Mobilize Now

Scaling up Direct Air Capture

Protect the Climate and Create Economic Prosperity

Turning a Threat into an Opportunity

About this Report

Addressing the threat of climate change while building a more sustainable, equitable, and prosperous future

In July 2020, over seventy leaders across science, business, finance, policy, and civil society came together for a Direct Air Capture Climate Mobilization Summit hosted by the Elk Coast Institute. Our objective was to assess the role that Direct Air Capture (DAC) should play in enabling the large-scale carbon removal that the world urgently needs to address climate change and to develop a high-level plan for radically accelerating its deployment globally. Over several weeks, the Summit participants – which included the leaders of all the major DAC companies as well as diverse, independent stakeholders from many disciplines – drafted a key set of findings and recommendations for how best to mobilize society toward this objective.

A critical finding of the Summit is that we have to scale Carbon Removal capacity even faster and higher than is commonly thought. We calculate that by 2040, society will need 45 gigatonnes of installed carbon removal capacity, with a significant percentage of that powered by DAC, to avoid the most dangerous impacts of climate change. To face this massive challenge -- and secure the benefits that a more sustainable, resilient and equitable circular carbon economy can deliver -- requires the establishment of a comprehensive public-private effort on the scale of the Apollo Program to demonstrate the performance, scalability, and utilization of DAC technology by 2025.

The critical milestones we identify for mobilizing to scale DAC by 2025 are:

1. **Installation of a DAC capacity of one million tonnes per year by 2022 and 8 million tonnes by 2025, combined with a cost reduction of DAC to between $50 and $100 per tonne. This program, using public-private partnerships, would cost less than $10 billion over 5 years, and form the basis for global mobilization to keep atmospheric CO_2 concentrations under control.**

2. **Demonstration of the economic viability of synthetic liquid fuels and materials such as carbon fiber and polymer production at scale. The inputs to this would be atmospheric CO_2, captured through DAC, and green hydrogen powered by renewable energy. The importance of materials like carbon fiber, concrete and plastics is that they sequester atmospheric CO_2. and can be utilized by society at the gigatonne scale.**

Together, as laid out in more detail below, these steps can initiate societal mobilization toward a sustainable circular carbon economy, which we specifically refer to in the DAC context as a Renewable Energy and Materials Economy (REME). REME will provide both the energy and materials needed by the growing global economy. This effort will initiate a sustained period of global prosperity, while at the same time addressing the threat of climate change. If we act now, we can literally turn the threat of climate change into an opportunity to create a better future for humanity in harmony with nature.

Summary

The DAC Climate Mobilization Summit participants aligned around a core set of foundational facts when developing these outputs:

- **Mitigation Alone Not Sufficient:** Eliminating humanity's ongoing emissions of Carbon Dioxide will not occur in a timeframe that avoids dangerous climate change and unacceptable impacts on humans and the biosphere
- **Carbon Removal Also Required:** To avoid those impacts, we therefore need to remove massive amounts of CO_2 accumulated in the atmosphere this century
- **The Key Solutions Already Exist:** The core technologies required to remove and sequester this CO_2, including Direct Air Capture, already exist, but must be rapidly refined and massively scaled to meet the cost, capacity, and overall system needs for doing so sustainably and equitably
- **There Is Precedent for the Mobilization Needed:** The magnitude and pace of the required scale up of these solutions has been achieved by human society many times in the past when addressing an existential threat, but has always required widespread cooperation between government, industry, and the public
- **Time is of the Essence:** Any delay in mobilizing to address the threat posed by growing atmospheric concentrations of CO_2 will increase the amount required to be removed and decrease the time for doing so
- **Direct Air Capture Can Play a Critical Role:** DAC has the potential to remove tens of billions of tonnes of CO_2 per year, and thus can be a critical enabler of the rapid, massive removal required to address climate change
- **The Key Obstacle is the Decision to Act, Not Cost:** Despite previous perceptions, the critical constraint for Direct Air Capture is not likely to be cost, but mobilizing industry, capital, government, and civil society to support its scaling in time to avoid catastrophic climate change
- **Acting Promotes Prosperity & Equity:** Far from costing society, transitioning from a linear, fossil-based economy to an air-based, globally distributed circular carbon economy that produces the carbon-based materials society needs can be a main driver of economic prosperity, human development, and global equity
- **Engaging, Educating, and Enlisting Key Stakeholders Critical Next Step:** Global decisionmakers and other key stakeholders need to be urgently engaged, educated, and enlisted to mobilize around DAC deployment in order for society to meet the climate challenge it faces and achieve the economic and equity benefits that DAC uniquely offers

Building on these foundations, this Report reflects the Elk Coast Institute's synthesis and elaboration of the output of the Mobilization Summit (and thus does not necessarily reflect the opinions of individual Summit participants). Our goal is to provide a cogent call-to-action and actionable roadmap for mobilizing around Direct Air Capture for global decision makers in government, business, finance, technology, and civil society. The remainder of this Report lays out the core analysis for why society-wide mobilization around Direct Air Capture is not only urgently needed and eminently possible but can also serve as a main driver of global prosperity in the 21st Century. We then lay out a set of specific **Findings** and **Recommendations** for decision makers to carry this essential work forward in collaboration with us and other global stakeholders. Our goal is nothing short of sparking – now – rapid, massive global mobilization around Direct Air Capture in ways that turn the threat of climate change into an opportunity for current and future generations.

A preview of some of our most critical findings and recommendations include the following:

- **DAC Essential to Avert Dangerous Climate Change:** Because of the inherent advantages of DAC (high scalability, precise measurability of CO_2 removed, high land efficiency, and many other factors), achieving the Paris Agreement targets of limiting global warming below 2 degrees Celsius will not be possible without massively scaling up DAC deployment and associated carbon utilization and storage
- **The Task is Even Bigger Than Commonly Thought:** We calculate that we need 45 Gigatonnes of installed carbon removal capacity by 2040 to avoid catastrophic climate change
- **This is Achievable, but Requires Public-Private Mobilization Now**: This goal can be achieved by, among other parallel efforts, immediately establishing global public-private partnerships similar to the Apollo Program to begin scaling DAC immediately to achieve critical installed capacity, performance, cost, and supply chain milestones by 2025
- **Immediate Actions to Ramp Direct Air Capture are Key:** Our analysis shows that installing one million tonnes per year of DAC capacity by 2022 and 8 million tonnes by 2025, combined with reducing the cost of DAC to between $50 and $100 per tonne, will put society on the right pathway to achieving gigatonne scale by 2040
- **Capital Required for this Effort is Modest:** We estimate that reaching these milestones, using public-private partnerships, would cost less than $10 billion over 5 years, which we suggest is a modest cost for beginning the global mobilization required to keep atmospheric CO_2 concentrations under control
- **Critical to Couple DAC Scaling with Carbon-to-Value Scaling:** We must also demonstrate the economic viability of synthetic liquid fuels and materials such as carbon fiber and plastics production at scale. The inputs to these products would be atmospheric CO_2, captured through DAC, and green hydrogen powered by renewable energy. The importance of materials like carbon fiber, concrete and plastics is that they sequester atmospheric CO_2 and can be utilized by society at the gigatonne scale

Process & Acknowledgements

The DAC Climate Mobilization Summit participants were organized into six Working Groups: Vision, Technology, Commercial Use & Carbon to Value Applications, Finance, Policy, Engagement and Sustainable Mobilization. The Working Groups prepared working papers before the Summit was held; these were distributed to all participants prior to the Summit and were presented and reviewed by the participants. Summit participants also reviewed the recommendations from each Working Group. A final review of the Summit produced a consensus on the major findings and recommendations. Each Working Group prepared a report following the Summit on its specific area of focus[1].

