I-WEST

Phase One Final Report | Detailed Chapter

# Direct Air Capture

VERSION 1.0

ARIZONA STATE UNIVERSITY

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# About this report

The Intermountain West Energy Sustainability & Transitions (I-WEST) initiative is funded by the U.S. Department of Energy to develop a regional technology roadmap to transition six U.S. states to a carbon-neutral energy economy. I-WEST encompasses Arizona, Colorado, Montana, New Mexico, Utah, and Wyoming. Each state is represented in this initiative by a local college, university, or national laboratory. Additional partners from beyond the region were selected for their expertise in applicable fields. In the first phase of I-WEST, the team built the foundation for a regional roadmap that models various energy transition scenarios, including the intersections between technologies, climate, energy policy, economics, and energy, environmental, and social justice. This chapter presents work led by an I-WEST partner on one or more of these focus areas. A summary of the entire I-WEST phase one effort is published online at www.iwest.org.

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# Key messages

- Direct Air Capture (DAC) offers two significant benefits: it can efficiently lower the atmospheric concentrations of $CO_2$ when combined with permanent sequestration in geologic reservoirs and the $CO_2$ captured can also be used to produce a range of sustainable fuels when combined with renewable energy that can displace and eventually end fossil fuel extraction.
- Bringing down the cost of DAC with the accompanying increasing deployment requires the creation of a market. Policies that require carbon removal by major current and past emitters would create that necessary long-term market.
- Three DAC technologies are tied to the Intermountain West, and two are currently being demonstrated. The region is well suited for DAC in terms of available land, renewable energy, sequestration potential, and a large workforce already trained in the mining and energy sectors.
- Development and deployment of DAC will find support from the Department of Energy (DOE) DAC hubs in terms of bringing the cost down, but will require policies that create the need for DAC by requiring polluters to pay.
- DAC is well suited for large-scale application in the Intermountain West, which may be the most favorable geographic and environmental location in the U.S. The region has open space, plenty of sunshine, an industrial workforce, opportunities to match DAC to renewables at a scale matching need, and abundant geologic formations suited for sequestration.

**"Make no little plans. They have no magic to stir our blood and probably themselves will not be realized. Make big plans; aim high in hope and work." Daniel Burnham, Architect.**

# Introduction

Since the 1850s, $CO_2$ concentrations have relentlessly increased to reach their highest level in at least 800,000 years[1]. In the 1990s, climate change was theoretically understood but obscured by natural fluctuations in weather. In the 2000s, climate change could be detected by careful measurement. In the 2010s, climate change became visible to everyone. However, it was still not large enough to rally people into action. In the 2020s the impacts of climate change will drastically exceed natural variability, likely forcing people to action. This decade will be less about studying climate and more about mitigating the impacts.

Part of transitioning to a sustainable energy system is dealing with $CO_2$ as a waste management challenge[2]. Much of the success needs to be in the reduction and elimination of the generation of $CO_2$. The other part of the solution will be to capture the excess $CO_2$ that is already in the atmosphere and oceans and to capture what is released during the transition to a future based on renewable energy.

The work to build a new carbon management industry depends on the development and implementation of requirements to eliminate carbon pollution and draw down what is already in the atmosphere. Once carbon neutrality is a requirement, tens of thousands of new jobs will be created to solve the accompanying challenges in a variety of ways. Of the solutions that will be implemented, carbon capture will directly affect millions with the goods and services it provides and give the benefit of reduced global warming to nearly everyone on the planet. By the end of this decade, Direct air capture (DAC) will have to grow from kilotons per year to hundreds of megatons per year. By harvesting carbon from the atmosphere for sequestration and carbon products a new industry will be born. The benefits will include the permanent storage of carbon and the development of renewable energy through recycled synthetic fuels. By recycling $CO_2$, it becomes possible to have renewable energy penetrate through the entire market. By providing the ability to remove $CO_2$ from the atmosphere, no one can be exempted from cleaning up their carbon emissions. For emissions that cannot be avoided and the legacy of past emissions, DAC and carbon disposal stands ready to balance the carbon budget.

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[1] IPCC, 2021: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change[Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, In press, doi:10.1017/9781009157896.

[2] Lackner, K.S., Jospe, C., 2017. Climate Change is a Waste Management Problem. Issues in Science and Technology 33, 83–88.

The world needs to sequester about 1.5 trillion tons of $CO_2$ to lower its concentration in the atmosphere by 100 ppm relative to where it would end up otherwise. Even if emissions were to stop right now, this would be insufficient to return to pre-industrial era $CO_2$ levels. Minimizing emissions will not be sufficient to stabilize climate below 2°C warming. The most plausible way out is to combine emission reductions with "negative-emission" or "drawdown" technologies. DAC represents a critical technology for such a drawdown. It also could play a major role in a closed carbon cycle, where fuels and plastics are produced from $CO_2$ from the air using renewable or recycled fueled electric power for the production.

Once mobilized, carbon stays in the atmosphere/hydrosphere/biosphere system for tens of millennia[3]. For the first hundred years half of the carbon remains in the atmosphere[4]. The rest acidifies the ocean and leads to the eutrophication of the biosphere[5]. Zero emissions is a noble goal, but until it is attained, $CO_2$ must be disposed of. This will require big political change, but a political solution for managing carbon may prove easier than forcing the necessary lifestyle changes to abandon fossil fuels. In the end, for every ton of carbon coming out of the ground another ton will have to be disposed of[6,7], and the emissions from the waste burned over the past two centuries will need to be cleaned up as well. This is the way the world's carbon budget will be balanced.

Can DAC be implemented in time? Analogs with other technologies suggest that after invention there typically is a latency time, which is followed by rapid growth that results in ubiquitous deployment, maybe a decade or two later. If we optimistically assume the start time as 20 years ago, the latency time is over and that growth starts now, we will take maybe around 20 years to reach scale. Then it still takes 40 years to draw down the carbon, so one could reach the end of the overshoot near the end of the century, which unfortunately leaves plenty of room for climate damage.

The really difficult question is, "How to get started?" If the foregoing paragraph is correct, we are in for a sizable amount of climate related damage before trends turn around. By the time we have grown our

[3] Archer, D., Eby, M., Brovkin, V., Ridgwell, A., Cao, L., Mikolajewicz, U., Caldeira, K., Matsumoto, K., Munhoven, G., Montenegro, A., Tokos, K., 2009. Atmospheric lifetime of fossil-fuel carbon dioxide. Annual Reviews of Earth and Planetary Sciences 37.

[4] Archer, D., Kheshgi, H., Maier-Reimer, E., 1997. Multiple timescales for neutralization of fossil fuel CO. Geophys. Res. Lett. 24, 405–408. https://doi.org/10.1029/97GL00168

[5] Archer, D., Kheshgi, H., Maier-Reimer, E., 1998. Dynamics of fossil fuel CO2 neutralization by marine CaCO3. Global Biogeochemical Cycles 12, 259–276. https://doi.org/10.1029/98GB00744

[6] Lackner, K.S., Wilson, R., Ziock, H.-J., 2000. Free-Market Approaches to Controlling Carbon Dioxide Emissions to the Atmosphere. Global Warming and Energy Policy 31–46. https://doi.org/10.1007/978-1-4615-1323-0_3

[7] Allen, M.R., Frame, D.J., Mason, C.F., 2009. The case for mandatory sequestration. Nature Geoscience 2, 813–814. https://doi.org/10.1038/ngeo709

capture capacity to its fullest, the amount of $CO_2$ to be removed will be well above current estimates. We have a lot of work in front of us. Capture and other mitigation are awaiting regulatory obligation to make the necessary changes. Without obligation there is no real demand and without demand there will not be much forward progress.

“Intergovernmental Panel on Climate Change (IPCC) finds “unequivocal” evidence that any more delays “will miss a brief and rapidly closing window of opportunity” for a globally livable future.[8] UN Secretary-General António Guterres called the report “an atlas of human suffering,” because it’s a comprehensive look at both recent and projected extreme weather events, lacerated ecosystems, and their human toll. “The facts are undeniable. This abdication of leadership is criminal," Guterres said in a statement. "The world's biggest polluters are guilty of arson of our only home."[9]

# How does direct air capture work?

DAC uses a nature-inspired design to absorb $CO_2$ directly from the air (Figure 1). The capture process may be driven by mechanical means (fans) or passive (relying on natural air movement). DAC uses a chemical compound (sorbent) to “catch” the $CO_2$ out of the air. Following capture, the sorbent is exposed to heat, moisture, or some combination that releases the $CO_2$ into an enclosed space that serves as a harvest chamber. This capture and harvest sequence is then repeated. Following the capture phase, except in a few applications, the $CO_2$ enriched air is fed to a compression and purification unit to produce $CO_2$ in varying concentrations, generally in the 90+ percent range. The basic operation relies on a sorbent cycle to bind $CO_2$ from the atmosphere and release it in an enriched form (Figure 2).

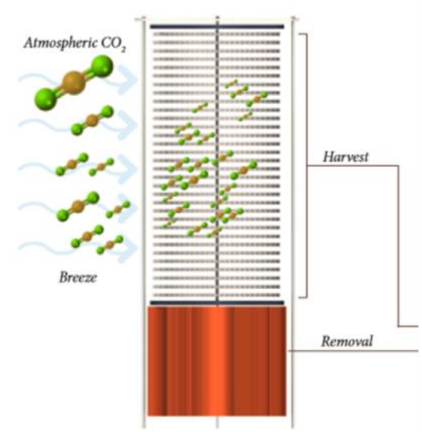


**Figure 1. A rendition of the ASU Tiburio design. Credit ASU/CNCE SRP Project 2017**

[8] IPCC, 2022: *Climate Change 2022: Impacts, Adaptation, and Vulnerability.* Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge University Press.

[9] Press Release Secretary General. Secretary-General Calls Latest IPCC Climate Report ‘Code Red for Humanity’, Stressing ‘Irrefutable’ Evidence of Human Influence. SG/SM/20847. 9 AUGUST 2021. Available at: https://press.un.org/en/2021/sgsm20847.doc.htm#:~:text=Today's%20IPCC%20Working%20Group%201,of%20people%20at%20immediate%20risk.

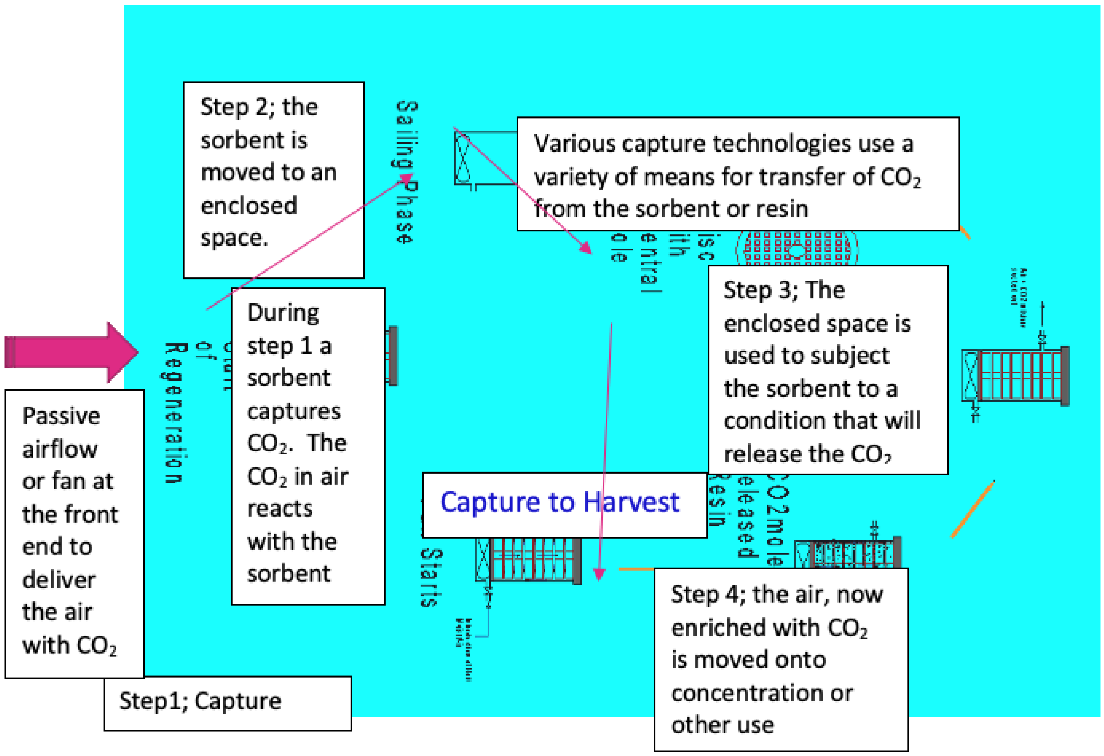


**Figure 2. The cycling phases of the Direct Air Capture process. (ASU/CNCE SRP DAC Project)**

DAC is in many ways like point source capture (PSC) in that it uses the same feed and capture mechanism along with the associated concentration. PSC is dependent on the air flow of concentrations of $CO_2$ greater than in nature, like those that can be found in the waste streams of fossil fuel power plants. However, DAC uses less equipment, has a simpler process, and the product $CO_2$ does not need to be transported for sequestration.

