different factors into account when supporting DAC companies. The next part of this paper highlights strategies for addressing different types of risk; it also identifies the product development stage and technology readiness level (TRL) typically associated with different types of risk and offers examples of existing programs.

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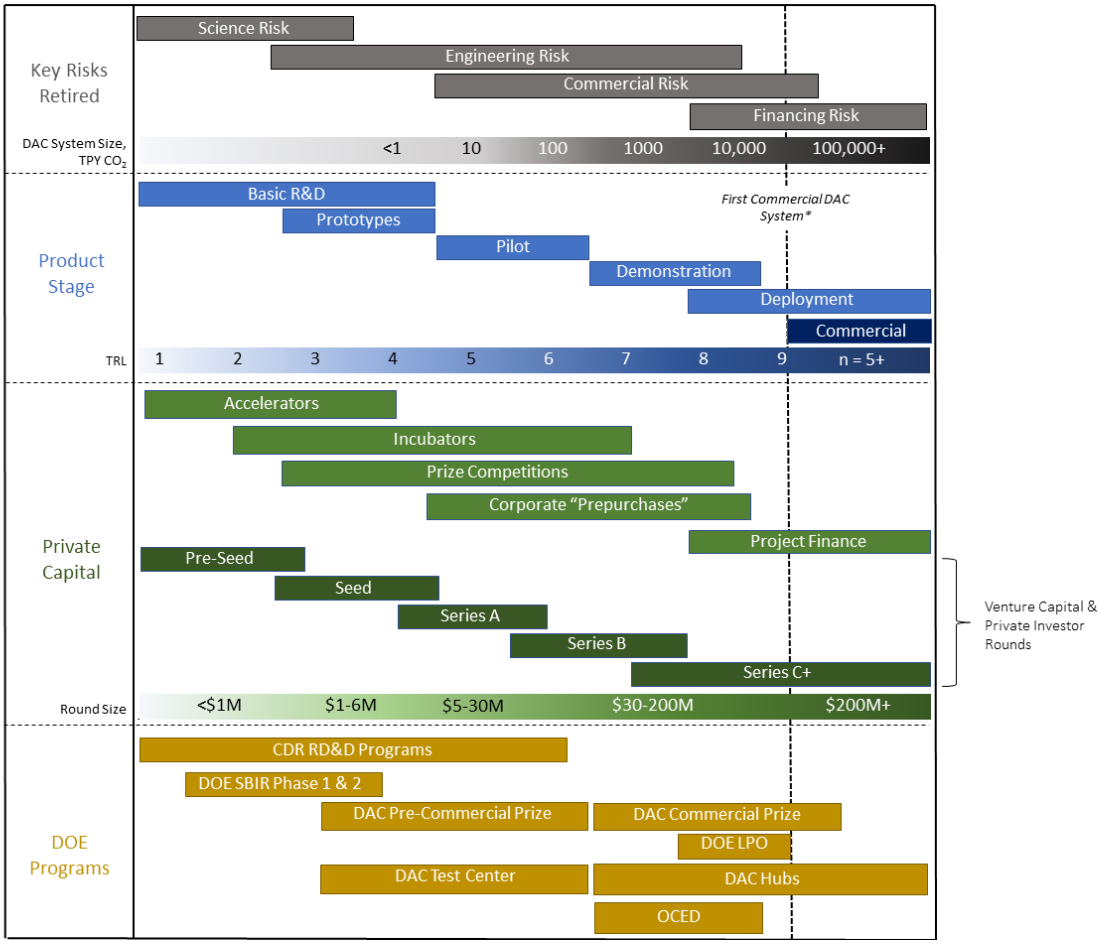
[5] Energy Innovation: Supporting the Full Innovation Lifecycle. American Energy Innovation Council. Feb 2020. https://bipartisanpolicy.org/download/?file=/wp-content/uploads/sites/2/2020/02/2020_AEIC_Report.pdf

Figure 2: Typical Stages In The Progression From R&D To Commercial-Scale Deployment For DAC Technologies



Note: The size of the "first commercial DAC system" shown here is approximate and is highly dependent on the specific DAC technology being utilized. Planned commercial systems range from a few thousand TPY CO_2 to 1,000,000 TPY CO_2.

SCIENCE RISK

TRL levels: 1-3+

Product stages: Basic R&D, early prototypes

Sources of private capital: Incubators and private accelerators, pre-seed and seed investors

Relevant DOE programs: CDR RD&D Program, SBIR (Small Business Innovation Research) grants

Typical funding level required: < $1,000,000

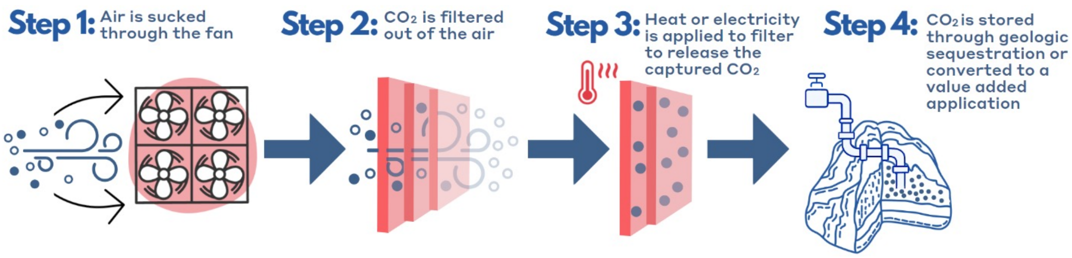
Time required to develop: 1-to-many years for early research

In the earliest stages of development, the primary focus is usually on addressing science risk—loosely defined as proving that all the steps in a process are scientifically or physically possible. A metric commonly used to describe the maturity of a new technology is “technology readiness level” (TRL), where a given technology’s TRL, on a scale of 1 to 9, is determined by the development milestones it has reached.[6] Science risk is typically associated with TRL levels 1–3, when the goal is to establish technical feasibility. A more detailed breakdown of TRL levels as applied to carbon management technologies is provided in an appendix to this report.