Before the Summit, volunteer contributors with deep expertise in the key dimensions of Direct Air Capture prepared the detailed working papers in each of the dimensions above based on multiple structured discussions, research, and inquiry over a period of several weeks.[2]. Following the Summit, each Working Group prepared a report on its specific area of focus[3]. We wish to deeply thank the volunteer contributors for the hard work, good humor, and extremely valuable insights they brought to this endeavor in a very compressed timeframe.

This report of the Summit's Findings and Recommendations was compiled by the Elk Coast Institute (Peter Eisenberger, Nicholas Eisenberger, Nadia Kock) with support from Valence Strategic (Colin McCormick). Disclaimer: Please note that Peter Eisenberger and Nicholas Eisenberger are associated with the Direct Air Capture company, Global Thermostat. They have an incentive for Direct Air Capture, and Global Thermostat, to see broad distribution. They also deeply believe that it will be necessary regardless of which specific companies succeed. Due to the need to get this report out in a timely manner the report was reviewed by the Working Group Chairs to make sure it was consistent with their findings and recommendations, but the organizers of the Summit are responsible for the report itself. We gratefully acknowledge the generous support for the Summit provided by the Global Mana Foundation and Patrick Furlotti founder of Projects for Good[4].

[1] For the Mobilization Working Group Reports, see https://elkinstitute.files
[2] For the full agenda of the Summit, see https://elkinstitute.files
[3] For the Mobilization Working Group Reports, see https://elkinstitute.files
[4] Projects for Good https://www.projectsforgood.org/

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Introduction

Overview

The scientific basis of climate change has grown clearer and clearer with each passing year. While research continues to resolve minor questions about just how bad the impacts of rampant CO_2 pollution will turn out to be, there is no doubt that it will involve enormous destruction for natural ecosystems, manmade infrastructure, and – worst of all – human lives. The world is increasingly witnessing the implications of this, with increasing wildfires, extensive flooding, higher-intensity storms, and growing sea level rise.

Unfortunately, despite the scientific consensus, political, economic and social factors have prevented the necessary steps on decarbonization (emissions reductions) and carbon drawdown (negative emissions) to avert further catastrophe. One of the key findings of the Summit is that the global capacity of Direct Air Capture (DAC) must be doubled every year for the next 25 years, as part of necessary large-scale action to avoid catastrophic climate change. Today's DAC capacity (approximately 1,000 tonnes CO_2/year in 2020) is vastly smaller than what is needed to remove and sequester atmospheric CO_2, but can achieve a total capacity of tens of gigatonnes through immediate action. This pace of technology scale-up has only ever been accomplished in the industrial mobilization for World War 2 – which is the reason we choose to use the metaphor of "DAC Mobilization". Given the urgency of the climate crisis, **we need to mobilize now!**

One of the key factors that prevents action is the misguided belief that responding to climate change will ruin the economy.

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> Far from being unaffordable, the transition to a decarbonized, drawdown economy is an opportunity to simultaneously build a vastly stronger, more resilient, more inclusive economy and a world safe from the ravages of runaway climate change.

The process of decarbonization and drawdown will involve large changes to physical infrastructure across many sectors, including energy, transportation, manufacturing, and buildings. It will also require developing and deploying new technologies to replace old, polluting ones, while still providing necessary energy services and materials. When viewed from a narrow perspective, these changes come with a considerable price tag, and this has been misperceived and misrepresented as unaffordable.

However, the real balance sheet at a social level is far different. These payments – manufacturing, installing and operating new clean infrastructure across almost all sectors of the economy – actually represent the **greatest investment in job creation the world has ever seen**. Money spent on decarbonization is ultimately money paid to workers across a vast range of sectors and job types, some of whom are already employed and many more who will be hired into new jobs. Far from being unaffordable, the transition to a decarbonized, drawdown economy is an opportunity to simultaneously build a vastly stronger, more resilient, more inclusive economy and a world safe from the dangers of climate change.

This message is not entirely unprecedented. More and more people and organizations are realizing both the urgency of mounting a major climate response, and the enormous economic opportunity it presents. Some of the most prominent of these include:

- **The Global Commission on the Economy and Climate:** "By shaping the major processes of structural and technological change now occurring in the global economy, we can create lasting economic growth while also tackling the immense risk of climate change"[5];
- **Michael Bloomberg:** "The choice is starkly clear, and it's not between environmental protection and economic growth, as some will try to claim"[6];
- **Nicholas Stern:** "From all of these perspectives, the evidence gathered by the Review leads to a simple conclusion: the benefits of strong and early action far outweigh the economic costs of not acting"[7];
- **Rewiring America:** "The good news is that these challenges also present opportunities, particularly in terms of the economic development and job creation associated with decarbonizing America's economy"[8];
- **The World Resources Institute:** "$1 million spent on clean energy in the United States generates more than twice as many jobs as $1 million spent on fossil fuels in the short- to medium-term"[9];

[5] New Climate Economy, "Better Growth, Better Climate", 2014
[6] Michael Bloomberg, "From Global Crisis to Global Turning Point", June 9 2020
[7] "The Stern Review Report on the Economics of Climate Change", 2006
[8] Rewiring America, "Mobilizing for a zero carbon America: Jobs, jobs, jobs, and more jobs", 2020
[9] Saha, D. and Jaeger, J., "America's New Climate Economy", World Resources Institute, 2020

- **BCG Henderson Institute:** “There are clear paths for most countries to achieve substantial reductions in greenhouse gas (GHG) emissions that can generate near-term macroeconomic payback”[10].

As these and many others have realized, the economic argument against large-scale climate action is deeply mistaken, and it stands in the way of the realization of major economic benefits. The goal of this Report is to correct this misconception and help policymakers understand that by mobilizing to build capacity for DAC, renewable energy, and hydrogen, one can both address the threat of climate change and create a period of sustained economic growth.

The Lessons of COVID

The current COVID-19 pandemic provides us with a tragic reminder of the consequences of failing to anticipate and prepare for large-scale disruptions to society. In the US, the necessary advance investments in vaccine development and disease surveillance, as well as the preparation for an organized, fact-based policy response, have largely been lacking. As a result, the disease has caused devastation across the country. The climate crisis bears many similarities to this situation: without advance investment in technology development and deployment, in tandem with a far more robust and fact-based policy framework, climate change will bring increasingly unmanageable impacts. Unfortunately, we have yet to fully absorb these lessons as a society and take action now to prevent even greater future dangers.

Notably, a more subtle and unanticipated lesson from the pandemic response is likely to emerge in coming years: the belated but relatively large investments in vaccine development will have many associated benefits that improve our ability to combat other diseases, from increasing our scientific understanding of pandemic dynamics to enhancing our ability to develop vaccines for future diseases. These benefits will be felt for many years, helping protect us from future pandemic events. This will lead thoughtful policymakers to ask why we failed to take earlier action that would have simultaneously prevented the appalling damages of COVID-19 as well as accelerated the many associated health benefits that those actions provided.