DAC comes in many forms and applications, and it is a technology that is adaptable to multiple environments and locations. DAC should grow rapidly to fill the need to capture $CO_2$ as it comes in a variety of sizes which are open to mass production and scaled growth.

# DAC technologies

The DAC industry is growing rapidly and globally. However, it is still at demonstration scale. Entrepreneurs are now responding at an increasing pace to the opportunity and need that DAC has created a solution to. Investment funding is beginning to flow, and emitters of $CO_2$ are aware of a future that will require producers of $CO_2$ to deal with the $CO_2$.

There are currently roughly two dozen DAC plants operating worldwide, capturing more than 0.01 Mt $CO_2$/year (Mt = million metric tones), and a 1Mt $CO_2$/year capture plant is in advanced development in the U.S. The latest plant to come online, in September 2021, is capturing 4 kt $CO_2$/year (kt = thousand metric tonnes) for storage in basalt formations in Iceland. In the International Energy Agency's Net Zero Emissions by 2050 Scenario, DAC is scaled up to capture more than 85 Mt $CO_2$/year by 2030 and ~980 Mt $CO_2$/year by 2050. This level of deployment will require several more large-scale demonstrations to refine the technology and reduce capture costs.[10]

Today, two technology approaches are being used to capture $CO_2$ from the air - liquid and solid sorbent based (Table 1). Liquid sorbent systems pass air through or over chemical solutions, which remove the $CO_2$. After releasing the $CO_2$, the system recycles the chemicals back into the process by applying high-temperature heat or other options. The rest of the air returns to the environment. Solid DAC technology makes use of solid sorbent filters that chemically bind with $CO_2$. The sorbent is then heated or otherwise placed in a modified condition that promotes release of the concentrated $CO_2$, which is then concentrated for storage or product use (Figure 3).

| **Table 1. Technological approaches for DAC capture** |
|---|
| Liquid and solid sorbents |
| Inorganic and organic |
| Passive and active air flow |
| Thermal swings |
| Moisture driven swings |
| Vacuum swings |
| Combination of different swings |
| Shaped after large industrial processes |
| Emulating the mass production paradigm |

[10] IEA (2022). Net Zero by 2050. A Roadmap for the Global Energy Sector. Report, Paris, May 2021. Available at: https://www.iea.org/reports/net-zero-by-2050

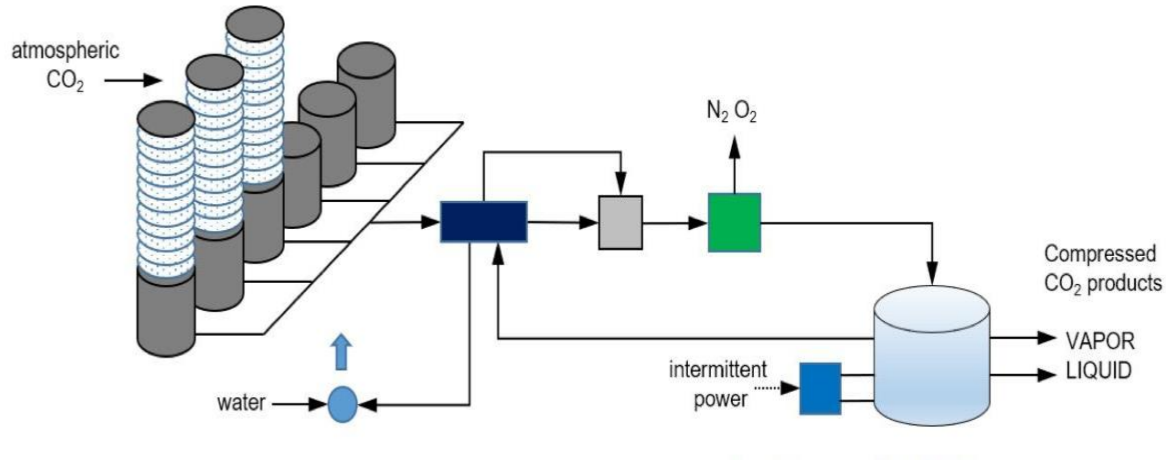


**Figure 3. Illustrative example of flow from capture through compression. ASU/CNCE graphic 2018**

Capture is the first step in the process (Figure 3). Following capture, the $CO_2$ will most likely be concentrated (this step may not be necessary for feeding $CO_2$ into agricultural greenhouses). Concentration provides a $CO_2$ stream that can be fed into sequestration for permanent disposal or into product application. For some applications there may also be purification steps to remove "contaminants" within the $CO_2$ stream. Figure 4 provides an illustrative process flow through concentration and purification.

While there are multiple DAC technologies currently in development none of the offerings can boast a capture cost that is likely to meet the projected pricing for capture of $CO_2$ in the hundred-dollar range, the current target. Some of the top players in the industry based on scale, investor backup, and publicly available articles, are listed below in Figure 4. This is not a comprehensive list as some capture technologies have not publicly revealed their approach and others are being introduced nearly every month. A few have completed pilot plants, while others are still at a "lab" stage.

Pilot (<5,000 tons/yr.)

Lab (1 ton/yr.)

**Figure 4. Some of the companies with announced capture technology (ASU graphic).**

## Companies with announced capture technology

**Climeworks**

The technology used by Climeworks is probably the most advanced, particularly regarding demonstrating sequestration. The Climeworks technology is based on a cyclic adsorption and desorption process with a filter material. Climeworks is based in Switzerland and has a demonstration plant in Iceland.

**Carbon Engineering**

Carbon Engineering uses existing technology first used for paper mill processing. Carbon Engineering "proved" that $CO_2$ capture could work. The capture process is done by using an air contactor and a regeneration cycle for continuous capture of atmospheric $CO_2$. Air is drawn through plastic channels coated with potassium hydroxide to separate the $CO_2$ from their gases. The process requires turbines to increase the concentration and the entire process uses a significant amount of energy. This approach uses large fans to blow air over the sorbent material to trap more of the gas. It then uses heat to drive the subsequent reactions that release the $CO_2$. Carbon Engineering is based in Canada.

**Global Thermostat**

Global Thermostat has developed a proprietary technology that uses leftover process heat to collect carbon from power plants. The process uses large fans which draw air through slabs made of ceramic cubes. The cubes hold proprietary chemicals that absorb $CO_2$ at room temperature. The slabs rotate and the cubes are heated, releasing a stream of $CO_2$ into a steel pipe. Devices called monoliths maximize surface area. That area is covered with amines, the nitrogen-based chemical that absorbs $CO_2$ from the air. The $CO_2$ generated is directly proportional to the energy generated from the power plant.

**Carbon Collect**A relatively new entrant into commercializing DAC technology, Carbon Collect takes a different approach than the aforementioned companies with their passive MechanicalTree concept

(Figure 1). The MechanicalTrees concept requires no energy for $CO_2$ capture. Instead, the wind delivers ambient air resulting in low capture costs.

**$CO_2$ Solutions**

$CO_2$ Solutions has developed proprietary enzyme-based technologies for CO2 capture from various industrial flue gasses for reuse or sequestration. $CO_2$ Solutions claims to use a genetically engineered E. coli bacteria to produce enzymes that convert the $CO_2$ into a bicarbonate. $CO_2$ Solutions has developed technology in Canada, the U.S., and E.U.

**Prometheus**

Prometheus technology uses water and renewable energy to capture $CO_2$ from air to produce gasoline and jet fuel. The technology uses a modular approach for the production of micro-cell gasoline production based on excess renewable energy. The collected $CO_2$ is placed in an electrochemical stack. Using electricity, the carbon is combined with hydrogen molecules from water to create alcohols, while releasing oxygen. The alcohols are harvested using a type of nanotube membrane. In a catalytic step, the alcohols are reformed into fuel, and water is recovered. This final step can be customized to produce gasoline, diesel, or jet fuel.

**Aircela**

Aircela Inc. is developing small-scale, modular DAC-to-fuels systems. The modular approach means any user of hydrocarbons is a potential customer. The technology can be scaled at the household level (making ~1 gallon per day, capturing ~3 tons per year) or to the level of utility. The technology is intended to operate intermittently with off-grid renewables to allow remote communities with little grid access to deploy the systems.

# The need for DAC

Climate related impacts cost the world $650 billion from 2016-2018[11]. Climate change could cut world economy by $23 trillion in 2050[12]. The IPCC makes it clear that mechanical capture and sequestration are essential if climate change is to be contained to below 1.5 °C[13]. Capture will also likely be necessary

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[11] Morgan Stanley Research (2020). Five Sectors That Cannot Escape Climate Change. https://www.morganstanley.com/im/publication/insights/articles/articles_fivesectorsthatcannotescapeclimatechange_us.pdf

[12] SwissRe (2021). The economics of climate change. Available at: https://www.swissre.com/institute/research/topics-and-risk-dialogues/climate-and-natural-catastrophe-risk/expertise-publication-economics-of-climate-change.html

[13] IPCC, 2018. Summary for Policymakers, in: Global Warming of 1.5°C. https://doi.org/10.1016/j.oneear.2019.10.025

to stay below 2 °C[1], given the pace of current emissions and the gap between pledged and required action[14]. Current policies will drive a temperature increase of 2-3.6 °C by 2100, while even the optimistic scenarios of new pledges bring the increase to 1.5-2.4 °C[14]. The current focus on small-scale, voluntary payments for carbon removal and the introduction of regulation of some industries such as passenger cars will not solve the magnitude of the problem. There needs to be a commitment to require all emitters to be responsible for their pollution.

We start from the observation that the world will need to return the $CO_2$ concentration in the atmosphere (or equivalently the amount of carbon in the mobile carbon pool) to a level that is lower than today's level (approximately 420 ppm[15]). We might assume we need to return to 300 ppm which although higher than pre-1800 level is probably within the "safe" range. To get to 300 ppm, we need to remove 120 ppm that is already in the atmosphere plus emissions during the overshoot. The reduction of the $CO_2$ concentration by 1 ppm will require the removal of approximately 15 Gt $CO_2$, which includes carbon that will return to the atmosphere from the ocean and the biosphere. To accomplish this, one must create an accounting system for the remaining fossil fuel use and achieve negative emissions. An important policy question is whether we recognize efforts of reducing or avoiding emissions as offsets or whether we limit offsets to carbon removal. Whichever way this will be resolved needs to assure that there are capture methods in use and that sequestration is handled in a manner that is permanent and meets a certification standard.

We might start from the idea that all emissions need to be driven to zero, and while we may not be able to achieve this right now, we do want to advance to that conclusion. One view might be that if an entity produces $CO_2$, it will also need to guarantee an equal amount of carbon removal[6].

The second issue is the quality of the storage. This area needs significant clarification as we have already let too much ambiguity in, and as a result, the problem has been made unnecessarily hard. For storage to be certified, the storage reservoir must be well defined, the addition to the storage site can be accurately measured, and the future monitoring of storage can assure that the carbon remains stored. Lastly, it needs to be combined with the acceptance of liability of the storage operator that if the carbon is lost, this is considered an emission that needs to be matched by a new certificate of storage. If these well-defined constraints are in place, storage is not that difficult. If one operates a storage site that tends to lose carbon after a decade, we might include the cost of a future certificate into the cost of doing business and decide whether this process is economical after adding the

[14] Climate Action Tracker (2021). Glasgow's 2030 credibility gap: net zero's lip service to climate action. November 2021. Available at: https://climateactiontracker.org/documents/997/CAT_2021-11-09_Briefing_Global-Update_Glasgow2030CredibilityGap.pdf

[15] The Keeling Lab (2022). The Keeling Curve Hits 420 PPM. Available at: https://keelingcurve.ucsd.edu/2022/05/31/2114/

additional costs. The storage operator might purchase an option on future storage or insurance in case there is a liability associated with "escape." The price for not doing that is that people can sell cheap certificates with unknown liabilities attached. We must ensure that storage is effective, long-term, and verified by an independent entity. As an example, if the biomass stored is going to rot away in a decade or two, there must be a functional and measurable means to understand how it is going to be retrieved or covered by other storage.