Most new technologies, including DAC technologies, begin with small experiments, known as “bench-scale” research, that can be carried out in a highly controlled laboratory setting to show that an idea works. In the DAC context, these experiments generally test specific properties of the CO_2 capture material being used and help researchers fine-tune inputs required for further development. Key questions at this stage could include:

- What is the maximum amount of CO_2 that a fixed amount of material will hold?
- How does the CO_2 uptake capacity change with temperature or pressure?
- How much heat or electricity is needed for the material to release the CO_2?
- How do oxygen, water, and other molecules present in the air affect how much CO_2 can be captured?

Figure 3: Schematic Overview of Direct Air Capture



Different variations of these questions will be relevant for different types of DAC technology. Text Box 1 provides a brief taxonomy of the key DAC technologies under development today. A more comprehensive review is available from the 2019 National Academies Negative Emissions Report[7] or from the web resource www.cdrprimer.org.

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[6] Official guidance on assigning TRL levels and an alternate description of TRLs with examples are available from DOE. Note that while the terms “prototype,” “pilot,” and “demonstration” are sometimes used interchangeably or differently by industry, our discussion follows conventions established by DOE and the American Institute of Chemical Engineers (AIChE) .

[7] “Negative Emissions Technologies and Reliable Sequestration: A Research Agenda,” NASEM, 2019. Available at: https://www.nap.edu/catalog/25259/negative-emissionstechnologies-and-reliable-sequestration-a-research-agenda

TYPES OF DAC TECHNOLOGY

Various pathways exist for capturing CO_2 from the atmosphere; these pathways can be loosely grouped as follows:[8]

- **Liquid Solvents.** Liquid solvents can be used to capture and release CO_2 subject to changes in temperature or pressure. Many solvents have been used by industry for decades; these solvents may therefore be cheaper than other options for CO_2 capture and may be available through existing supply chains.
- **Solid Sorbents.** Solid materials can also be used to capture and release CO_2 when the temperature or pressure is changed. A wide range of traditional solid sorbent materials continue to be investigated, including aminated cellulose, zeolites, metal-organic frameworks,[9] activated carbon, silica materials, porous organic polymers (e.g., PEI), and more.[10] A different approach to solid sorption of CO_2 is through the mineralization[11] of naturally occurring materials to create mineral carbonates. Relative to liquid solvents, solid materials may require less energy to release the captured CO_2, which has the potential to reduce energy costs.
- **Electrochemical.** Materials with unique chemical properties can capture and release CO_2 when electricity is applied (the processes involved are similar to those used in batteries).[12] This pathway offers potential efficiency gains over solvent and sorbent-based approaches, since the capture and recovery process does not require changes in heat or pressure.

The maturity of candidate technologies varies significantly across, as well within, each of these carbon capture pathways. Currently, each pathway has been demonstrated in a research setting, but the first two pathways are significantly more mature than the third and have been demonstrated at pilot scale or above. Carbon Engineering has demonstrated a liquid solvent system for capturing CO_2 at atmospheric concentrations on a scale of 4 ton per day (~1,400 TPY) and similar solvent-based systems have been used to capture CO_2 at higher concentrations from concentrated emissions sources.[13] Climeworks has also demonstrated a solid adsorbent-based process at its first-of-a-kind pilot commercial-scale Orca Project (4,000 TPY).

Electrochemical DAC systems, by contrast, have yet to be demonstrated at pilot scale but show potential for scale-up in future years.[14] Heirloom, for example, has demonstrated a mineralization reaction at the prototype scale in the lab.[15] "Electroswing" or electrochemical approaches have likewise been demonstrated in lab settings.[16]

Sources of early-stage funding to address science risk include **accelerators** and **incubators**, which typically provide $75,000 to $200,000 to startup founders. Incubators that provide public funds or **philanthropic capital** do not need to take equity, while private accelerators often charge companies a membership fee or, in some cases, may require an equity stake in the company being funded. After this stage, most startups will attempt to raise seed financing from venture capital (VC) firms. More details about VC funding can be found later in this report.

Public funding has historically played a critical role in early R&D and technology origination. Academic teams working on new DAC-related materials and processes have received funding from the National Science Foundation, DOE, the National Aeronautics and Space Administration (NASA), and European science institutions. Several DAC companies initially developed from publicly funded research projects. DOE's newly authorized **CDR RD&D program** is well positioned to support companies in this stage of development.