Direct Air Capture:
Needed to Address the Climate Change Threat

The response to the climate crisis must involve many different parts, with one being the reduction of greenhouse gas emissions to essentially zero as rapidly as possible. Unfortunately, society has delayed large-scale action for

[10] “The economic case for combating climate change”, BCG Henderson Institute, 2018

long enough that this vital step, even if implemented extremely quickly, will no longer be enough to keep global average temperatures low enough to avoid major climate change.

It is now clear that active CO_2 drawdown from the atmosphere, also known as "negative emissions," will be required to halt runaway heating and bring the climate back into balance.

Many approaches have been proposed for accomplishing this, and some have been realized in practice. Within the broad suite of negative emissions methods, direct separation and removal of CO_2 from air using chemical means – Direct Air Capture (DAC) – is one of the most promising. Based on a long history of technology development in other industries, DAC offers a number of important advantages:

- **It can be installed essentially anywhere**, since there is excess CO_2 everywhere there is air. In order to act as a complete drawdown mechanism, DAC only needs electricity, heat, and a destination for removed CO_2 (either storage or recycling) – all of which are widely available across the globe.
- **The CO_2 removal provided by DAC is fully verifiable**, since it can be directly measured as it is produced by the system. There is no need to estimate or model the removal process or use extensive sampling technologies.
- **DAC produces high-quality, high-purity CO_2 that can be used in a wide variety of valuable commercial applications.** With an increased supply of CO_2 from atmospheric removal, many more uses are likely to be found across the economy, with important long-term implications for global materials flow (see below).

Graphical representation of one of the Carbon Engineering's large-scale air capture plants.

- As an emergent technology, DAC is also at the early stages of its development, meaning that **its costs are likely to fall quickly as systems are built, installed and operated.** Similar to the rapid price decreases of solar PV and lithium-ion batteries, DAC will get exponentially cheaper with scale, meaning that achieving important overall drawdown targets will cost far less than today's technology suggests.

By themselves, these attractive features of DAC justify a significantly greater investment by national governments in developing and deploying the technology. Rapid progress can be made on cost reductions and performance improvements that will have significant near-term benefits for CO_2 drawdown with relatively modest public funding. In the context of the severe damages already being inflicted by accelerating climate change, sharply expanded DAC investment clearly belongs on the list of high-priority national government technology spending. However, DAC offers an important additional set of benefits beyond its climate impact: widespread job creation.

Direct Air Capture as a Job Creator

While DAC is an advanced and emerging technology, its core components are relatively easy to understand. Large fans move air into air filtration units, which contain materials that extract CO_2 from ambient air. Like a sponge that soaks up spilled water by a sink, these materials fill up with CO_2 sourced from the air and are then "wrung out" by heating or other mechanisms. This produces a stream of nearly pure CO_2, which can then be compressed and processed for further use in other ways.

DAC facilities can range in size from small, containerized units to large installations similar in scale to a natural-gas-fired power plant. These facilities require concrete, steel, and plastic, as well as piping, electric power, and other infrastructure for the plant to operate. While R&D will likely improve the lifetime of the filtration materials, these need to be periodically replaced and refreshed with newly manufactured materials.

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> Removing large quantities of Carbon from the atmosphere will create jobs, as will the new carbon to value industries that will form to create a Renewable Energy and Materials Economy.

The manufacture, construction, and operation of DAC plants therefore needs labor – a lot of it. The jobs associated with DAC range from construction trades very similar to what would be needed for a new oil refinery or pipeline, to manufacturing roles for advanced filtration components and novel materials. Concrete and steel production are required, with associated jobs in those industries. DAC plant operators are needed with skills that are similar to those at a chemical plant, and CO_2 pipeline operations and trucking require workers familiar with industrial gas handling and transportation. The use of CO_2 captured by DAC in commercially valuable products leads to many other jobs, in sectors ranging from alternative fuels, chemicals, and polymers to construction to agriculture to food and beverage.

Previous research has estimated that a single 1 million tonnes per year DAC plant could generate up to 3,500 jobs across the supply chain[11]. Countries that choose to invest in the deployment of DAC as a response to the growing climate crisis will see the benefits of job creation as a result.

Pathways to DAC Deployment

Today, there are a limited number of companies commercializing DAC solutions and corporate partners actively working with them to scale and deploy their solutions. Expanding the interactions among these companies, and broadly across other industries, will greatly accelerate the deployment of DAC. **The pathway to large-scale DAC deployment can best be thought of in two phases:**

Phase 1
Achieving an initial scale of 1 million tonnes per year of installed DAC capacity globally will move DAC down the cost curve to approximately $100 per tonne or less, and firmly establish the initial footings of an integrated industry, including initial supply chain development, performance data, financing, and other elements.

Phase 2
Starting from this initial scale, a trajectory that doubles the installed DAC capacity every 12 months between 2022 and 2025 and beyond, achieving 8 million tonnes by 2025, will continue to drive cost reductions through learning-by-doing and put the world on target to achieve the necessary scale of CO_2 removal as informed by science-based targets.

Within both of these phases, the emphasis should be on a combination of public sector support through government deployment incentives and funding with developing an understanding of where demand can be created or accessed at increasingly higher levels. This will require a focus on (a) speed to demonstrate key breakpoints in cost and performance that open up further demand (through demonstration of success and scale) and (b) identifying where capital may be accessible. Overall, this reflects a need to efficiently buy down the cost of DAC through investment, subsidy, and demand creation.

[11] "Capturing New Jobs and New Business", Rhodium Group (2020)

The Renewable Energy and Materials Economy (REME)

Because excess CO_2 acts as a pollutant in the atmosphere, it is often seen as a valueless waste product that must be thrown away. Indeed, under the conventional carbon capture and storage approach, a large fraction of removed CO_2 will need to be put into secure geologic storage to ensure an overall climate benefit. This viewpoint envisions the important project of drawdown as essentially a global waste-management challenge, with few ancillary benefits. Unsurprisingly, this is an unappealing program to offer policymakers and the general public, and it reinforces the misperception that climate action is purely a form of expense or drag on global economic prosperity.

However, this view is profoundly mistaken, because it fails to recognize the enormous opportunity that CO_2 removed from the atmosphere represents. At the same time as we are examining the ways we can collectively remove large quantities of carbon from the atmosphere, carbon in other forms is at the heart of the modern materials economy. Our transportation infrastructure and built environment are deeply dependent on it, and the extraction of fossil carbon in the form of oil, gas and coal is a multi-trillion-dollar industry – with ongoing environmental damages of many different types. We must therefore ask ourselves how we can harness carbon removed from the atmosphere to alter and improve the global liquid fuels and materials economy, displacing our use of fossil carbon and transforming a problem into an opportunity.