The problem with some storage systems (for example in agricultural soils) is not that they cannot be made to work, but that by not delivering permanent storage and by avoiding measured accountability they will flood the market with cheap storage, which in the end turns out not to be storage (because of its short storage time) after all, but its low price point prevents real (long-term) storage from being implemented. With forced accountability, these kinds of storage options may still work, but they will need to be priced right. We must implement and independently audit verifiable certification program that has international recognition and support.

To start we might demand that all produced $CO_2$ going forward must be put away by the emitter with a grace period of increasing capture and storage while the cost of capture/storage comes down. The grace period would not eliminate the obligation for capture and storage but would allow for some portion of one's emission to be resolved later (say ten years in the future). If we ramp up 5% per year, in 20 years we may reach a point of all emissions being neutralized. If prices threaten to come down too fast (a nice problem to have) governments could intervene by buying negative emissions and thus tighten up the market. By requiring a percentage of $CO_2$ emissions to be removed (with an increase over time of that percentage) a market is created that will increase the options for carbon removal and drive down the capture price. Carbon removal science needs to be put on a firm footing. This is about more than engineering. DAC makes it possible to treat $CO_2$ as a waste stream to be cleaned up. The deployment of carbon capture will put a real price on carbon emissions, the moment waste management is mandated.

Roughly two-thirds of all energy generation emissions currently cannot be captured at point sources due to operational restrictions and the reduction in fossil power plant capacity (decreased capacity makes the capital cost of capture unacceptable). As fossil energy production continues to decline, economic applications of point source will continue to reduce. Another consideration is that much of the $CO_2$ comes from distributed sources, smokestack removal does not apply to the $CO_2$ distributed in the air due to indirect sources like transportation and past emissions.

Biological capture and storage will play an important role and be the early solution. Unfortunately, biological capture is limited by its transience and competition with food production. In spite of these limitations biological capture may rise as high as capturing a third of the excess carbon in the atmosphere with a massive reforestation program[16]. The challenge for biological capture and sequestration is permanence, proof of capture, and land use. Biological solutions are going to be most challenged by climate change. As the climate heats and weather patterns modify, we may find that biological capture and storage will not even maintain its traditional role in the mix.

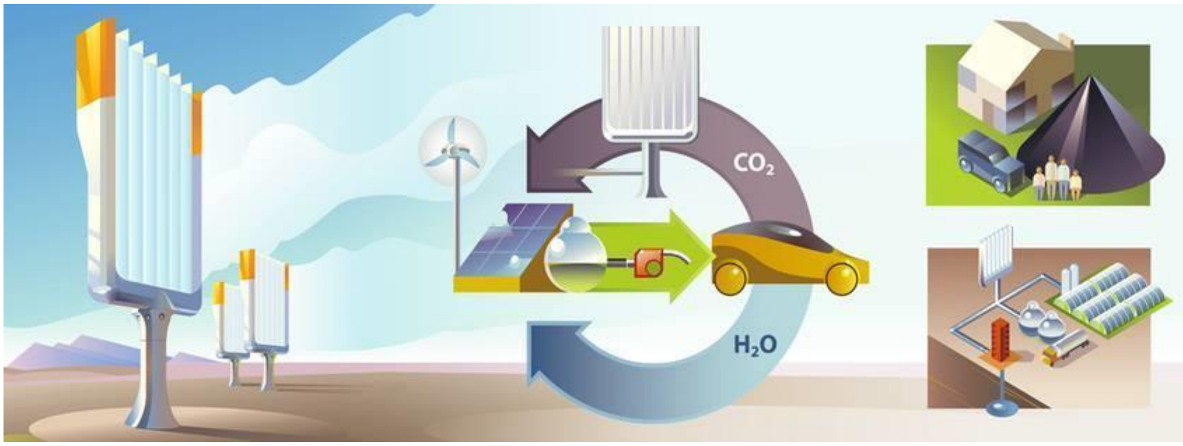


**Figure 5. A model concept of the uses of $CO_2$ capture as fuels or sequestration. Captured $CO_2$ combined with renewable energy can be transformed into fuels and can be sequestered in various carbon reservoirs. Credit: Klaus Lackner, (April 2019 ASU)** [17]

Therefore, we returned to the question of how to remove $CO_2$ from the air by technical means. Climate stabilization has been challenged from a technical and a policy perspective. Yet, mechanical capture is feasible and necessary. Here is a simple technical model to make the point about feasibility: Windmills harvest kinetic energy while DAC scrubbers (artificial trees) remove $CO_2$. If one values kinetic energy at five cents per kilowatt-hour and considers a tipping fee of \$30 for a ton of $CO_2$, then the $CO_2$ content of the atmosphere has a seventy times higher value than wind energy. Yet, windmills are clearly feasible and economical.

DAC, as envisioned, offers important opportunities (Figure 5). First, it can over decades return the world to a pre-industrial $CO_2$ concentration if the captured carbon is sequestered and maintained in a sequestered state. Second, it can enable the transition to renewable energy as it solves the intermittency problem of renewable energy by providing recycled liquid and gas fuel for those times when renewables are not producing. There will continue to be a need for liquid and gas fuels to support the economy and to provide backup generation for renewables. Far better to provide that fuel

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[16] Conservation International (2022). Exponential roadmap for natural climate solutions. Available at: https://www.conservation.org/roadmap-pdf

[17] A Capture Graphic. Klaus Lackner. ASU (multiple dates)

from carbon taken from the atmosphere than to add more to the atmosphere carbon taken from fossil pools. Also, the use of carbon for various products will not disappear, and this carbon should be provided from capture.

Like for most new technologies, the cost is a concern. Small field demonstration and lab models are not overly helpful in projecting large scale production cost. Today cost appears to be high, however modeling the possibilities for cost reduction in production and operation has led to encouraging conclusions. Although there are many steps between today and large-scale application there is hope for <$100/ton for capture, and even down to the $50 range.

For comparison, mass production has managed to drive down the cost of solar energy to the point that it competes with primary energy not just grid electricity[18]. This required a hundredfold cost reduction. DAC will have a range of economic opportunities. Sequestration of $CO_2$ for the most part will be a cost of removing a waste and the producer will probably need to bear that cost. Sequestration can have some positive economic gain such as with EOR, but generally will be a cost. Sequestration is necessary, even an existential need, so by indicating that it is cost is not an argument for not doing it. Mass production has been successfully applied in the past allowing us today to postulate on how mass production might bring down the cost of direct air capture.

DAC will also have opportunities for the synthesis of products with economic value and thus a potential for profitability or at least an offset of costs of capture. For example, captured $CO_2$ might be a feedstock to be used to produce liquid fuels. By combining capture with solar energy, or other renewable energy sources, sunny parts of the world can deliver all the fuel that is necessary to operate the rest of the world. Solar energy converted into liquid fuels might feed into the transport sector and provide energy in rainy and cold parts of the country in places where renewables are not available. Moving solar energy from one season to another and across continents may require synthetic fuels produced with air captured $CO_2$. This synthetic fuel production via DAC would presuppose that there would be an ongoing re-capture and recycling.

The same rational and forward thinking might apply to carbon related products that we wish to retain. Carbon capture might feed into carbon fiber, plastics, cosmetics, tires, and detergents. Carbon has advantages and future uses; we need to understand how they might continue to be used without carbon extraction from the ground. While meeting the challenges we are going to be faced with very

[18] IPCC, 2022: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [P.R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, J. Malley, (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA. doi: 10.1017/9781009157926

difficult choices that ought to balance prudent decisions based on what is best for the human and the environment's well-being.

DAC has a significant appeal. When combined with sequestration, it is a long-term and permanent carbon removal technology that can address both emissions from sources that are not easily or cheaply decarbonized and collect the $CO_2$ that is already in the atmosphere. While the land area required for the technology to capture the carbon is non-trivial, it is much less than that required for forest management. Though DAC has some infrastructure limitations such as connection to energy sources and water source requirements for some sites, it can be undertaken even in areas that are unsuitable for farming or forests.

DAC technology can be modular, and to date most DAC facilities have been relatively small, decreasing the barriers to entry, increasing the opportunities for learning-by-doing, and reducing the political salience of individual projects. The granularity of DAC technology may also allow it to be ramped-up relatively quickly. DAC application is flexible geographically and it is less dependent on transportation networks as DAC facilities can be co-located with geological storage, requiring only small-scale transportation systems, and avoiding long $CO_2$ pipelines. A key problem for all carbon capture technology is to create interest groups that will adopt. The flexibility of DAC to capture adjacent to storage, to use renewables to build recycled fuels, and to rapidly scale up may provide a bridge to support.

The low-carbon technology transition is a problem of policy sequencing: initial policies need to bring down technology cost and broaden political support for the adoption of more ambitious policies for global technology diffusion while committed to the elimination of fossil extraction. Ongoing transitions to low-carbon technologies offer important lessons on what policy mix is most likely to drive investment and create a niche market that both can grow a new technology and support emerging interest groups that can advance additional policy. Financial incentives, such as subsidies or tax rebates have been pivotal to the deployment of renewable energy technologies and electric vehicles. Given the cost of DAC, substantial government incentives will be necessary to make DAC viable. It is important to invest in the advancement of the technology and then create a market that will support its growth.

The history of low-carbon technology transitions suggests that creating government incentives for DAC will be the lower political hurdle, while mandating DAC presents a significantly greater challenge. We need to accept that both are required, and soon. Incentives are a short-term incentive for growth, large scale application of capture and storage is going to occur only when it is mandated.

One of the product developments that we recommend for DAC is to replace fossil fuel extraction with new recycled fuel form capture. Possibly a more palatable long-term solution will be to have DAC provide both capture and carbon for products (fuel, plastics, etc.) rather than fossil carbon extraction. We need to have the option of committing to an end to extraction, even while there remains a need for carbon. Assuming wide use of DAC, and that the captured carbon is split between permanent storage (sequestration) and carbon for use as fuel, plastics, etc. the following product developments could be anticipated:

- Liquid fuel production – airplanes, ships, other transport, and specialty fuels such as race cars.
- Gas fuel production for power plants, blast furnaces, and heating
- Production of base material for plastics, poly, and other carbon-based structural materials
- DAC device manufacturing, installation, and operation of DAC farms and concentrators.
- $CO_2$ sequestration using geologic formations and mineralization

The attraction of this scenario is that it provides a path to end fossil extraction. The discussion of ending fossil extraction tends to be made in absolutes as if we can end air flight and blast furnaces and continue to have a vibrant economy. Even if the U.S. or other nations were to take such a step, it would have the impact of moving those functions to other countries. The resolution of this scenario needs a bit of balance. We need to commit to a program that ends carbon extraction and then build an off-ramp that allows the economy to continue to provide the revenue to realize the transition. For this adaptable kind of program, DAC appears to be more appropriate for capture, sequestration, and carbon product development, based on current experience[19].

In summary, what is needed to move ahead is demand and an existing market with longer-term viability. Most likely, we will need policies to require $CO_2$ removal from those who have created and continue to create emissions. Mandated removal may seem harsh until compared to the alternative. The combination of universal mandates with validation of storage is the answer we are waiting for.

# A story about DAC development and deployment

Thinking about a roadmap for DAC in the Intermountain West involves so many different elements and inputs that it is by nature too complicated for rational analytic prediction. So, at the start let us tell a story that can use an imaginary company that is attempting to commercialize a DAC device.

Our device for our imaginary company provides capture using large scale commercial HVAC as the source of airflow and structure. This device is parasitic to the HVAC system and scavenges power from the HVAC to avoid the upfront energy costs for airflow. Energy use drives cost, so we need to minimize

[19] Post Combustion Capture or Direct Air Capture in Decarbonizing US Power? Environmental Science & Technology. D Azarabadi & K Lackner. April 2020

that and for our new DAC device we piggyback onto HVAC. Let's call our company "Capture America" or *CA* and our device the "Catcher's Mitt" or *CM*.