DOE's Small Business Innovation Research (SBIR) program also provides support to small companies in the R&D stage. **Phase 1 SBIR grants** can be hugely impactful despite their relatively small size (generally $250,000); these grants can allow a company to generate early technical evidence for proof of concept. Larger **Phase 2 SBIR grants** have enabled companies to begin prototyping and testing components. At this point, companies have mostly addressed science risk and are in a place to begin addressing engineering risk.

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[8] Another option is to keep the CO2 permanently stored in the form of a carbonate, either above ground (ex-situ) or underground (in-situ). However, the "mineralization" pathways involved in implementing these forms of CO2 storage are distinct from those used to implement DAC. See www.cdrprimer.org for more information.

[9] Sinha et al, Ind. Eng. Chem. Res. 2017, 56, 3, 750–764.

[10] Noah McQueen et al 2021 Prog. Energy 3 032001

[11] The natural "mineralization" of rocks absorbs CO2 from the atmosphere on geologic timescales. "Carbon removal mineralization" is any process which attempts to speed up this process on shorter timescales (years to decades). Mineralization-based-DAC, such as the technology demonstrated by Heirloom, uses this same principal but is designed to release pure streams of CO2 following capture so that the solid sorbent can be reused.

[12] "Faradaic electro-swing reactive adsorption for CO2 capture," Energy & Environmental Science, 2019. Available at: https://doi.org/10.1039/C9EE02412C

[13] Shell Quest, Air Products Port Arthur Project, NRG Petra Nova.

[14] Noah McQueen et al 2021 Prog. Energy 3 032001

[15] https://www.heirloomcarbon.com/

[16] https://news.mit.edu/2020/new-approach-to-carbon-capture-0709

ENGINEERING RISK

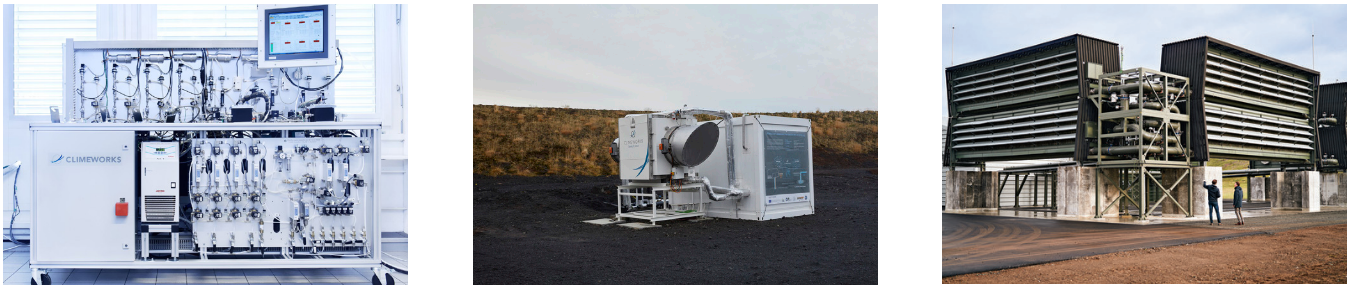
TRL levels: 3–8+
Product stages: Prototypes, pilots, demonstrations
Sources of private capital: Accelerators, incubators, prize competitions, corporate “prepurchases,” venture capital (seed, Series A, Series B)
Relevant DOE programs: CDR RD&D Program, SBIR, DAC Test Center, DAC Pre-Commercial Prize
Typical funding level required: $1–$8M for prototypes, $2–$10 million to construct a DAC pilot system
Time required to develop: 2–5 years for prototypes, 1–3 years for pilots

Once the general idea for a CO_2 removal system and its basic components has been validated experimentally, the process of figuring out how to turn a concept into a product begins to dominate further development efforts. This period is focused on reducing engineering risk, which can be expected to persist until the company proves it can deploy projects at commercial scale. Around TRL 3, a startup will begin developing small prototypes in a controlled setting (DAC prototypes would likely capture much less than 1 ton of CO_2 per year) to validate that components will work together and allow engineers to optimize the capture process. Reaching TRL 4 requires demonstrating that basic steps in the CO_2 capture process work together on a small scale.

Prototypes are often designed to be flexible and to test a range of potential process steps and conditions in a controlled environment. The overall set-up of a prototype will likely differ from the set-up for a full-scale version. For instance, the heat source for a prototype may differ from the heat source used at commercial scale. It is normal for early prototypes to resemble “Frankenstein” systems, with clear inefficiencies and some manual operations that can be automated at later stages. Given the very small scale of operation for a typical prototype system, there is generally also no expectation that captured CO_2 will be used or stored. More importantly, prototypes allow the technical team to validate that the basic process steps can be integrated together.

Once a company has developed a technology to sufficient maturity at the prototype level, it usually transitions to developing a pilot-scale system (for DAC systems, this might translate to a CO_2 capture rate of 1–500 TPY). Pilot-scale systems are designed to operate in “relevant” or operational environments with commercial-grade or near-commercial-grade components rather than laboratory-grade components. Pilot systems may still be bulky and expensive, as some parts of the CO_2 capture process will have yet to be optimized and may still be changed at later stages of development. Often, startups will begin pilot testing a first generation or “Gen 1” machine, with plans for future versions to include vastly different features. This stage covers TRL 5, where the company has validated that the components work, and TRL 6, where the company has operated a full subscale system in a relevant environment.