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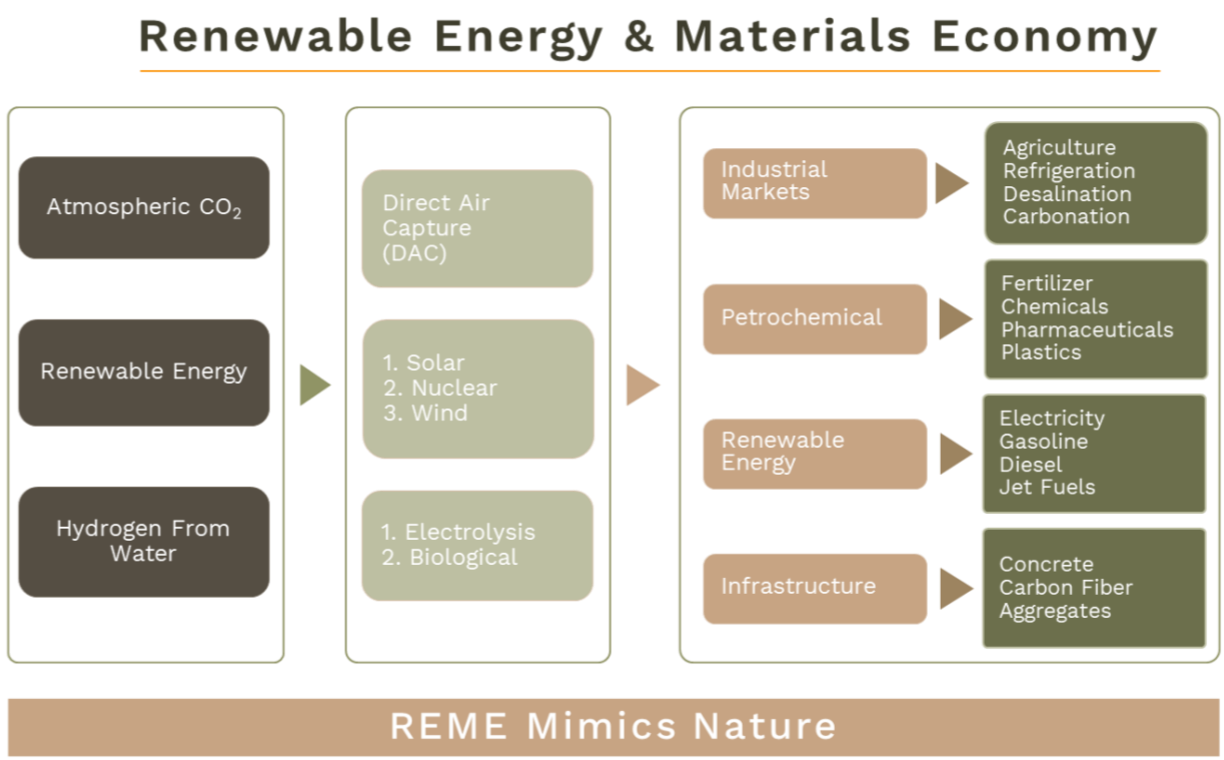
> The transition to a sustainable REME can be compared to the industrial revolution itself in terms of how we use our energy and has many benefits over our current use of energy based on exploiting natural resources.

Utilizing removed atmospheric carbon is already a technological reality at small scales today. The primary barrier to using it in other applications is energy given the need to convert CO_2 to other forms of carbon through energy-intensive processes. While this barrier has seemed insurmountable for many years, the recent astonishing growth in solar power production, and the plunging costs associated with it, have transformed the situation. Renewable energy (particularly solar, but also wind, geothermal, hydro and biomass power) is now on the cusp of being able to provide vast amounts of low-cost clean electricity and heat to upgrade removed CO_2. This will increasingly become economically competitive with fossil-sourced forms of carbon. Although legacy investments and conservative engineering cultures will be a source of inertia that slows this transition, the economic advantages of using renewably powered, air-sourced carbon rather than mined fossil carbon will eventually become overwhelming. Renewable energy can similarly power DAC, leading to synergies between the effort to increase renewables and removing and transforming atmospheric carbon for useful purposes rather than purely waste disposal.

Two other important technological transformations are emerging that contribute to this situation. The first is the rapidly improving ability to produce clean hydrogen (also known as “green hydrogen”) from the electrolysis of water. When combined with DAC-sourced CO_2, this can become a nearly limitless source of carbon-neutral, recyclable liquid fuels, as well as a variety of chemicals, pharmaceuticals and polymers. Embedding removed carbon from the atmosphere into these products can create an accelerating positive feedback loop, whereby the value they create helps fund the expansion of the global DAC-sourced CO_2 sector, further lowering costs and improving this system’s economic attractiveness. Importantly, the transition to the use of DAC-sourced CO_2 for these materials enables us to take advantage of our existing extensive infrastructure around energy-dense liquid hydrocarbons, since the products themselves (e.g. liquid fuels) remain identical – only the source of their feedstock materials is changed.



These “hydrogen-enabled”, DAC-sourced-CO_2 technologies offer great promise for displacing fossil carbon and delivering large-scale economic value. But they are primarily a short-term form of carbon utilization, in which the removed carbon is eventually returned to the atmosphere on short or medium timescales. To meet climate goals and realize the full range of opportunities for transforming the emissions-intensive sectors of the economy, it will be necessary to utilize removed carbon in more permanent ways. To this end, the emerging solutions for making carbon-based materials for the built environment, such as carbon-fiber composites and concrete additives, is tremendously important. Embedding DAC-sourced CO_2 in these building materials offers the possibility of large-scale, long-term sequestration of carbon in the built environment, with major associated economic value (this is particularly salient given the enormous demand for built infrastructure in the rapidly urbanizing developing world). In fact, in many areas of construction and industrial production, designers and engineers already would prefer to use advanced carbon-based materials for their superior properties, if they were widely available. A system of DAC-sourced CO_2 for carbon-based building materials could finally provide this supply.

In addition to the job impacts associated with the "front end" process of removing CO_2 from the atmosphere, there are opportunities for substantial job creation in the use of that CO_2 for economically valuable purposes. While these jobs are less immediate than those described above, they may ultimately scale to dwarf the direct and indirect employment from DAC itself.

The transition to a sustainable REME can be compared to the industrial revolution itself in terms of how we use our energy and has many benefits over our current use of energy based on exploiting natural resources. Therefore, it is something we would do even if the climate threat did not exist. This transition turns the climate threat into an opportunity with the only difference being that the time of the transition needs to be driven by the threat and not the opportunity. We need to mobilize now and there is literally no time to waste. This is the major observation of the Findings and Recommendations that follow.

Findings

Technology status and development

1. **Direct Air Capture (DAC) is a Carbon Dioxide Removal (CDR) technology that can scale to remove CO_2 from the atmosphere at the rate of tens of gigatonnes per year, which is needed to address the threat of Climate Change** (Technology Report). We concur with the IPCC and other assessments that one cannot at the same time meet the growing demand for energy necessary to address global poverty, switch entirely to renewables, and reduce emissions fast enough to avoid catastrophic climate change. Driving emissions to zero just by completely phasing out fossil fuels cannot be achieved within the necessary timeframe while still providing global energy services, without CO_2 concentration going well past 500 ppm, far beyond the 450 ppm target needed to meet the 2-degree Paris Agreement target. All the below findings are expressed in terms of DAC capacity, but clearly any other CDR effort that can contribute is both welcomed and will reduce the challenge of scaling up DAC (but not the need to mobilize in an historically short time).