Our imaginary company and device are at the demonstration phase. How do we move from demonstration to sufficient capture of the $CO_2$ that is not either avoided or captured by all the other potential solutions? We ought to assume that DAC is the solution for all the $CO_2$ that isn't picked up by $CO_2$ reduction or the other capture methods such as point source capture and capture from biomass. That means DAC has a big job and CA needs to get moving.

CA is at demonstration, so they are learning how the CM needs to be re-engineered for the next round of fabrication at a small scale but large enough to add demonstration concentration and sequestration. Movement from demonstration to commercial scale is often the graveyard of new technologies. It will be important for physics to work in an enlarged environment, for the cost of equipment to fall within our target, and for operations to be as smooth and productive as we assumed.

Following a small-scale demonstration with a commercial sized unit, we need to move to mid stage, say installing the CM at a large commercial building complex. Adding to the capture the piping of $CO_2$ between the buildings and to a $CO_2$ pipeline that takes the $CO_2$ to a sequestration site. Moving to a building complex will be costly but within the range of the funds that investors can handle.

At this point in the story CA is stuck. We are unlikely to be capable of raising funds to continue building out larger applications, because there isn't a sufficient market with a determined future. The market for capture, hydrogen, and many other carbon neutral solutions currently doesn't include enough demand to move them ahead. There are volunteer applications of carbon credits for companies such as Microsoft and Stripe, but these are not sufficient to create a market for CA or any other capture venture.

Market examples do exist. Countries have made it clear that EVs will replace ICE passenger vehicles in 2030 creating a firm market for EVs. Also, countries are forcing the phase out of fossil generation creating a market for renewables and back-up power such as batteries and companies like Mainspring Energy. Therefore, part of the answer is being developed, but only part.

So, the main conundrum for the *Mitt* is where is the market? In the end the U.S. and other governments are going to need to say if one emits, one must capture and sequester then there will be a market. Thus, unless a market with a future isn't created quickly, we are not going to make the rapid progress that is needed for carbon neutrality in the next 30 years.

# Roadmap

### Assumptions

DAC is not an answer to climate change. Rather, it is one of many tools. Application of DAC must presuppose that many other mitigation tools are being vigorously pursued. We must assume that the extraction of fossil fuels is being tightly constrained with a goal of zero extraction by 2050. Further we must assume fossil fuel for cars and light trucks is being phased out and heavy land transportation is transitioning to hydrogen, biomass, or some other fuel. We would be looking at a world that has converted to electric application using renewable or other non-fossil sources for generation. DAC would be one of a suite of capture technologies employed to smooth the transition by gathering the excess $CO_2$ already in the atmosphere and removing the emissions created by those sectors of the economy which are extremely difficult to decarbonize or are decarbonizing but not completely converted.

### I-WEST roadmap considerations

The Intermountain West is "home" to at least three demonstrated DAC technologies. As is true elsewhere in the U.S., demonstration efforts are underway but no large-scale deployment. The region has the advantage of favorable environmental conditions for DAC, open spaces for capture, and sufficient geological formations for sequestration.

### A deployment scenario over a 5-, 10-, and 15-year period

**5 years:** After some form of requirement for controlling $CO_2$ is in place, DAC could reach a level of capture of several million tons per year in the region. The scale up will take time as manufacturing gears up. New technologies need to create a supply chain, develop production facilities, create standards and processes, and build a workforce for everything from design to operations.

**10 years:** In a ten-year period, DAC in the Intermountain West, due the many favorable conditions in the region for DAC, might expand to a million tons per day of capture and sequestration. Once requirements for carbon reduction are in place both manufacturing and capture would likely expand rapidly. The environment and the workforce available in the region are favorable.

**15 years:** In a fifteen-year timeframe, DAC should be an established form of carbon reduction in the region. The geological- and business-friendly environment will be critical in developing a large DAC footprint. During this period the region should be adding a variety of production facilities to take advantage of carbon recycling through $CO_2$.

## Consideration

**Current State:** DAC is at the demonstration stage for a few devices and at a conceptual design stage for many others. While it is tempting to believe some of the demonstration devices are going to be shortly manufactured at scale, it is too early to determine winners and losers. Most devices are focused on similar principles and use solid sorbents (although liquid sorbent technologies are moving ahead). It is hard to believe the field will end up being this limited, so one must assume there will be new ideas[20].

**Impetus:** Every new technology that succeeds has a period of discovery followed by a period of "push." Sometimes the push is market demand, sometimes it is better cost, and sometimes it is the emergence of a need. DAC will fall into the need category. Currently the need is known but not being pushed very hard. The next step for DAC appears to be the DOE DAC hubs. This will not fulfill the need, which will come eventually, but will push several of the device technologies forward. Hub financing will deliver some devices from modest demo to funded limited production. By pulling a few devices forward some of the others will benefit from the directional thrust.

**Demo to Field:** The hub financing will allow 3-4 DAC technologies to produce sufficient machines to capture 1 ton of $CO_2$ in a 12-month period. The hubs are four years long, and we can assume that around the year 2027, we have a few "proven" DAC technologies that are capable of proceeding to larger production. If removal is mandated by the year 2027 the devices will move into production and broad implementation.

**Demand:** The next step is demand. With the assumption of proven technologies around 2027 will the demand be there to bring about mass production? Will demand be there in the mid 2020s? This concept of capture will proceed or die depending on demand. We assume that a requirement for removal will come and certainly the DOE is making a large bet that this will be the case. It seems likely unless there is another option to reduce the existing and future $CO_2$ in our atmosphere[21]. Eventually the absence of capture to balance the carbon emissions will be too obvious to continue to overlook.

**Infrastructure:** If it proceeds, DAC will be a large industry and will require a large infrastructure to support it that includes:

- Land – Land needs to be acquired.
- Supply chain – Difficult challenge for new industries.
- Fabrication – Could be focused in the Intermountain West and tied to capture farms in the area.
- Assembly – Site assembly creates new set of employment needing manpower.

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[20] Lackner, K. S., & Azarabadi, H. (2021). Buying down the cost of direct air capture. Industrial & Engineering Chemistry Research, 60(22), 8196-8208.

[21] Carbon Futures and Certification of Sequestration. ASU/CNCE paper April 2022 (multiple authors)

- Ops Staff – Operating the DAC Farms is an opportunity for many well-paid jobs.
- Maintenance support – Many new support companies will be built to maintain the new farms.
- Concentration and Purification Process (CPU) – CPU of $CO_2$ is a new field that has proven. applications that work. The next step is to improve on quality, efficiency, and cost.
- Sequestration – Mineralization, geological and EOR permanent storage are available in the region. The Intermountain West, along with the rest of the country, needs to do more work on how best to approach sequestration. Early geologic survey work in the region indicates a number of viable locations for geologic and EOR storage. Mineralization should work as well in the region as elsewhere.
- Products – The use of carbon will not suddenly cease and one path to ending extraction of fossil carbon is to use carbon recycled through capture. The region would benefit from capture.
- Codes and Standards – The rules for capture, sequestration, etc. need to be developed, implemented, and monitored.
- Certification - Sequestration should be based on rules drafted and administered by an independent body. Fraudulent carbon credits have grown into an industry, creating a disproportionate amount of storage that is not real.

**Mass production**: The past indicates production can bring down cost. Factory production provides a path to cost reduction through higher production, and also increases quality and worker safety. Large scale, or mass production is key to cost reduction. Just as with photovoltaics the capture industry needs to design devices that can be factory produced. This requires a smaller scale and a sameness of production.

**Cost curve:** Time and large-scale fabrication along with replication of the same design will bring costs down. This assumes the devices are designed for ease of production. And are readily shipped and can be field assembled with a rational amount of field labor and equipment. Bringing down cost is about volume and success in volume is about efficient and quality devices.

**Product uses:** $CO_2$ is going to take a long time to get under control. While the first consideration should be to permanently store the captured $CO_2$ there may be a need to use the captured $CO_2$ to fuel transportation and gas furnaces, support the growth of crops, and to provide chemical feedstocks for plastics and other applications. Figure 5 provides a graphic recycle concept for desalination, one of the potential uses for recycling of airborne carbon.

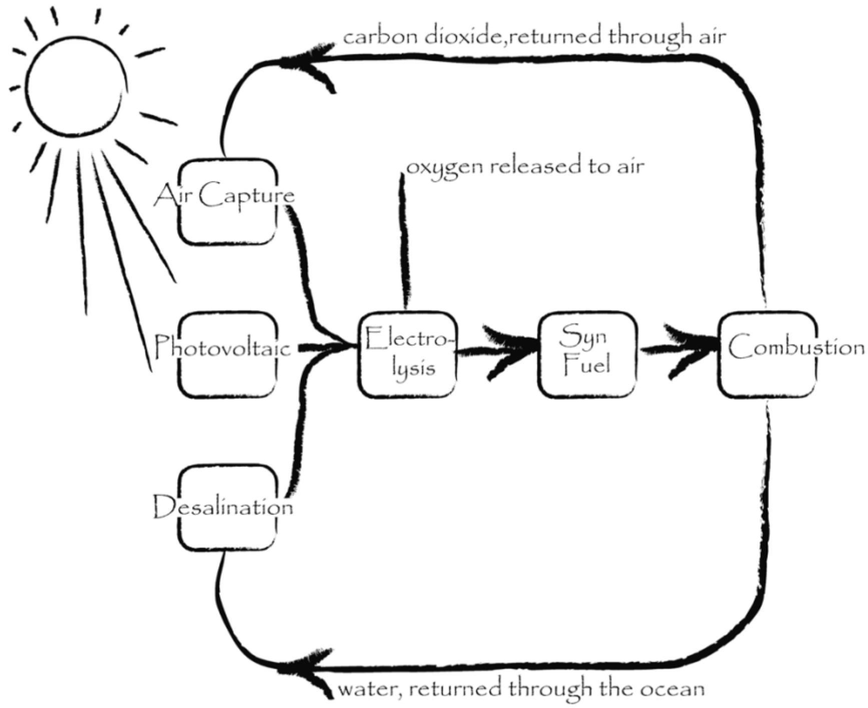


**Figure 5. An illustrative look at capture. K. Lackner Feb 2020 to ASU Engineering Seminar.**

## I-WEST Roadmap

A roadmap is a journey from concept through full production capture. DAC is currently at the concept to early demonstration stage. The most advanced concept is Climeworks of Switzerland who have full demonstration from capture through sequestration in Iceland. After demonstration, which should occur in 2022 for four to six concepts detailed previously, the devices need to move to small scale production and field demonstration. Implementation of small-scale production should begin to happen in 2023 and 2025. If the DOE Hubs launch the size of the production of devices will ramp up.

The DOE commitment of $3-4 billion for four devices and a demonstration capture of 1Mt/year in 2026 or 2027 would have an igniting effect on at least the selected technologies and likely influence the speed of development of some others. The opportunity provided by open investment and a hard goal is an encouraging step and should provide results.

Let's say as many as three make the end date and produce DAC technology capable of 1 million tons of capture. They will have done several important things: 1) learn what is wrong with their current concept and start iterating the design, 2) attract customers and investors, 3) grasp the enormity of the manufacturing process ahead of them, 4) need to consider a workable business model such as leasing or outright sales and 5) issues that are now hidden regarding certification and verification will become obvious.

Next, there will be a new design basis based on learnings, updated specifications, negotiations with fabrications facilities and supply chain, and a new timeline for design completion and new fabrication of units at an increased production rate, which should indicate how cost might be brought closer to the \$100/ton $CO_2$ target.

Concentration, sequestration, and product ought to be getting more attention and initial resolution worked out. Sorbent advances and form factor for sorbent may require some alliterations in design, along with narrowing down of sites that will be viable. Engineering teams for design, crews to assemble, operators and maintenance will all become critical and likely slow progress as these professionals need to be trained and gain experience to efficiently operate the equipment.

### Caveats

We should be clear in our understanding that the hubs will develop the technology, but they will not create mass capture. For large-scale capture there needs to be market demand that is recognized as being sustainable over decades. This will occur when most nation-states demand a path to carbon neutrality in a set timeframe. This path would need to include some form of forced reduction or capture by emitters.

Customer demand and the ability to produce large numbers of units in a mass production setting will become critical for cost and availability. There must be some creation of a future market with a scale to drive growth of capture and the growth of technologies to reduce the reliance on carbon. This wait for a long-term market is the critical unaccomplished feature of climate mitigation.