Figure 5: Climeworks Has Continued to Refine Its Technology from Early-Stage Lab Tests (Left) to Field Prototypes (Middle), to the Orca Pilot Commercial Facility in Iceland (Right). Pictures Provided By Climeworks.



At the pilot stage, a company has mostly finalized the key steps in the CO_2 capture process and is beginning to focus on scaling the technology. If not done already, the company may begin conducting front-end engineering and design (FEED) studies for demonstration facilities (500–1 million TPY). Such facilities are generally designed with commercial plant specifications; the aim is to demonstrate that the components of the company's capture system work together at larger scale, in a relevant environment. This may require building multiple, incrementally larger iterations of the system, eventually leading to "deployment" level systems. While there are similarities in that both phases proceed incrementally, a key distinction between demonstration and deployment is the focus on transitioning toward profitability in the deployment phase. Addressing engineering risk in the demonstration phase is critical to ensure that larger funders feel comfortable supporting later- stage deployment efforts.

Private sector funding from **accelerators** or **incubators** to address science risk in the early stages of technology development may roll over into later efforts to address engineering risk in the demonstration phase. Some states and philanthropic organizations will also offer continued funding through non-dilutive grants with fast award cycles, such as the California Institute of Technology's RocketFund.[17]

Prize competitions are also an increasing source of funding for startups that have reached the point where they are focused on engineering risk. Two privately funded CDR prize competitions are noteworthy in that they are agnostic to the stage of development of candidate technologies. XPRIZE, a non-profit that designs and hosts public prize competitions, launched its first Carbontech XPrize, the COSIA XPRIZE,[18] in 2015. This was a 5-year, $20 million prize for breakthrough technologies to convert CO_2 emissions into usable products. Ten teams reached the final round; each won $500,000. In April

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[17] The CalTech Rocketfund provides grants of $25,000–$75,000 to early-stage companies to perform critical demonstration tests.

[18] https://www.xprize.org/prizes/carbon

2021, two grand prize winners were announced. Both winners, CarbonBuilt and Carbon Cure, have developed technologies for decarbonizing cement production; each won $7.5 million. At the time of the award, CarbonBuilt had raised just $5 million in seed funding; Carbon Cure had more than 100 employees and had completed several rounds of "late VC" funding.

The 4-year XPRIZE for Carbon Removal was launched at the conclusion of the Carbontech XPRIZE in April 2021. Currently more than 1,000 teams are participating. One year after the launch, milestone prizes of $1 million were awarded to 15 teams, including six DAC companies (Calcite/8 Rivers, Carbyon, Heirloom, Mission Zero, Sustaera, and Verdox). A grand prize of $50 million will be awarded in 2025 to a team that "demonstrates CO_2 removal at the 1,000 ton per year scale, models costs at the million ton per year (megaton) scale and presents a plan to sustainably reach gigaton per year scale in future."[19]

Since 2022, Stripe, Microsoft, and other public companies have begun to provide small but catalytic amounts of funding to startups that have firm plans for a CDR project and are anywhere from the pilot stage through the demonstration stage. This funding takes the form of **corporate "prepurchases"** or upfront purchases of CO_2 credits at premium prices. For example, Stripe paid $200–$2,000 per ton CO_2 for six projects in 2021, including two projects by DAC companies (Mission Zero and Heirloom).

Public funding for prototype DAC technologies is available from DOE's **CDR RD&D program**; in addition, Phase **2 SBIR grants** are a potential funding source for prototyping and testing components. Unfortunately, the lag time between applying for SBIR funding and having a contract in place (typically, 6-15 months) can significantly delay development.[20] The IIJA authorized funding for a **DAC Test Center** to address engineering risk, similar to the way the National Carbon Capture Center supports work to test materials and address scale-up challenges for carbon capture, utilization, and storage (CCUS) equipment. According to the National Energy Technology Lab (NETL), the DAC Test Center will cater to experiments at the lab, lab bench, and small pilot scales (corresponding to capture rates of ~0.1 kg CO_2 /day, ~4 kg CO_2 /day, and ~30 kg CO_2 /day, respectively). The center is scheduled to be fully operational by summer 2024.[21]

The IIJA also authorized funding for DOE to sponsor multiple **DAC Prize Competitions**, which DOE announced as part of its "American-Made Challenges" program[22] in December 2022. These competitions are squarely focused on addressing engineering risks for a DAC company and could potentially supplement funding from private-sector prize competitions.

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[19] https://www.xprize.org/prizes/carbonremoval

[20] Reforming the Department of Energy's Small Business Innovation Programs, Bipartisan Policy Center, May 2022 https://bipartisanpolicy.org/download/?file=/wp-content/uploads/2022/04/SBIR-Energy-Brief_.pdf

[21] National Energy Technology Lab Direct Air Capture Center. https://netl.doe.gov/node/12331

[22] https://www.herox.com/DAC-pre-commercial-EPIC

COMMERCIAL RISK

TRL levels: 5–9+
Product stages: Pilots, demonstrations
Sources of private capital: Prize competitions, corporate “prepurchases,” venture capital (Series A, Series B, Series C+), project finance
Relevant DOE programs: CDR RD&D program, DAC commercial prize, DAC hubs
Typical funding level required: $2–$10 million to construct a pilot system, demonstrations depend on technology type and tonnage but can range from $3 million to >$100 million
Time required to develop: 1–3 years for pilots, 3–4 (or more) years for demonstrations

As a company begins to develop its first pilot project, commercial risk—that is, risk associated with demonstrating demand for DAC as a commercial service, demonstrating the ability to fulfill that demand, and determining whether a market exists for the technology—emerges as an important factor for consideration. To address commercial risk, DAC companies must reach agreements with customers and partners to develop confidence that there will be consistent market demand for their product. In some cases this can mean preselling CO_2 offtake or credits well in advance of deployment. Commercial risk can be expected to remain a factor until a company deploys a full commercial-scale DAC system and manages its capital effectively.