   The following assessment of the need to mobilize the carbon dioxide removal effort even more rapidly than commonly assumed was carried out using IPCC generated scenarios for emissions. The technical details of the models used can be found in the QANM (Quantitative Analysis of Need for Mobilization), which was developed by Dr. Matthew Realff, a noted researcher on DAC at Georgia Tech.

Global Thermostat, Huntsville, Alabama

The total installed capacity of DAC today is about 1,000 tonnes per year. In the (QANM) analysis two scenarios were analyzed – a "limited mobilization" case achieving 4 million tonnes per year capacity by 2025 and a "full mobilization" case achieving 8 million tonnes per year capacity by 2025. The results of that assessment are displayed on the next pages.

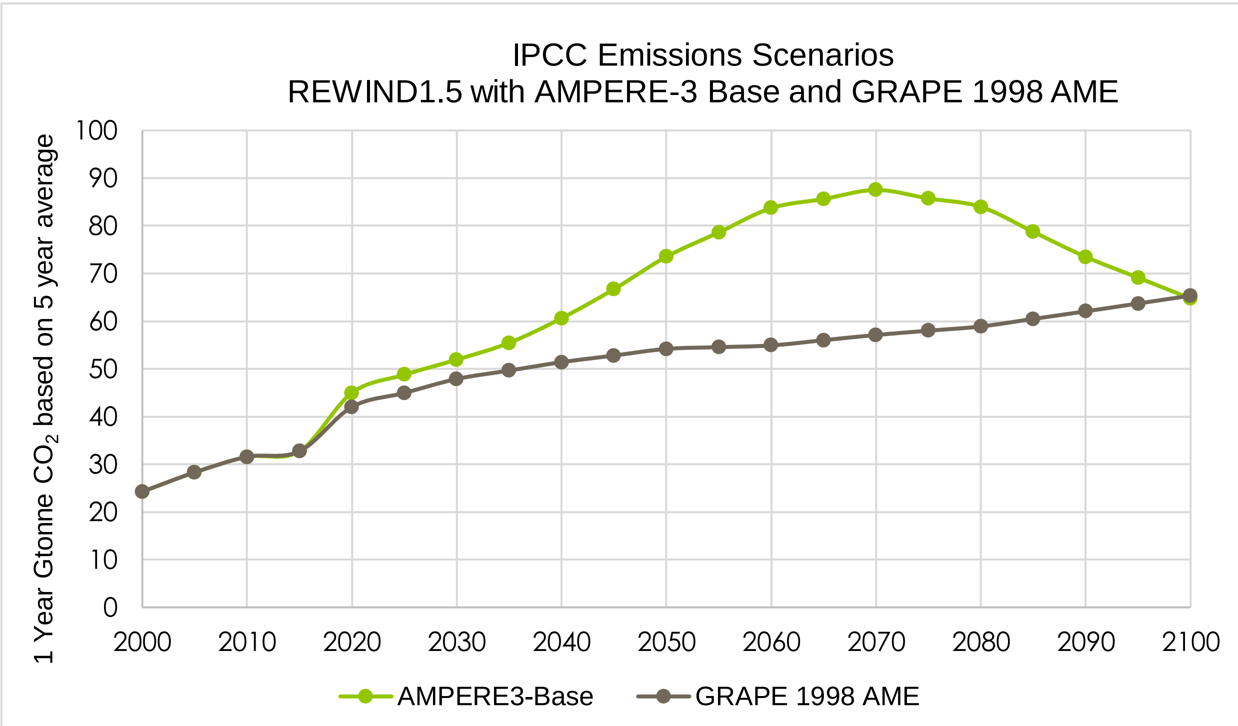


Figure 1. Two among the more optimistic IPCC Emissions Scenarios modified by using actual estimated emissions 2000-2015. Yearly CO_2 emissions based on a 5-year average or model projection. These include estimates of economic growth, switching to renewables, emissions reductions, efficiency improvement efforts and are among the most optimistic scenarios. The global emissions continue to increase despite these efforts.

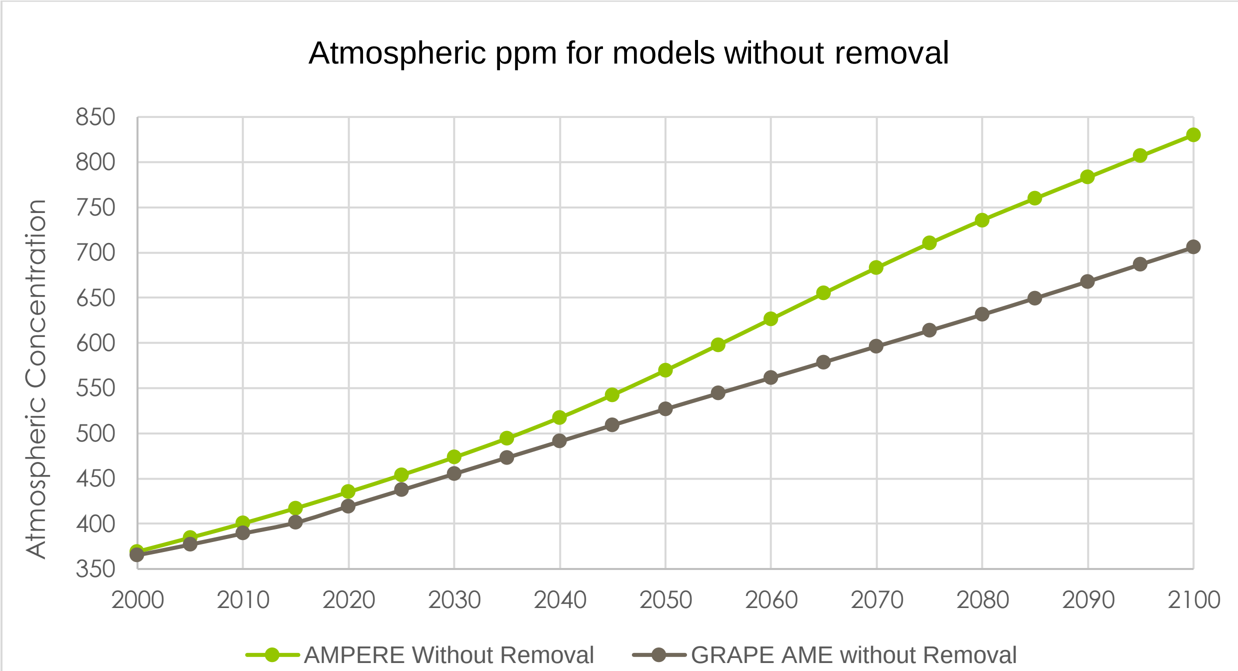


Figure 2. Atmospheric Concentration forced by REMIND 1.5 AMPERE 3 Base Scenario and the GRAPE 1998 AME Reference Scenario.

The full mobilization scenario (8 million tonnes per year by 2025) was brought forward and analyzed with a two-year doubling rate and a one-year doubling rate for DAC capacity growth, with each reaching 450 parts per million CO_2 concentration and stabilizing there by subsequently adjusting the DAC capacity to balance out the net emissions, both from human and natural sources. “Net zero” is reached when human emissions are fully offset, which corresponds to the peak in atmospheric concentration. However, a reduction in atmospheric CO_2 concentration will lead to release of the CO_2 stored in the ocean (as dissolved gaseous CO_2 and dissolved bicarbonate ions); this will act to slow the drawdown of atmospheric CO_2 and must be included in the analysis. This is described in detail in QANM. Below are some of the more important figures from QANM.