### Requirements to get "passive" DAC into the marketplace

- For a committed market, first there needs to be demand.
- Technology must be licensed to encourage growth.
- Prototypes must be produced quickly, that fit a mass production scenario.
- Energy costs for capture need to be low, and energy usage should be from renewables.
- Communication and marketing promotion and branding.

### Keys to success

- Public understanding and acceptance must grow.
- A market will be created by regulation or tax.
- The market will be paid for by the polluting entities.
- Market timing will be staged to allow growth of capture production.

– Renewables will grow to meet the energy demand of capture and sequestration.

### Summary execution plan: a sample idea for the Intermountain West

The DAC devices and the accompanying Concentration and Purification Process (CPU) needs to complete development, go through prototype testing and begin production by 2028 based on the DOE Hub schedule. It is our assumption that the market will enter a stage of increased vigor around 2027/2028 and DAC needs to be ready to participate in that market. To achieve readiness all aspects of development need to be pushed forward quickly. Early on during DAC device development a few critical decisions need to be made:

- Confirm design and size
- Select sorbent and absorbent alternatives
- Develop a material for the sorbent to reside within that is strong and flexible
- Design and fabricate "low cost" machines out of "low cost" materials
- Prepare for mass production and large farm operation
- Require removal of new $CO_2$ creation and the removal of some existing $CO_2$
- Determine tactical approach to markets based on the type of customer and location
- Develop price mechanisms and marketing strategies
- Build the trained staff for fabrication, assembly, operations, maintenance, and support
- Determine who handles the scope of services – fabrication, assembly, operations, maintenance?
- Will regional companies develop to fill these roles?
- Develop an on-going R&D to revise and improve

The execution will be determined by early planning and a waterfall schedule focused on the next five years. A ten-year plan and schedule will focus on growth to profitability. DAC companies will need to recognize and acknowledge that planning will be subject to the whims of the marketplace. This is an entirely new market, served by an entirely new industry that may develop vastly differently than we currently assume, and thus there will be adjustment to the realities on the ground.

For the Intermountain West, now will be the time to lay the groundwork for future success from production through sequestration. It is now clear that DAC will play a large role in reaching carbon neutrality, and the companies that are going to play in the new industry will form in the next couple of years. There are many opportunities for enterprises to have a role in this new industry. It is time for those interested in this future within the region to create the corporate foundations.

For the capture devices, sequestration, carbon products, and transition infrastructure there are many steps still to be taken. All of these areas and more are potential enterprises for regional entrepreneurs. This is going to be an industry that will rival in size to the current commercial aerospace industry. There will be a host of opportunities for those who are bold enough to enter at the start.

# DAC and the Intermountain West

### What is the starting point in terms of DAC for the region?

#### Technology overview

Three DAC technologies are tied to the region, and one is currently being demonstrated. As DAC is relatively adaptable to different climates and environments most of the technologies are likely to fit into application in this region. Having technology tested in the region is beneficial.

#### Aspects of siting

**Sequestration:** DAC sites used primarily for sequestration will most likely be located near sequestration opportunities. Potential geologic and well sequestration sites are abundant in the region.

**Energy:** DAC sites may be located where renewable power is plentiful and less costly to benefit from non-carbon power. The Intermountain West has large areas that are likely to be used for wind and solar generation.

**Land:** DAC requires land. Ideally the DAC the device ASU is testing would be able to capture 80 kg $CO^2$ per day and >1.1 million tons per year per $km^2$. While the ideal may not be reached the amount of land is not prohibitive and the region has open land that would be better suited for capture farms than areas of the country that are more congested.

#### Policy and funding

**Policy:** Congress has moved forward with funding for four Hubs to support DAC devices. While this is an indication of interest, or at least increased interest, there is not a firm U.S. policy or policy by any of the Intermountain West states supporting DAC.

**Funding:** As indicated above the legislation funding the Hubs is substantial, and there are other funding opportunities for DAC coming out of the DOE.

### What is the potential for DAC in the Intermountain West region?

#### Conceptually how might DAC best be funded and supported?

- Capture in general and DAC, in particular, needs a future. If there is a sizable market identified that has volume and timing capture investment will occur. There does need to be government funding to support early development, but the private sector will need to step up with investment and build out if there is to be a future. For example, if oil and gas companies or some other entities were regulated to pay for the capture of the $CO_2$ that result from their activities, and they were allowed to "owe" the capture and removal to occur in the future as long as they completed removal within a ten-year period, there would be created a known future demand that would drive commercial investment in capture.

- The level of federal support is not yet resolved; however, the current round of funding is a good beginning. The Hubs and other funding provide a start.

### What is the best-case scenario when everything aligns, and all resources are available?

- **Technology:** The DAC technologies that are being demonstrated are indicative of a successful future for DAC. The current ideas are diverse and show signs of potential. Best case these and off-shoots from these, plus other new ideas, will reduce their energy and capital costs allowing for the beginning of a new industry.
- **Build-out:** While funding is the current impediment to growth, once devices begin down a commercial development road there will be supply chain, manufacturing, assembly, and operations challenges. All of the challenges are manageable, the reason for concern would be the ability to ramp up in a timely fashion.
- **Cost of capture:** Once a ramp-up in manufacturing begins, the benefits of mass production kick in and should begin driving down the cost curve. Ideally, the cost ought to drop below $100/t, potentially close to $50/t.
- **Price:** Cost may not be the main driver of price. If we continue to delay application of capture and sequestration there will come a time when the public demands that it be done, if we delay that time too long the need by those who are required to capture may be too much for the existing production, which will drive up the price until production can catch up to demand.
- **Timing:** Many factors impact timing including how quickly manufacturing can begin, what drives demand, what the cost is, and what other options might be available. An ideal scenario might look like this:
    - Funding allows several devices to emerge – 2 years
    - Market established by tax or regulation – 2 years
    - Commercialization of a dozen or more devices funded for growth – 2 years
    - Engineering moves to mass manufacturing – 3 years
    - Sales, assembly, and operations (multiple business models) – in parallel
- **What does that pathway look like?**
    - As noted above the pathway appears to take a decade
    - The true start date will be when there is a known demand going forward
    - After the start and within a decade there will be commercial machines; after that ramp up of production and building a knowledgeable workforce will determine application volume.

### What are the assumptions that we are making?

### Constraints:

- **Interconnections with other tech:** DAC needs renewable energy, an ability to sequester, and potentially synthesize products with carbon and hydrogen.
- **Competition:** Competition with other DAC devices is a good thing. Competition with other solutions is also favorable.
- **Supply chain:** Supply chain for new products is often a very difficult challenge.
- **Policy:** There is no push in the U.S. to make this happen. Policy, as it currently exists, is not sufficient to move capture forward.
- **Raw materials:** DAC does not have need for materials that are in general hard to obtain. The issue that will play a constraining role is water.
- **Financing:** First there needs to be a known market with a timeframe before private financing emerges, and without private financing there isn't commercialization.
- **Demand:** This is the critical constraint. The need for gigatons of capture exists, now there needs to be a compelling tax and regulation that drives demand.

### What would create a pathway that is more plausible?

- Funding to build out some of the potential devices to scale to determine what works
- Government action to create demand

### How would a plausible pathway for the Intermountain West differ from other regions?

- Demonstrations in the region that are publicly supported
- Leverage the existing environment by increasing the build out of renewables
- Land made available to demonstrate viability of capture and sequestration
- Sequestration geologic investigation on a broad scale across the region
- Prepare areas that are economically distressed to play a role in new types of employment
- Train a workforce for this new industry from fabrication through certification. A portion of the potential workforce already exists due to closed fossil generation

Regional policy makers will need to get actively involved in promotion and practical applications if the region is to gain economically from the energy transition. Other states, such as Nebraska, are already leveraging their lead in renewables to attract companies working on carbon neutrality. An opportunity this large will (and already is) attract policy makers in other regions to make commitments that will give them advantages. The natural advantages in the Intermountain West will be useful only if other efforts are made to build off of that opportunity.

“The sovereign power of all civil authority is founded on the consent of the people”[22]. Our challenge is not whether we are capable of meeting the challenge, it is whether we are as a community willing to get started on the solution. To date, the people are not committed to make the hard choice and accept the restraints that solving global warming requires. We are on the cusp of solutions, but we need commitment to proceed.

# Gap analysis

Plans to be effective should consider what is missing and where the pitfalls might be. Capture and DAC are so new that many of the gaps are not yet apparent. However, let’s review some of the more obvious ones:

- Definition of what parameters are acceptable as a part of capture needs to be worked out. Today this does not appear to be difficult, but once there are many devices’ standards will be needed, it would be best to start now and define what may and may not be before the field is inundated with unacceptable choices. Standards boards are typical in industrial applications, and it is time for capture to form one.
- There needs to be a market created by demand. This will probably require a broad scale application of government insistence that this problem be fixed, and that those who emit pay for the clean-up.
- Capture devices including biological capture need to improve design and application quickly. Designs are slow and mass manufacturing is nonexistent. While market demand will speed this up, there needs to be far greater investment.
- Fabrication, supply chain, and delivery mechanisms do not exist. Capture fabrication is going to compete with existing fabrication for space and with existing supply chains for equipment and material. Early development is going to be costly as it seeks to edge in and disrupt current production.
- The trained technicians to fabricate, assemble, and operate the capture farms are not in place. Teams need to be trained, procedures need to be written, and operating practices developed. The same is true for the engineers who should be drafting the drawings to build and install. Training can be developed but the experience that builds good teams takes time.
- Educational and research facilities working on capture are few and scattered. There needs to be platforms for sharing and cross fertilization of ideas.
- Higher education of the engineers, scientists, lawyers, accountants, and teachers for this field is almost entirely absent. Imagine aerospace without education. We are late in designing the courses and course work for this future.

[22] Roger Williams 1603 - 1683

- Storage needs to be permanent and few of the intended storage solutions have been tested and verified.
- Product transition of using recycled carbon for fuel, plastics, and other transition products has been explored in the lab but not at scale.
- Certification is not in place to control claims and false applications. Many credits only store for a brief period of time (often only a few decades) and some carbon credits are being exposed as fraudulent. Permanent long-term sequestration will need vigorous rules that include audits and monitoring.

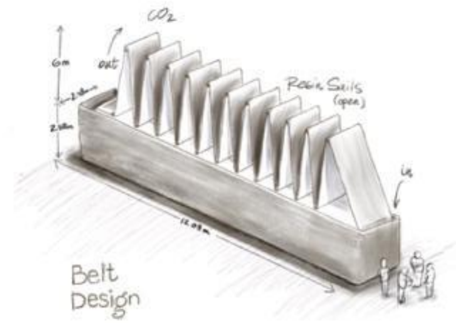


**Figure 6. Conceptual drawing of a DAC device. Image credit: ASU/CNCE patented design for DAC $CO_2$ capture.**

Gaps include new ideas: There are multiple design options for DAC devices. This drawing (Figure 6) is a concept focused on continuous flow of air enriched with $CO_2$. Today's design ought to be a starting point with more ideas to come.

### Gap analysis of options other than DAC

Point Source Capture (PSC) is very similar to DAC. One might consider PSC as the first line of $CO_2$ capture, by capturing at the smokestack. PSC has several drawbacks that may over time favor DAC. First, PSC must be located by the smokestack. Not being located close to the sequestration site often adds to the cost and hassle of piping $CO_2$ to a sequestration site. Second, PSC only captures when the plant is operating. Thus, when the plant is not operating the capital cost of the capture equipment is idle, and not returning on the investment. This second item is a particular problem with fossil power plants that will gradually be reducing the amount of operating time resulting in reducing the time initial investment can be recovered and the cost of operations crew. Third, PSC is not easily adapted to mass production as PSC units will need to be customized to the configuration and flows of each plant.

Industrial scavenged capture is a newer conception and has less demonstrable applications to judge. The idea of piggybacking on existing equipment that already provides an airflow is intriguing and may be successful in the future. The downside is each application is unique to the industrial equipment that one is merging into. There may be industries with a large amount of similar equipment that will make this a rational form of capture and in a sense, this is DAC in a new context. Tying to already in place equipment has the same disadvantage of needing to remove and deliver the $CO_2$ to a sequestration or product conversion location.

### Photosynthetic methods

Forests will likely be the early capture and storage method. It is available now and can be expanded. Forests have several drawbacks including the need for constant maintenance to keep the forest alive and to hold the designated amount of $CO_2$ for thousands of years. Forests have difficulty expanding as they compete with food production. Forestation will have an early application but likely fade as we expand the amount of capture and sequestration. Forests are also less easy to accurately measure regarding the amount of capture and sequestration. Gross measurement averages will probably be applied but will face questions and future policy risk.