Companies that have successfully navigated the pilot stage typically begin to plan for one or more demonstration projects to show that they can operate profitably at a commercial scale. Such projects are critical to prove to partners, funders, and customers that the company is ready to sell its product. Manufacturing and supply chain development, for both process equipment and CO_2 capture materials, becomes a major area of focus. As a result, many companies face expanded workforce needs at this point, often adding to their engineering staff, bringing on a vice president of engineering, and pursuing other senior hires with relevant industry experience.

The minimum scale for a demonstration facility, and thus the amount of funding required, depends on the type of DAC technology being utilized.[23] In general, solid adsorbent systems are more amenable to modularization and smaller commercial units. Several DAC companies using solid adsorbents have proposed a modular system, formed of individual CO_2 contactor modules that capture 500–10,000 TPY CO_2 with potential to scale up to megaton and beyond in the future. A representative example is Climeworks’s first-of-a-kind commercial pilot Orca system, which is designed to capture 4,000 TPY CO_2.

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[23] A modular DAC demonstration system may require $3–$30 million in capital; larger demonstration systems (e.g., >100,000 TPY CO_2) may cost more than $100 million.

In contrast, equipment costs rather than the cost of solid CO_2 capture materials dominate capital expenditures (CAPEX) for DAC technologies that use liquid solvents or mineralization. Equipment costs for these DAC technologies are expected to scale like traditional chemical and industrial equipment: the bigger the facility, the lower the costs on a per-unit basis.[24] A representative example is 1PointFive's facility, Stratos, currently under construction in Ector County, TX, which will use Carbon Engineering technology to capture 500,000 TPY CO_2 and is expected to be commercially operational in mid-2025.[25]

As CAPEX grows, a company's financial practices typically begin to mature. A team will be expected to have developed well-informed "bottom up" cost projections for demonstration- and commercial-scale facilities; these projections will be further informed by FEED studies. Financial overhead, including payroll, facilities, and operating expenses, as well as overall capital burn will increase significantly, necessitating larger sources of financing.

The **corporate "prepurchase"** financing arrangements described in the last section can play a major role for companies and often offer flexible terms. Companies may also, in parallel or concurrently, secure funding through **private investors** and **VC** firms.

Private investors and VC firms generally seek a ratio of financial upside to risk that (a) fits their investment model and (b) is competitive with other market opportunities. Whereas nonprofits or philanthropic organizations may invest based on mission alignment, and federal or state governments may invest to advance policy goals, including economic development and job creation, private investors and VC firms are typically more interested in investing in emerging and expanding businesses to get early access to new technology. These private sources are commonly tapped in subsequent funding "rounds".

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[24] This is particularly true for calciners, the furnaces that heat calcium carbonate to release pure CO_2 in the Carbon Engineering and Heirloom processes. In these cases, the demonstration systems for DAC companies will be much larger, likely 50,000-500,000 TPY CO_2, and commercial scale systems are designed to capture 500,000+ TPY CO_2.

[25] https://www.1pointfive.com/ector-county-tx

PRIVATE INVESTOR AND VENTURE CAPITAL BASICS

Startups typically seek funding from private investors and VC firms in "rounds" that are tied to distinct phases of business development:[26]

- Pre-Seed: $100,000–$1 million. Funds company formation, finding product-market fit, and developing a business plan.
- Seed: $1–$5 million. Funds early prototyping and beta testing of a product in a controlled setting.
- Series A: $5–$30 million. Funds preparations for commercial production, including proof-of-concept and market development.
- Series B: $20–$100 million. Funds demonstration in a relevant environment, business growth, and expansion of market reach.
- Series C+: $50–$100 million and above. Provides capital to maintain and accelerate growth and enable the company to reach profitability.

In each "priced round", companies typically sell a 10%-40% equity stake in shares of stock.[27] Pre-seed and seed investments typically fund company formation, early product development, and customer discovery and engagement. Series A often funds advanced prototyping and pilot activities to further de-risk the technology, plus customer pipeline development and team expansion.

Unlike many public grant programs which focus heavily on technical merit, VC firms may evaluate the investment opportunity with greater weight on commercial and organizational maturity, including the leadership team. For instance, if a startup or spinoff has a leadership team with a proven track record (low organizational risk) or has signed contracts with customers (low commercial risk), it will generally be able to raise larger sums of funding on a higher valuation compared to a company that has a similarly mature technology but lacks the other factors. The process of raising private capital usually takes several months and significant effort to complete, with the level of effort and due diligence increasing in later funding rounds.