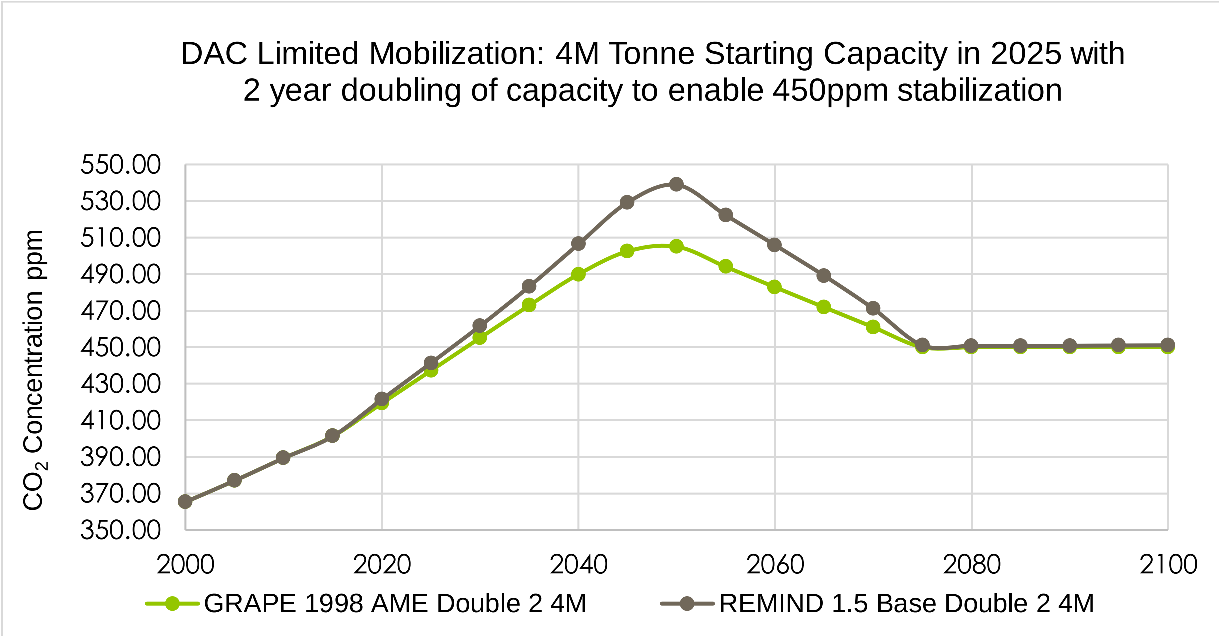


Figure 3. Atmospheric *CO_2 Concentration this century with limited DAC mobilization implemented starting in 2025 with 4M* Tonne *CO_2* removal *capacity that can be doubled every two years. Net zero atmospheric CO_2 is achieved by 2050 with the capacity to reduce CO_2 below peak levels back to a 450 ppm stable level by 2075.*

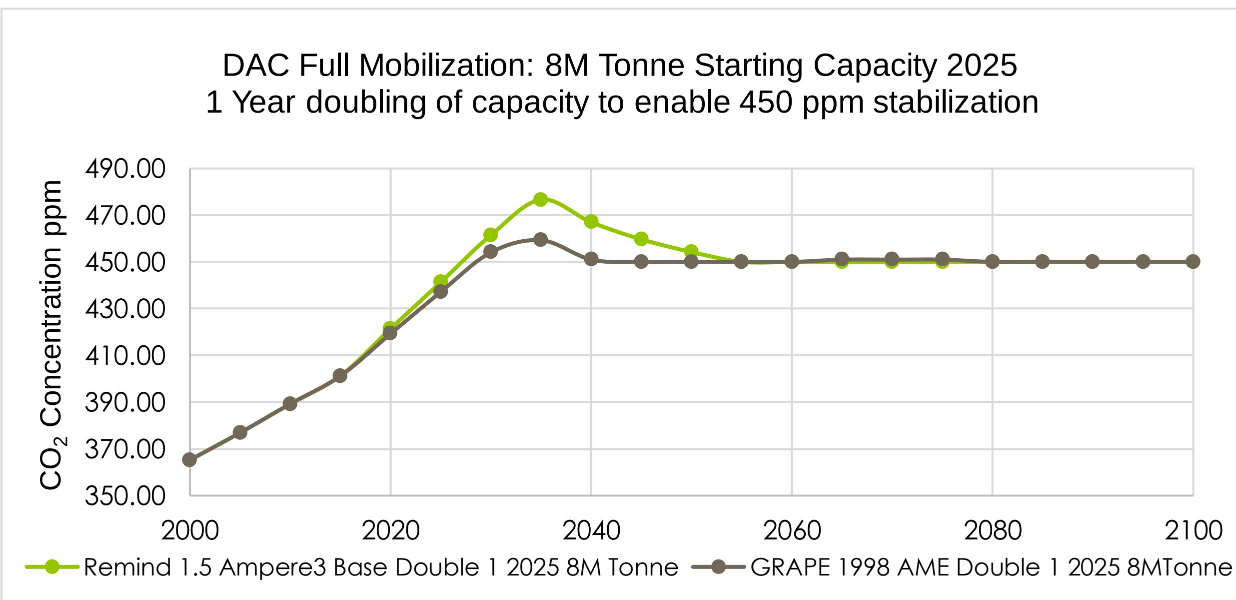


Figure 4. Atmospheric CO_2 Concentration with DAC mobilization implemented starting 2025 at 8M Tonne CO_2 removal capacity that can be doubled every year. Net zero atmospheric CO_2 is achieved by 2035 with capacity to reduce CO_2 below peak levels of 450 ppm by 2040 in the case of the optimistic scenario and 2055 in average the scenario.