Crops and fallow land will be used although the amounts sequestered will be small with a slow pickup. Measurement and land use will be issues that still need to be worked out. This may be helpful financially to agricultural interests but will not be much of a competition to DAC.

Algae may play a role once an application is determined that can be demonstrated at scale over an extended period. Algae also have a problem with the issue of long-term sequestration. Algae in general has suffered from die off and species transfer.

Alkalizations of oceans by adding magnesium hydroxide to ocean water to get to magnesium bicarbonate would capture and store $CO_2$. Projects ought to carefully assess impacts on biodiversity and ocean processes. Issues with certification and verification will need to be worked out, as does some clarity on how much the oceans can sustain this and other capture concepts.

Building materials will be enhanced to capture and hold $CO_2$. Currently there are test demonstrations using building materials for capture and long-term storage. Building materials will pick up $CO_2$ slowly in small volumes but considering the number of buildings in the world this is an intriguing addition to capture. Measurement will be hard to quantify and will probably be estimated based on lab demonstrations. Certification and verification will be challenging, although probably doable.

# Cost factors and risk

All DAC devices are in the conceptual design phase or early demonstration. From there, a lot of steps have to be made, as briefly noted below. If there is funding and a future market, these steps can go fairly rapidly, if there aren't too many unfortunate occurrences. New technologies do have unfortunate events as they evolve. Required steps:

- Prototype design and engineering upgrades from the demonstrations.
- Demonstration testing and building the supporting infrastructure.
- Revised design will be required based on testing and innovations.
- Sorbents that can handle different environments will be critical to the future.
- Sorbent improvement will go on for many years.
- The form factor of sorbent is proving difficult although some recent exciting breakthroughs.

- CPUs to support DAC have been designed; however, the current designs are costly to build and operate. Engineering and testing of revised CPUs needs to occur.
- Fabrication process using a mass production approach will be the appropriate goal. As this hasn't begun, the learning curve will need to be steep.
- Mass manufacturing is viable only for devices that are produced with the same basic configuration tens of thousands of times.
- Assembly cost in the field will be determined by location and experience. A priority to reduce field costs is to place as much equipment as possible on the skids during fabrication.
- Need to build trained teams for multiple site installs. Well-trained and experienced assembly teams might be a large cost benefit.
- O&M processes being uniform may also reduce overall costs. Again, repetition is critical.
- Operations teams should be multi-disciplined and trained against the same training program and manuals.
- Common parts over multiple units will decrease supply chain and warehouse costs.
- Sequestration design and build-out for multiple applications and different types of applications need to be developed and the detailed engineering accomplished.
- Education and training need to be expanded exponentially to accommodate the variety of new jobs.

### Mass production

There are many excellent treatises on the values of mass production related to cost, quality, safety, and other advantages. Fabrication at an adaptable scale allows exploitation of the learning curve and reduced cost during field assembly. Below is a sample set of equations that build on this concept applied to carbon capture devices (Eq. 1, Table 2). The values are theoretical which allow for the progression of the quantification. Assuming mass production for the device one may also calculate the advantage of growth in numbers in the field (Table 3). The lessons and advantages of mass production are multiple[23]. Replication reduces cost. Work is repetitively done in stages. Machinery to support labor can be applied and adapted to each production step. When labor laws are upheld, workers in conditions that are environmentally and socially better than field work are more productive with less time lost to movement from one work area to another. Factory work is better controlled and results in higher quality equipment. Factory work has a lower incidence of worker loss time accidents. Factory production has less wastage than field assembly. Factory work is more energy efficient.

**Mass manufacturing scaling law.** $c(n) + r = c_1\, n^{\varepsilon} + r.$ **Eq. (1)**

[23] Parsons Brinckerhoff Power Division; London Presentation of the US Power Labor Study and PM Process.

**Table 2. Analysis of scaling impacts on the reduction of cost**

| Parameter | Value | Comment |
|---|---|---|
| $\alpha$ | 2/3 | Power coefficient relating size to cost. Typical value for rules of scaling up. Seen in both scale-up by numbers or scale up by unit size. |
| $\varepsilon = 2^{\alpha-1}$ | 0.79 | Learning cost reduction. Estimate for PV has been between 0.76 and 0.8. Note that the assumption of a residual price lowers the effective learning rate we use. |
| $c_1$ | \$470/t | The initial cost of a ton of $CO_2$, which we assume is \$500/t minus the irreducible cost. The current cost is based on public statements of current prices. |
| $r$ | \$30/t | Estimate of the irreducible cost. This is based on estimates of raw material and energy inputs into the manufacture and operation of DAC systems, which for the ASU system are less than $r$. |
| $t$ | \$100/t | Starting point for a self-sufficient industry based on industrial cost of $CO_2$ and current trajectories of $CO_2$ prices |
| $Y$ | 5 yr | Lifetime of an early farm unit |
| $M$ | 1000 t/yr | Starting size of a unit farm. The size of the total established system based at the initial scale of $CO_2$ capture. It defines the scale at which $c_1$ is measured. |

**Table 3. Value equations on increasing the number of devices and impact on price**

| Threshold Values | Value | Comment |
|---|---|---|
| $n_t = \left(\frac{c_1}{t-r}\right)^{1/(1-\alpha)}$ | 300 | The number of unit farms required to drive the cost down to the target price. |
| $E = \frac{1-\alpha}{\alpha}\left(\left(\frac{c_1}{t-r}\right)^{\frac{\alpha}{1-\alpha}} - 1\right) YMc_1$ | \$50 million | Total cost above the threshold price |
| $T = MYn_t = MY\left(\frac{c_1}{t-r}\right)^{\frac{1}{1-\alpha}}$ | 1.5 million tons | Total amount of $CO_2$ captured at breakeven |
| $K_{\text{threshold}} = YMc_1\left(\frac{c_1}{t-r}\right)^{\frac{\alpha}{1-\alpha}}\left(\frac{1-\alpha}{\alpha} + \frac{t}{t-r}\right)$ | \$200 million | Total cost of $CO_2$ produced by break-even |

### Large scale application

Developing devices and DAC farms that are identical and replicable will be critical to keeping down costs. From fabrication to operation similarity is a natural cost reducer. Fabrication will work best in reducing cost by manufacturing many multiples of the same device. Over 100 years ago, the U.S. demonstrated the advantage of mass manufacturing, using the same design, form, and parts to drive down cost.[24] DAC needs to follow the same pattern.

Operations similarly benefit from sameness. If multiple devices and farms are similar, or only vary in a few particulars, this will result in lower operating costs as operators and maintenance technicians can learn and perfect their craft. There are a host of opportunities from savings in "sameness" including parts, tools, training, and safety.

During the ASU/CNCE Salt River Project (SRP) program students calculated capital cost reduction due to growth. The resulting learning curves were adapted to a host of assumptions and the team applied variables to different models. The resulting "Best, Worst, and Likely" curves provided illustrative examples of growth resulting in cost reduction, within the assumptions. Below is a demonstrative curve from the most likely scenario of DAC cost reduction as more and more units are built and put into production (Figures 7 and 8). The assumptions used in the study for SRP are feasible for actual DAC unit production and operation. Develop devices that can be fabricated and assembled in a controlled production setting. Make many thousands of the same device with modest variations (such as different sorbents) that can be shipped over common rail or truck applications and the manufacturing costs will

[24] Srinivasan, B. (2017). Americana: A 400-year history of American capitalism. Penguin.

come down. Combine that with ease of assembly at the capture site, including such features as skid mounting of the devices, and again apply that to many units at a site and there are additional savings due to learning and ease of handling. One gets additional quality, safety, and supply chain advantages.

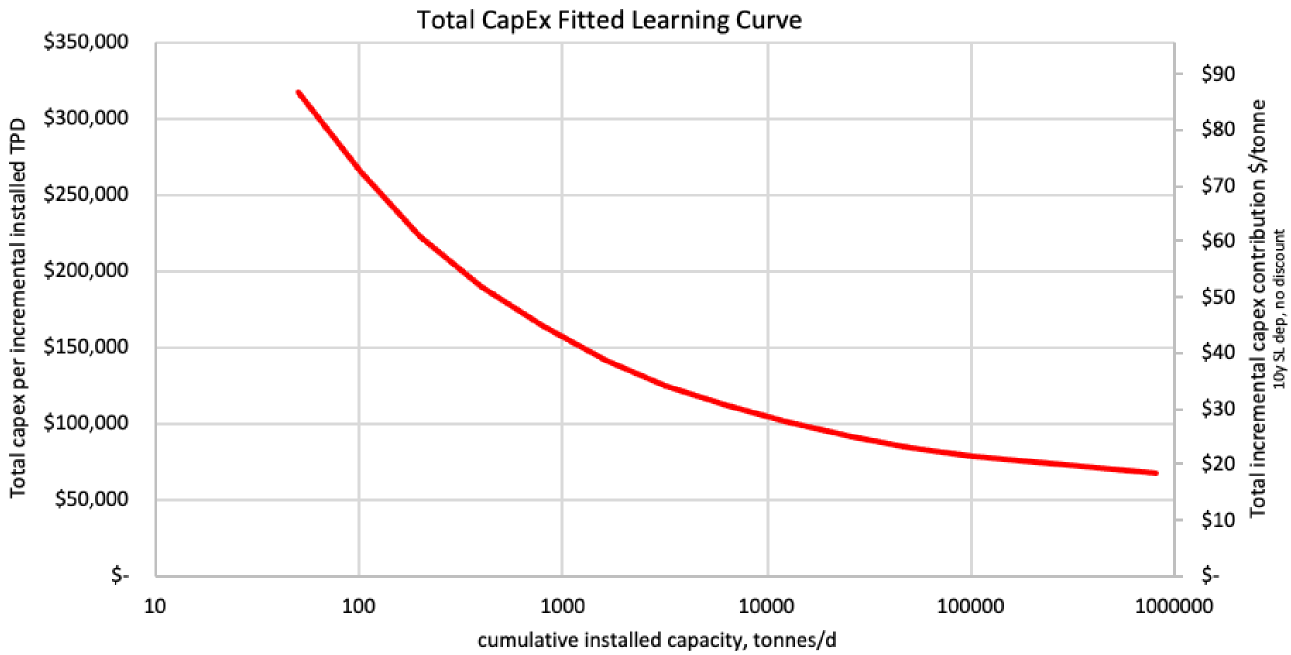


**Figure 7. Total CapEx fitted learning curve for DAC. ASU/CNCE exercise in 2020 for SRP program.**

Once the devices are at a site there are further cost and efficiency gains to be made by operating large numbers of similar units. As above the chart below was the result of an extensive student project on learning curve gains related to operation of DAC devices. The device chosen was one developed by the university and may not directly reflect on any actual device. The operating assumptions were matched to real world experience from several gas fired combined cycle power plants. Briefly the advantages of replication and learning curves for DAC operation are:

– Operator learning is critical for efficient and safe operations. As operations (and maintenance teams) learn the behavior of the equipment they continually get more efficient, modify preventive maintenance to better anticipate failure, and adjust mechanical settings for optimum production.

– Optimizing parts on site for routine and other maintenance requires time and experience. As learning progresses the site will warehouse fewer of the less needed items and more of the items that are more frequently required. This increases operating time and reduces cost.

– Safety is first and foremost about sending everyone home at the end of every shift as fit as when they started the shift. There is also a cost factor tied to safety. Using factory made skids means a safer working environment, as does more time and experience operating the facility.