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[26] See the well-known accelerator Y Combinator's guide to startup stages, with two caveats: a) YC is heavily oriented towards software startups, and b) the size of funding rounds (especially in climate tech) generally increased in 2020 and 2021. Note that geography and founder experience highly influence the startup's perceived value.

[27] For example, a founding team initially owns 100% of the company and raises $5 million in seed funding from a single investor at a $15 million pre-market valuation. Following the round, the company is worth $20 million, and the founding team owns 75% of the company's shares while the investor owns 25%.

VC firms have made significant investments in DAC technology over the last decade. Publicly announced VC funding for DAC companies exceeded $1.3 billion between 2009 and 2022. The vast majority of this investment occurred between 2021 and 2022, including $630 million in Series F funding raised by Climeworks in early 2022. DAC accounted for nearly 50% of all carbon capture, removal, and conversion funding raised in 2022, according to the Circular Carbon Network 2022 Market Report.[28] More than 15 DAC companies have raised early-stage funding from VC firms (pre-seed to Series A), including Verdox, Heirloom, and Carbon Capture, all of which raised exceptionally high-dollar-amount Series A rounds in 2021.[29]

More recently, VC funding for DAC startups has slowed, reflecting deteriorating financial market conditions, even in the relatively strong climate tech sector. In this context, federal funding under recently passed legislation like the IIJA and Inflation Reduction Act (IRA) will be especially important in terms of supporting efforts to address commercial risk for DAC companies. As previously noted, DOE's CDR RD&D program, DAC Test Center, and DAC Prize Competitions all can play key roles in concurrently driving down engineering risk and commercial risk. New adjustments to the federal 45Q tax credit, taken in tandem with credits sold in voluntary carbon markets, are helping to demonstrate the longer-term appetite for DAC services and the existence of a market for these services. Moreover, $3.5 billion in federal funding to launch four regional DAC hubs can drive down risk by enabling companies to leverage shared infrastructure and resources for future demonstration efforts.

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[28] https://www.xprize.org/prizes/carbonremoval/articles/ccn-2022-report

[29] The recent increase in private funding going to DAC companies reflects a number of factors, including macro investing trends, increased maturity of DAC technologies, greater investor confidence that future government policies will create markets for DAC, growing demand for high-quality carbon credits to meet voluntary climate commitments, and the perception that climate tech investments are "hot." Another positive factor for DAC and the climate tech sector in general has been the emergence of several large, climate-focused early-stage venture firms (e.g., Prelude Ventures, Breakthrough Energy Ventures, and Lowercarbon Capital, all of which have invested in multiple DAC startups) and the movement of later stage financial organizations towards divesting fossil assets.

FINANCING RISK

TRL levels: 8–9
Product stages: Demonstrations, deployment, commercial-scale products
Sources of private capital: Prize competitions, corporate “prepurchases,” venture capital (Series B, Series C+), loans, project finance
Relevant DOE programs: DAC commercial prize, DAC hubs, Loan Programs Office
Typical funding level required: Costs for demonstration facilities depend on technology type and capture rate but can range from $3 million to >$100 million, similar to commercial-scale facilities
Time required to develop: 3–4 years for demonstrations, possibly more for commercial-scale projects

As a company enters the deployment phase, financing risk —i.e., risk related to the company’s ability to access capital and manage debt—emerges as a key concern. Having reached “nth-of-a-kind” technology deployment, companies typically begin to take on debt from larger sources of capital. Before they will lend, these sources require robust cost estimates and FEED studies which typically take months to years to complete depending on the size of the facility. Developing these studies, while also developing manufacturing and supply chain capabilities, often determines how quickly a new technology startup can make progress at the demonstration and early commercial deployment stages.

After a company has deployed at least one system on a scale sufficient to demonstrate the efficacy of its technology, additional facilities may be built at a commercial scale. In the case of a DAC company, its first commercial systems may consist of single capture modules to meet customer demands for smaller quantities of CO_2. For example, producers of cement or concrete that are interested in offsetting their emissions may need only a few thousand tons per year of CO_2 capture per facility.

Companies that are pursuing commercial sequestration of CO_2 via underground mineralization (e.g., Carbfix and 44.01) will require sequestration wells with capacities on the order of several thousand tons per year. Other locations with potential to sequester larger quantities of CO_2 will also be required to enable some companies to be cost effective. For example, new Class VI sequestration wells in saline aquifers are designed for 500,000 TPY CO_2 or more.[30] Co-locating DAC facilities with other emissions sources may make financial sense for early project developers in these regions.

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[30] For this reason, there are some plans to co-locate early DAC facilities with other emissions sources. It is relatively easy to increase the capacity of an existing well by 50,000 TPY CO_2 for a moderately sized DAC facility. Source: Lonquist Sequestration Services and Frontier Carbon Solutions. Available at: https://medium.com/prime-movers-lab/webinar-recap-emerging-carbon-sequestration-markets-6e6724f0c90a

It is worth noting that very few DAC startups so far have matured sufficiently to raise later stage or growth capital (Series B/C+). These rounds are used to grow and scale new businesses and usually require that a company is generating revenue and is on a path to strong margins. To raise Series B funding, a DAC company will likely need to have favorable results from pilot tests and be demonstrating (or preparing to demonstrate) its technology at a commercially relevant scale. The company must also show strong commercial engagement and have a solid business plan.