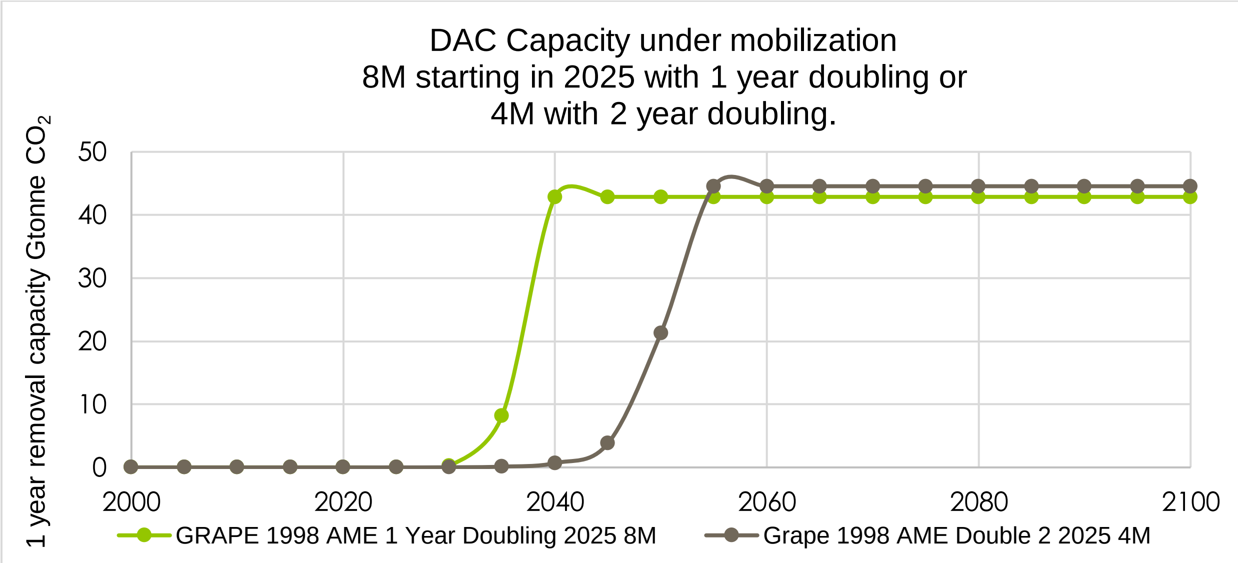


Figure 5. DAC capacities under limited mobilization and mobilization respectively for the GRAPE AME emission scenario.

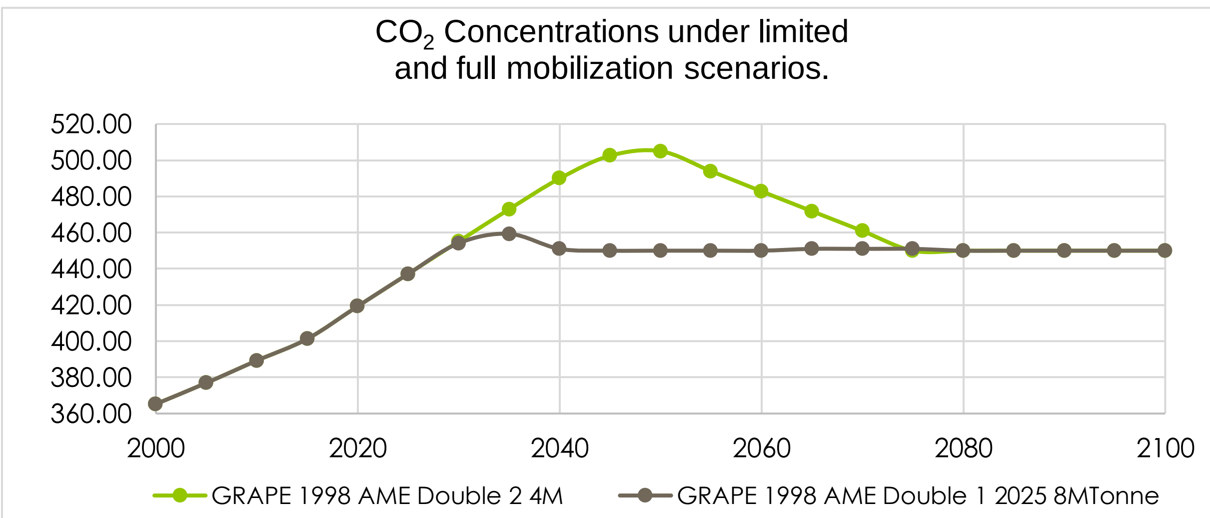


Figure 6. Atmospheric CO_2 Concentrations with Limited and Full Mobilization

Although the ultimate DAC capacity installed under the limited mobilization scenario is very similar to that installed under the full mobilization scenario, the different consequences can be seen in the resulting CO_2 concentration trajectories, shown in Figure 6. The slower doubling rate and lower starting capacity of the limited mobilization scenario means that the CO_2 concentration peaks 15 years later than in the full mobilization case and at a value that is 45ppm higher. The installed DAC capacity of the limited mobilization scenario could be increased further to bring the CO_2 concentration down faster but at significantly increased cost.