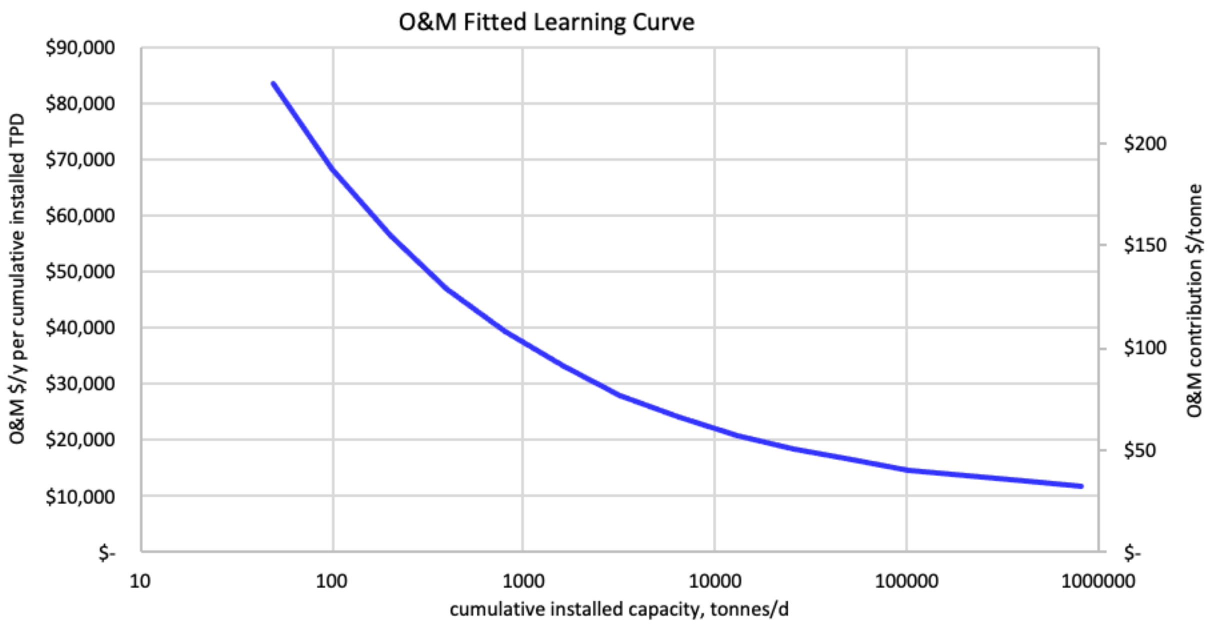


**Figure 8. O&M fitted learning curve for DAC. ASU/CNCE SRP DAC project 2020.**

### Barriers to entry

The capture market is a new, emergent market, where every player is new. Therefore, barriers to entry such as economies of scale, brand loyalty, patents, switching costs etc. all need to be worked out by the new players. One barrier to entry we do see is high set-up costs for a fabrication facility. A large-scale facility manufacturing business is highly capital intensive, which deters inadequately funded startups from entering the market. A summary of barriers include:

– Technology – is the idea good enough to compete?
– Recognition – newer entrants will need to find a means of being recognized outside of the ones already in the market.
– Capital – new fabrication facilities new supply chain, new site assembly, new standards to meet, and new operations which will require extensive capital infusion.
– Product delivery chain - any entrants to this field must develop a valid idea, fabricate the device, get it into the field, and develop an operating process; this is a long chain that will require extensive expertise to accomplish.
– Personnel – the acquiring and training of staff will take time and good planning. Staff will need to be trained for many new functions, and training takes experience that is missing.

- Cost – the cost for all entrants is from development to end-use product. Leasing and other options may lower the cost or spread the initial cost.
- Time – once there is a commitment to DAC, it will take time to build the infrastructure of equipment, parts, fabrication, trained personnel, building codes, siting and a host of other challenges.

## Risk assessment

Many potential pitfalls exist for new technologies particularly when the introduced technology is reliant on a shift in behavior and cultural patterns. The following summarize the most recognized risks, and indications of how they may be overcome.

### Market development

- Risk: New advancements in renewables can lead to a wider spread adaptation of those technologies. This leads to lower emissions thus reducing the need for carbon capture technologies.
- Mitigation: Even at the best scenarios for renewables, the need for carbon capture technology will exist and grow. This is due to the past $CO_2$ emissions and the need for continued large-scale energy production to enable economic growth. Renewables only reduce future emissions and have no impact on already produced $CO_2$. Some carbon uses do not currently have non-carbon solutions.

### State-sponsored requirements or taxes

- Risk: The profitability of the business model is heavily reliant on future government push. Though we are seeing a trend in governments recognizing the need to contain global temperature rise, there is a possibility of inaction and delay over the next decade.
- Mitigation: Various coalitions and work groups are working towards educating both the public and private sectors to acknowledge the need to adapt carbon removal technologies. In time, the damage associated with the changing climate will force mitigation.

### Design deficiencies

- Risk: The designs are new and untried.
- Mitigation: The building of commercial scale prototypes through programs such as the DAC Hubs and investor financing such as Climeworks will begin to sort out what works and what needs to be upgraded. Upgrades and improvements will continue for many years.

### Cost of the device

- Risk: The final production and operational cost might be higher than expected, which will impact our competitiveness in the market.

– Mitigation: We have reviewed many ways that DAC can reduce costs. In the final say there will be competition between capture methods and devices, and there will also be competition between means of reaching neutrality. If capture cannot compete with avoidance, then we will have a lot more avoidance.

**Advances in technology**

– Risk: Technology may advance to stifle all of the current capture methods, or one or more of them will evolve to dominate.
– Mitigation: Research and advancement of design through operation as well as being well run and conscious of the advancement in other areas may serve to mitigate.

# Business model

Let's assume there is a requirement for the reduction of $CO_2$ production and release into the environment. Assume that each ton of $CO_2$ released is required to be captured, which would spur reduction and capture. With that demand for the end of the release of $CO_2$ the market becomes real, and an industry of capture and sequestration (plus carbon products) will develop. Worldwide one might assume DAC capturing and sequestering 40 to 50 gigatons per year for most of the century, once fully implemented. To meet international limits, emissions must fall by about 13% a year. Emissions grew about 6% in 2021 after dropping in 2020 during the pandemic[25]. The Intermountain West could be the center of capture for the U.S. The region has the environment, the sunshine, and the space to be the leader in capture. How might the new businesses in this new industry be organized?

### Manufacturing business

– DAC would begin with fabrication, assuming the acceptance of one or many designs. Fabrication of devices and the associated building of the $CO_2$ concentration, sequestration, and product creation could all be new regional industries. Fabrication will likely be located close to capture farms favoring short-distance delivery; therefore, if farms located in the Intermountain West could also be accompanied by a fabrication industry.
– Manufacturing will likely be based on an assembly line approach with components mounted on skids. Assembly line production remains the most efficient and highest quality approach to manufacturing, at least at present. Skid mounting facilitates fabrication at a central location which increases productivity, enhances quality, upgrades worker safety, and is most efficient.

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[25] IEA (2022), Global Energy Review: CO2 Emissions in 2021, IEA, Paris https://www.iea.org/reports/global-energy-review-co2-emissions-in-2021-2

- R&D and design of sorbents also provide an economic future for the Intermountain West. Sorbents will likely be mass-produced and the focus of large chemical companies, but that doesn't remove the manufacture of sorbents from the region. If large-scale DAC is present, the work on sorbent improvement may also be focused in the region.

### Operations for capture and sequestration:

The DAC industry and its supply chain will create a suite of new products and services. The main ones include a new mechanical service industry and products from the captured $CO_2$. A range of customers are anticipated. As with any new industry there will be opportunities and pitfalls, including the opportunities to build new businesses that directly or indirectly relate to the new industry. For the Intermountain West, it is important to early on consider the opportunities that may be presented through DAC and to create avenues for the region to take advantage of the growth. While the potential is too broad to exhaustively cover here, it is important to point out a few of the regional businesses that might be developed, and to highlight the potential for local or smaller scale business. Carbon capture, utilization and sequestration will create a new fabrication and services infrastructure. Workers will be hired for operations, assembly, and maintenance. New maintenance support companies will emerge to service the new industry. A new set of occupations will be developed with new skill sets and training. Many opportunities for large and small businesses will emerge. Figure 9 offers a graphic example of some of the business models that may emerge. A partial list of work that will be needed is noted below:

- **Research:** A new world of how to capture and sequester needs to be researched and developed.
- **Engineering:** Design and engineering firms (both large and small) will have many opportunities in this new industry.
- **Fabrication:** The facilities to mass produce will probably be large but may intentionally be located near potential farms.
- **Siting:** This is going to be a new field adopting some of the practices from other industrial siting practices but also creating new techniques and approaches. This is a brand-new business.
- **Assembly:** Site assembly will need contractors who build familiarity with this work and have the equipment to do it efficiently.

– **Performance testing and initial startup:** This is a specialty field often handled by small highly qualified teams. The extensive start up experience resident in the region for oil well, mining, power generation, and large-scale building may serve as a good launch for this business.
– **Operator and maintenance training:** Training is a specialty area that is suited for small companies.
– **Operation:** Turn-key operations and maintenance are as likely as operations owned by the initial DAC developer. This provides another opportunity.

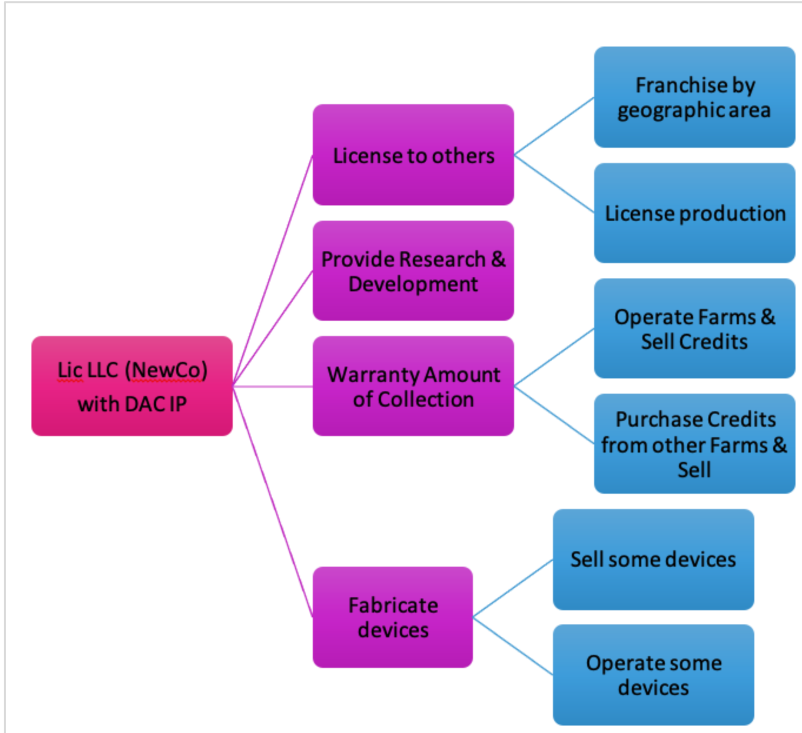


**Figure 9. Sample of option for business model.**

– **Maintenance:** Site on-going maintenance will probably be a part of the work accomplished by the Farm owner/operator. However, there are generally opportunities to develop local business to support no-routine maintenance and outages.
– **Upgrades:** DAC will be similar to other industrial applications that will learn and modify as it learns. Operators and design teams will seek and find means to improve. Work will be generated by the need for improvement and small local firms will have opportunities to participate.
– **Supply:** Supply chain will create many opportunities for large and small contributions.
– Sequestration operations and monitoring along with the supporting geologist and geologic studies and analysis.
– **Geologic analysis:** Sequestration, plant siting, and pipeline routing will all require extensive geological and other forms of environmental investigations and planned mitigation.
– **Product:** This will be a big area of opportunity. There are many products that may be developed using the carbon from capture. Each of these offers an avenue for business development that may remain in the region, and in many cases be developed by rural and tribal communities.
– **Small scale capture:** Another "local" opportunity for small business would be to do capture on a smaller scale. Applications such as Aircela are designed for this type of applications and there are other devices that would fit the small entrepreneur model.

– **Monitoring, auditing, certification, and testing:** Capture and storage will engender a new industry that tests and certifies the capture and the storage.
– **Education:** This new technology will need to be learned.

The options for the creation and formation of new businesses and types of businesses are as large as the business community's imagination. The need for capture and tying capture to the production of $CO_2$ is coming. Opportunity will draw imagination and investment. States and regions will need to be prepared to allow for some interesting new applications and enterprises.