Financial market conditions can affect the availability of private capital, especially for later stage companies. As previously mentioned, a massive amount of private capital has been deployed to DAC startups since 2020 and 2021 saw a historic number of funding "megarounds" (such as the Climeworks Series F). In the first half of 2022, however, the number and size of large, late-stage funding rounds dropped precipitously. While climate tech is still enjoying stronger investment activity than other sectors, it will likely be more difficult for the cluster of "DAC 2.0" companies to access similar levels of late-stage capital to build larger demonstration facilities and generally move down the learning curve to reduce costs.

Beyond funding from private investors and VC firms, successful **project finance** will be increasingly important for DAC companies that are ready to build commercial facilities. More generally, early project finance is of growing importance to the climate tech ecosystem as a whole as companies look to raise $50+ million to develop first-of-a-kind projects. The first step typically involves gaining access to debt finance. In contrast to VC and private equity firms which take ownership or equity stakes in the companies they fund, providers of debt finance lend funds depending on the perceived level of risk. To borrow, a company must have a business model that shows sufficient revenue generation to make payments on its debt.

PROJECT FINANCE FOR EMERGING CLIMATE TECHNOLOGIES

As with any startup, the goal of a new DAC company will be to reduce commercial and financing risk so that private lenders are willing to finance larger-scale projects; this is sometimes called reaching "bankability." Project finance is a financial tool that can help reach this goal, by using a unique combination of *equity* and *debt* financing to support larger-scale projects.

VC and private equity firms are willing to make *equity* investments (providing capital in exchange for partial ownership) in companies that still have a certain degree of technical risk in hopes of receiving high returns on their investment. However, these equity investments can be costly for the recipient company because they typically come with the expectation that shareholders will see a high return to make their risky investment worthwhile. By comparison, taking on *debt* may offer a cheaper path to financing a project, but it requires that the project has a sufficiently low risk profile that the lender is willing to provide a loan with a reasonable interest rate, or make a loan at all. Project finance allows a company to use equity investments to prove its technology is commercially viable and reduce risk, which then makes the risk profile acceptable to lenders who can provide debt financing at a lower interest rate.

Providers of DAC project financing will require a feedstock agreement (or siting study), an offtaker for captured CO_2 or associated carbon removal credits, and a rigorous technical review of the proposed process. Past work to move through prior stages of risk all serves to facilitate these arrangements. Additionally, the credit worthiness of offtakers (i.e., buyers of captured CO_2 or of CO_2 removal credits) is relevant, since this provides the basis of future revenue streams, as is the technical credibility of the engineering partners—both factor into a company's ability to secure project financing for a commercial-scale DAC system.

To move DAC technologies toward bankability, other groups have emerged to provide other financing arrangements to early (ranging from first-of-a-kind to approximately tenth-of-a-kind) energy transition and climate-focused projects. This includes **DOE's Loan Programs Office** (LPO) who provides loans and loan guarantees below market rate to projects that can demonstrate a reasonable prospect of repayment. With a significant injection of new loan authority from the IRA, LPO currently has about $80 billion in loan authority for clean energy projects under the Title 17 program, $55 billion in loan authority for clean vehicle manufacturing projects under the Advanced Technology Vehicles Manufacturing (ATVM) program, and $250 billion in loan authority for projects that fall under the new 1706 program for reutilizing existing energy infrastructure. Loan amounts need to be at least $70 million (and ideally in the hundreds of millions) for the administrative costs of securing the loan to make sense.

The Policy Context: Supporting the Near-Term Needs of DAC Companies

As shown in Figure 4, most of today's DAC companies are clustered between TRL 4 and 6. These companies have shown that their CO_2 capture process works in the lab, but now need to productize their technology and deploy pilot and demonstration DAC facilities in the field.

Figure 6. Estimated technical maturity of private DAC companies, Q2 2023

Given the current technical maturity of DAC companies, there is a clear short-term need for non-dilutive funding to support the development of 1,000+ TPY facilities in the pilot-scale demonstration stages. Achieving the goal of net-zero emissions by mid-century requires that DOE and policy makers meet these companies where they are today in addressing risks and achieving long-term scale-up.

A recent DOE funding opportunity announcement (FOA) makes clear that the $3.5 billion in federal funding for DAC hubs authorized under the IIJA will be reserved for the herculean task of convening, planning, designing, and deploying at-scale DAC hubs capable of reaching 1 million TPY capacity in the short term. It could be beneficial to co-locate some pilot projects so they can leverage shared infrastructure for CO_2 storage and transport, but the DAC hubs funding stream is intended for the broader activities required to support a large-scale hub. It is critical that Congress and DOE continue to support alternate funding streams for DAC pilot projects in the coming years.

Given the engineering risk and high levels of investment required for pilot and demonstration projects, private investors are unlikely to act on their own. DOE and policymakers should therefore prioritize near-term funding opportunities for supporting DAC pilots. Some DOE programs for funding DAC pilots already exist, including the carbon removal RD&D program and DAC pre-commercial technology prize competitions,[31] but more funding opportunities are needed. One interesting idea is for the newly authorized Office of Clean Energy Demonstrations (OCED) to create an SBIR program under existing authorization to fund DAC pilot-scale demonstration projects. [32] DOE's existing SBIR program has been criticized for an overly complex application process, infrequent application windows (only once per year), and a lack of focus on technology commercialization. In the past year, BPC has released recommendations to address these issues and maximizing the utility of the SBIR program for startups across the energy landscape.[33] Taken together, these recommendations can create more funding opportunities for DAC start-ups looking to build pilot-scale projects.