### Sample product uses

(Figures 9 and 10)

– **Storage:** Envisioning the future is always fraught with challenges and none of us get it right. However, one might postulate that $CO_2$ will be captured, and probably in the early years the $CO_2$ will be sequestered. $CO_2$ storage opportunities remain under development with high potential for the Intermountain West. Multiple possible options exist including sequestration in rock formations or pumped and sealed in deep caverns. The DAC designs ought to fit most, if not all, storage applications.
– **Fuel:** At some point, enterprising companies will begin to convert some portion of the captured carbon into fuel and other products. Currently one might be able to value concentrated captured $CO_2$ at $200/ton based on the California rules for capture if the carbon is redirected into a fuel. There are many parts of a fuel conversion process that are currently not in place. However, a fuel recycling industry based on capture is technically feasible and some new technological advances indicate it may come soon. Some form of gas and liquid fuel is going to be necessary for the foreseeable future, and it ought to come from someplace other than underground pumping.
– **Cement production:** According to the IEA, cement production all around the globe produces more $CO_2$ than any other manufacturing process. A ton of $CO_2$ is emitted for every ton of cement produced. The plants produce as much as 7% of global $CO_2$ emissions.[26] It may be possible for cement production to be a part of the solution. Research is currently underway to feed DAC $CO_2$ into cement as a permanent sequestration, New York will shortly begin requiring cement producers to feed DAC $CO_2$ into cement production. Other steps are underway to deal with emissions emerging from the cement plants. For example, a private company based in New Jersey claims to have come up with a solution to reduce emissions by 70% by using an alternate chemical formula and procedures to manufacture cement. Instead of curing the concrete using water and steam, the new method involves $CO_2$ which in turn decreases the usage of water as well.

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[26] Gutenberg, J. (2021). Less risk, less costs: Portable spectroscopy devices could soon become real. Science Daily. Nov. 9, 2021. Available at: https://www.sciencedaily.com/releases/2022/09/220901135754.htm


Figure 10; ASU/CNCE student project 2018

- **Closed agriculture for greenhouses, algae production, and tube-based crops:** $CO_2$ is an essential component of photosynthesis. The difference between the rate of photosynthesis and the rate of respiration is the basis for dry-matter accumulation (growth) in the plant. In agricultural production, all growers aim to increase dry-matter content and economically optimize crop yield. $CO_2$ increases productivity through improved plant growth and vigor. For most greenhouse crops, a $CO_2$ level increase from 410 to 1,000 ppm is advantageous and will increase photosynthesis by about 50% over ambient $CO_2$ levels. The recent increase in interest in greenhouse agricultural applications and the growth of algae production may open a meaningful market for $CO_2$ capture and product delivery.
- **Electronics fabrication:** Electronic fabrication creates a considerable amount of $CO_2$ during the fabrication process. Semiconductor industries use $CO_2$ for precision cleaning and machining applications. While less than 1% of greenhouse gas emissions are caused due to these industries the source of the $CO_2$ might come from DAC and be part of a greater recycling process.
- **Plastic production:** According to an article published by the Stanford magazine, approximately one ounce of $CO_2$ is emitted for each ounce of polyethylene (PET) produced[27]. The Environmental Protection Agency's (EPA) indicates that between 100 million tons to 500 million tons of $CO_2$ are emitted during plastic related production, this represents 4.5% of global greenhouse gas emissions[28].
- **Volunteers:** There is an intriguing market for $CO_2$ capture using volunteers. It is not unusual for Earth-based challenges to be first addressed by citizen volunteer action; such as 4-Oceans (4-Ocean is a global movement actively removing trash from the ocean and coastlines while inspiring individuals to work together for cleaner oceans). One might envision a major gasoline distributor,

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[27] Chui, G. (2019). Scientists finally find superconductivity in exactly the place they've been looking for decades. Stanford Earth Matters Magazine; September 2019. Available at: https://earth.stanford.edu/news/scientists-finally-find-superconductivity-exactly-place-theyve-been-looking-decades#gs.du43k7

[28] World Economic Forum article Dec, 2021; E H Zurich

car manufacturer, or utility, formulating a program to accept some level of voluntary contribution toward cleaning up a car or a home's carbon footprint.

DAC can be a means to remove emitted $CO_2$. The big picture for DAC is to remove $CO_2$ that is being produced and has been produced. There is today a need to mitigate the $CO_2$ being delivered to the ocean and atmosphere. This production of $CO_2$ is going to continue for some time and needs to be dealt with. $CO_2$ delivery to the atmosphere will continue because it is going to take many years to make the transition to renewables, more efficient energy use, and overall reduction in fossil fuels. It will continue in order to sustain the economic viability that is needed to make the carbon neutrality transition possible.

**Capture is going to be a very large industry. This will open up many new opportunities for large and small corporations and communities in the Intermountain West. With some foresight and direction, the region and its communities will have immense opportunities within this new emerging industry. Opportunity needs foresight if it is to be grasped, and the efforts of states like Wyoming, New York, Texas, and California will hopefully be a guide for the region to adopt policies that favor taking advantage of the coming change.**

**$CO_2$ Markets**

**Merchant $CO_2$** - Markets are small and distributed

**Chemical commodities** – May include plastic feedstock and carbon fiber

**Biomass production** – Greenhouse agriculture, algae reactors may operate with $CO_2$ enriched air limiting water consumption in the produce foods

**Enhanced oil/gas recovery** - Air capture aims at small fields, exploratory work in the absence of pipelines; providing fuel and sequestration

**Synthetic renewable fuels** - Input is excess, intermittent renewable power, often distributed, energy rather than $CO_2$ drives cost

**Sequestration** – DAC is amenable to remote locations therefore adaptable to the be geologic formations for permanent storage

**Air capture has a competitive advantage in satisfying small, distributed or remote demands**

Figure 11. A sample of carbon uses. K Lackner CMTC Presentation 2015.

### Review of the Intermountain West's advantages in establishing a DAC industry

- **Workforce, education and training:** The Intermountain West has the available workforce but needs training programs. Please refer to the Workforce chapter of the I-WEST Phase One Final Report.
- **Space:** The capture application will require space to deploy. Ideally DAC would be deployed near sequestration locations. The region is ideal for this type of combination.
- **Access to renewable energy:** Renewables would be preferred to help play a role in progress toward carbon neutrality, particularly in the Intermountain West where solar could be the energy source and provide over 300 days a year of power.
- **Community support:** DAC has workforce and other opportunities that communities might be pleased with. However, industrial applications in or near a community have downsides. DAC companies will need to be adroit at landing community support. This is particularly significant based on the need for rapid deployment to meet the 2050 target. The organizing work by Boulder and Flagstaff provides a model for communities to promote and benefit from capture.
- **Supply chain and manufacturing:** The needs of fabrication and supply chain is critical to the timing and rate of growth for DAC. Breaking into existing supply chains with needs for a new industry requires effort and perseverance.
- **Sequestration location:** Ideally, sequestration would be preferably close to the capture sites, and the regional geologic features seem to fit this need.
- **Fuel as a product:** The future of DAC-to-fuel is intriguing but today only a potential product. The region could become a net producer of renewable fuels. With renewables to power DAC, captured carbon could be converted to liquid and gas fuels. Those fuels could then be pumped through existing pipelines to the rest of the U.S. The favorable weather, space, and environment make region an ideal "new recycled fuel center" for the U.S.
- **Other products:** Carbon may be used for plastics, chemicals, and other product uses. Many products will lose fossil carbon feedstock and DAC may offer a replacement.
- **DAC inventions:** The Intermountain West is the birthplace of at least three viable DAC entrants for large scale capture, and regional universities are working on several more. Access to the research teams that created the devices will play a role in the locations of future capture farms.
- **Education:** Regional universities have taken the lead in several significant fields vital to the future success of capture. Additional growth in this area would position the Intermountain West as a place that would support physical growth of this new industry.
- The I-WEST initiative has demonstrated the interest and viability of the region becoming a centerpiece for future carbon neutrality programs and industry, DAC among them.

# Impacts on social and economic justice

Chaos breeds opportunity. It is unfortunate that jobs are being lost and industries are going to be closed due to actions required to address the climate crisis. What might seem like a loss may open doors to new opportunities. It is difficult today to perceive how dramatic the changes that are coming will be, but we are entering into a time of tectonic shifts. We have been going through a period of rapid changes since World War II and have come to accept change. The next round of changes forced by climate change could be far more dramatic, disruptive, and rapid than anything that has preceded. Just consider one impact: forced migration. Recently, the global community has been appalled and fixated on the 4 million refugees inside Ukraine and the two million-plus that have crossed into other countries. Yet, during 2020, there were 30 million climate refugees.[29] Fortunately, most of these were temporary but more and more will be permanently displaced people looking for a new home. By 2050, the estimates for the displacement of people might rise to as high as 216 million.[30] Few of us can even fathom what such a number of refugees would mean, but history is filled with the impacts on society when large groups of humans are uprooted and seek shelter elsewhere.

The change will be negative in many ways. However, there will be opportunities for positive progress. One example that I-WEST is assessing is the ability to implement massive DAC in the Intermountain West. The capture, sequestration, and product development could be a huge industry for the region, providing high-quality jobs for thousands. As a benefit to rural communities, these jobs will often be outside of urban areas, as the capture takes space and needs to be co-located with a sequestration site.

There will be opportunities for communities that have not previously had opportunities. Tribes located in rural areas, as well as communities in rural locations across the region, have often been left out of economic advancement opportunities. DAC and sequestration have the potential to offer an alternative to that too-common narrative. With a large number of sunny days, open land, and good sequestration geology, the Intermountain West could be an industrial center for DAC from fabrication to deployment focused on rural locations upgrading the economic opportunities of those areas.

Opportunity is not enough without careful planning and application toward helping the communities that have recently and historically been left-behind. The region will be better off not relying on

[29] Jordan, R. (2021). How does climate change affect migration? Stanford University Earth Matters Magazine. June 2021, Stanford Woods Institute. Available at: https://earth.stanford.edu/news/how-does-climate-change-affect-migration#gs.dcgt22

[30] Plewa, P. (2021). Climate change and migration. Duke University Center for International Studies. October 28, 2021. Available at: https://igs.duke.edu/news/climate-change-and-migration

happenstance to direct where business develops within the capture industry. Education, training, and investment support for communities that are economically distressed can make a difference.

The energy transition must address the energy needs of at-risk communities. In finding a solution to excess carbon we need to assure that communities have adequate and affordable access to electricity and other energy options.

# Conclusion

There are currently a couple of dozen small scale DAC plants operating worldwide[31], thus we have begun, and now we need to ramp up progress. The technology has been proven in the same way as photovoltaic energy was proven before Germany decided to stimulate demand for the technology through liberal feed in tariffs. Back then, photovoltaic power was proven but was too expensive to be considered a serious player in the world's energy infrastructure. The promise of renewable energy appeared to be worth the risk.

DAC has been demonstrated in the laboratory, in small commercial applications, and it has been shown to work at a cost that is roughly ten times higher than what markets could support in the long run. DAC achieved this goal with much less effort than renewable energy providers did, as it started much closer to this point. The challenge for DAC is easier than it was for photovoltaic energy as it starts from a much smaller base. The financial gap between today's implementations and commercial viability is also much smaller because the size of the required operation is much smaller. The risk of trying out this novel technology seems well worth the potential benefit if it succeeds. Even a failure would be worth the effort, as it would suggest that negative emissions technologies cannot be relied on, making far more painful adaptation necessary.

DAC is the "overflow" capture technology that will need to gather the $CO_2$ that other solutions cannot handle. For example, if biomass takes care of 50% of aircraft $CO_2$ emissions, DAC is the likely candidate to absorb the other 50%. Today it is unclear how large this role for DAC will be. It will depend on the future cost of DAC, and the future cost of all the other alternatives. However, even if DAC plays a very minor role in balancing the world's carbon budget, this role is still very large and will include the removal of billions of tons of $CO_2$. As the one part of the solution that must adapt to the need not yet handled by other means, DAC will be critical in our removal of excess $CO_2$. A successful implementation will provide a backup to other technologies. Its simple presence makes it impossible for emitters to

[31] IEA (2022), Direct Air Capture, IEA, Paris https://www.iea.org/reports/direct-air-capture

drag their feet. Either they are forced to remedy their emissions with DAC, or they find a sector specific solution that is more cost-effective. DAC will remove the option of doing nothing.

When it comes to sequestration, DAC offers another important service. It makes it possible to quantify the cost of the loss of $CO_2$ from storage. If sequestered carbon escapes, recapture and restorage via DAC is always an option, it therefore sets the cost of losses. Since costs can be specified upfront it is possible to demand assurances in the form of bonding or insurance that losses are taken care of. By quantifying the damages, it becomes possible to integrate them in the cost analysis from the start. This makes the existence and viability of DAC important, even if it is only used for a small fraction of all $CO_2$ emissions.

"We have been called on to solve a challenge. It is a big challenge, but one with solutions. It is time that we step up and solve the problem." Klaus Lackner, April 10, 2022