DOE and policy makers should explore all tools at their disposal to support DAC companies at every stage of deployment. If implemented effectively, DOE support for pilots, coupled with funding for DAC hubs can help catalyze the commercial deployment of a broad range of DAC technologies in the coming years. The sooner these activities begin, the faster DAC costs will come down the learning curve.

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[31] A DAC pre-commercial technology prize competition was authorized by the Energy Act of 2020 and funded by the IIJA. For more on the prize competition rules, see: https://www.herox.com/DAC-pre-commercial-tech

[32] BPC recently released several recommendations for the optimal design of an OCED SBIR program to support pilot-scale demonstrations. These recommendations include making funding available for flexible purposes that advance scaleup and commercialization, building a pipeline for de-risked demonstration projects (similar to the role that SCALEUP plays for ARPA-E), and raising the cap for SBIR awards. For the full report, see: Tham, Natalie. Innovation at Scale: Supporting Pilot-Scale Demonstrations. Bipartisan Policy Center, 2023.

[33] BPC has published specific recommendations for reforming DOE's SBIR program, including: accepting startup-like pitch decks as applications instead of concept papers (similar to the National Science Foundation SBIR program), offering multiple application windows each year (or rolling applications), and hiring staff with private sector expertise who understand pathways to commercialization. For the full report, see: Das, Tanya. Reforming the Department of Energy's Small Business Innovation Programs. Bipartisan Policy Center, 2022.

Conclusion

The nascent DAC industry is clearly at an inflection point. Recent legislation along with private sector investment is creating tailwinds, but current and future federal funding must be spent wisely within the parameters of DOE's purview. This decade will see billions of dollars invested in DAC and first-of-a-kind DAC hubs coming online. But maximizing the chances of success for growing this new industry to the scale needed to achieve net-zero emissions by mid-century will require investments in the full innovation life cycle of DAC technologies and supporting DAC companies as they continue driving down costs and increasing efficiency. For now, simultaneously accelerating progress in both scale and innovation remains the core challenge for the DAC industry—one that is key to the industry's long-term commercial prospects and to achieving America's climate goals.

Appendix

Technology Readiness Levels (TRL) Description of Carbon Management Infrastructure (National Energy Technology Laboratory)

Table 3: Description of TRL Levels as Applied to Carbon Management Infrastructure. Taken from DOE FOA DE-FOA-0002614, 000007.

TRL	DOE Definition	Minimum Simultaneous Requirements to Achieve TRL based on NETL Interpretation of DOE Definitions & Descriptions					
		Scope	**Integration**	**Fidelity**	**Scale**	**Environment**	**Metrics**
1	Basic principles observed and reported	Any experimentation is limited to discovery and validation of fundamental scientific principles. Formulation of the technology that applies the fundamental science is initiated in conceptual paper studies but experiments on the applied technology have not begun.					N/A
2	Technology concept and/or applications formulated						Project-specific TMPs should define cost and/or performance metrics for relevant TRLs. To attain a given TRL, the technology must achieve the metrics for that TRL (or show a likely potential to do so).
3	Analytical and experimental critical function and/or characteristic proof of concept	Single Component	None	Low (ad-hoc hardware)	Lab	Lab (simulated conditions)	
4	Component and/or system validation in laboratory environment	Total system or multi-component subsystem	Integration of some or all components				
5	Laboratory scale, similar system* validation in relevant environment			High (nearly a prototype)		Relevant (regulated expected conditions)	
6	Engineering/pilot-scale, similar (prototypical) system validation in relevant environment	Total system (The total system is equivalent to the "TRA System," which is the system or subsystem for which technology readiness is being assessed)	All components and subsystems integrated	Prototype	Small Pilot **		
7	Full-scale, similar (prototypical) system demonstrated in relevant environment				Large Pilot or Full **		
8	Actual system completed and qualified through test and demonstration. Technology has been proven to work in its final form and under expected conditions.			Actual system in final form	Full	Operational (unregulated actual conditions)	
9	Actual operation of the technology in its final form, under the full range of conditions.			Commercially warranted			N/A

*The DOE TRL 5 description states that the "similar system" matches the final application in "almost all respects" and is "almost prototypical." This table interprets the similar, but not fully prototypical, system as being either: a) the total system for which readiness is being evaluated, or b) a multi-component subsystem of the total system. This interpretation is supported by the DOE TRL 6 description which states that "TRL 6 begins true engineering development of the technology as an operational system."

** DOE defines TRL 6 as a pilot-scale prototype and TRL 7 as a full-scale prototype. DOE defines TRLs 8 and 9 as involving "actual" systems at full scale. This table assumes that the scale of the TRL 7 full-scale prototype could be less than or equal to the scale of the TRL 8 full-scale actual system. At a minimum, the scale of the TRL 7 prototype must be sufficiently large to support subsequent testing of a TRL 8 full-scale actual system without the need for testing at an intervening scale.

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