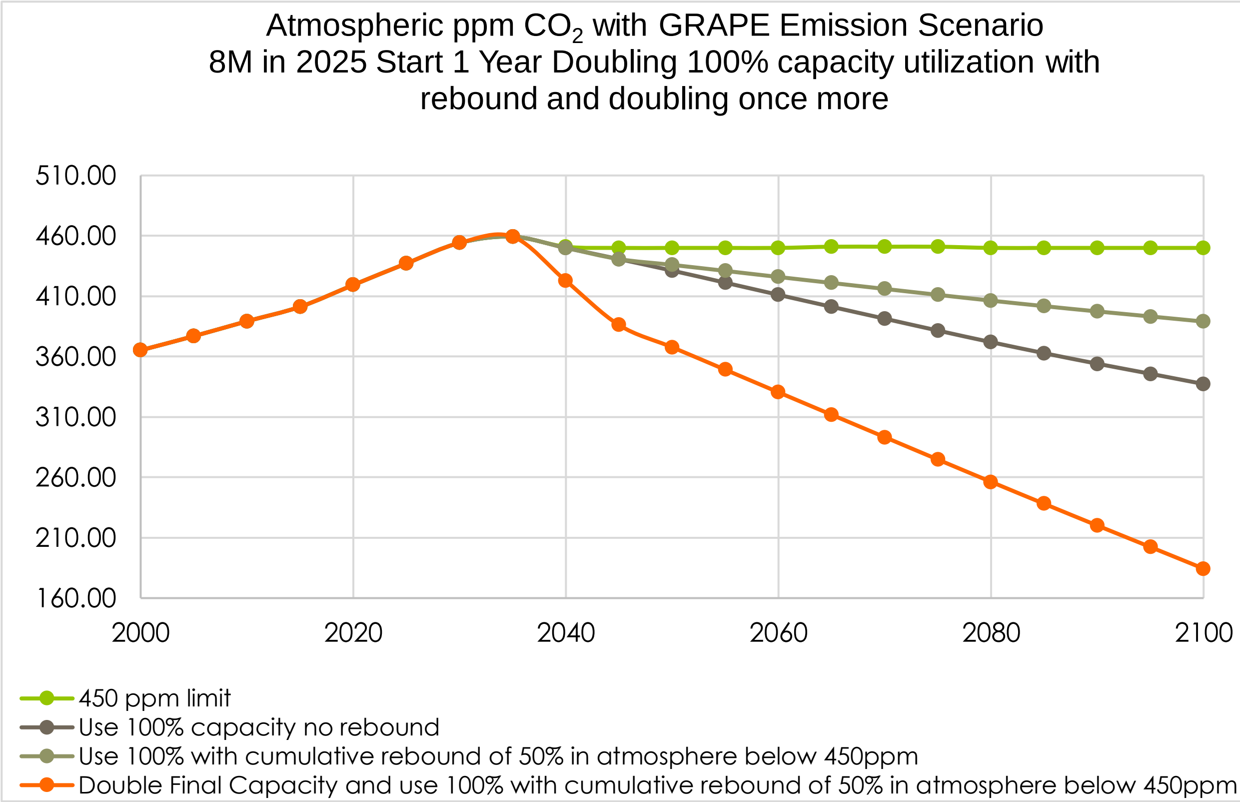


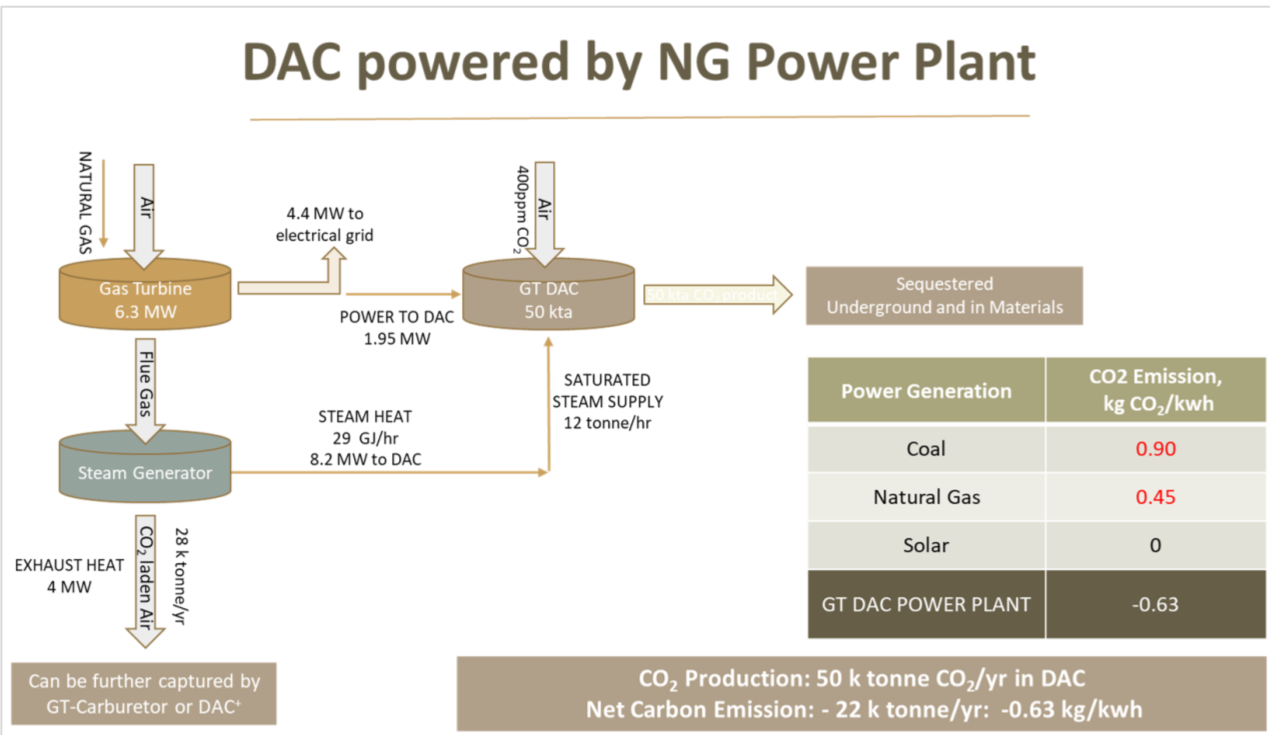
Figure 7. CO_2 *Concentration for the GRAPE Model with AME Emission Scenario with 2025 start and 8Mtonne capacity in 2025. Peak concentration occurs in 2035. The system with this capacity can drive the* CO_2 *below 450ppm but this will likely cause rebound of ocean* CO_2 *to the atmosphere.*

2. **For comparison, the full mobilization scenario would install DAC at a rate that is much faster than the deployment of solar energy over the past several decades**, although the rate of solar deployment nearly reached such levels when governments specifically mobilized industry to do so[1]. When governments have responded to an imminent threat, even faster doubling rates have been achieved, albeit for short periods of time[2].

3. **Delaying the start of mobilization, like delaying the response to the Pandemic, will increase the amount of CO_2 that needs to be removed, shorten the time available to remove it, and increase the irreparable damages from an overshoot**. The world is already late in developing the necessary DAC capacity and any further delay will exacerbate the damages and increase the risk of catastrophic harm. We need to start as soon as possible to develop the needed DAC capacity.

4. **Given the urgency of the situation, taking advantage of existing industrial capabilities is critical**. Particularly, the petrochemical industry has the capacity to successfully address the climate threat in the time needed. Connections to other industries must be considered as well. Opportunities for creating capability in developing countries are particularly important.

5. **Stand-alone systems that combine low-cost, but intermittent, renewable energy, with combustion-based power can make renewables dispatchable**. To decarbonize this system, CO_2 can be captured from flue gas in combination with removal from air, at a ratio of roughly 1:2. The resulting CO_2 can be sequestered in a wide range of economically valuable materials (carbon fiber, cement, plastic, desalinated water) creating an additional source of revenue to the generated electrical power. This combined approach can help develop a sustainable energy infrastructure while simultaneously addressing the threat of climate change.[12]



6. **Developing DAC capability in time and at scale requires cooperation between and amongst governments, innovative DAC companies and established industries**. Such cooperation does not preclude competition, but rather accelerates the development of the market opportunity as well as the carbon drawdown. Once DAC is

[12] Carbon Negative Power Plants, Graciela Chichilnisky and Peter Eisenberger, 2011

recognized as an important contributor to balancing the carbon budget, the challenge will be to fill unmet demand in a timely manner rather than fend off potential competitors.

DAC costs and learning-by-doing

7. **There are currently a handful of DAC companies who assert that their technologies can remove CO_2 from the air at between $600 per tonne and $200 per tonne and at scale could capture CO_2 from $100 to under $50 per tonne** (Mobilization Technology Report). They each have large-scale demonstration projects scheduled to come online in the 2022 to 2023 timeframe. That such low costs are achievable has been confirmed by a study of DAC carried out by the US National Academies[13].

8. **As with most hardware technologies, the costs of DAC will fall due to learning-by-doing.** Typical learning rates suggest that DAC could drop below $100 per tonne by the time it reaches a cumulative capacity of 1 million tonnes per year which will be achieved early in the first stage of mobilization. By this same estimate, the cost would reach $50 per tonne with 16 million tonnes per year of cumulative installed capacity. This learning means that at full scale, the cost of removing 20 gigatonnes of CO_2 from the atmosphere per year would require several trillion dollars in capital investment over 24 years, with annual costs measured in hundreds of billions of dollars. While these numbers are extremely large, this amount is in fact less than 1% of the annual Global GDP. Additionally, as described below, the net cost to the economy can be positive through the development of a REME economy. Thus, the true challenge we face is not economic, but rather creating the needed DAC capacity in the limited time available to avoid potentially catastrophic climate change.

CO_2 storage and use

9. **CO_2 removed from the air can be sequestered underground or in materials like carbon fiber, concrete, and synthetic aggregate.** This approach (carbon-to-value, also known as CO_2 utilization or carbontech) is highly preferred because of its economic benefits, although geological sequestration must continue to be developed. When combined with renewable energy and green hydrogen, the carbon-to-value path can be used to make the liquid fuels and materials needed by the global economy. **Using captured CO_2 to make materials that sequester CO_2 is part of a Circular Carbon Economy that also includes producing renewable synthetic gasoline using CO_2 from the air and hydrogen from water** - just as nature does. The transition to a Renewable Energy and Materials Economy (REME) can create jobs and stimulate global economic prosperity in a sustainable fashion. In fact, the transition creates a positive feedback between growing the economy and

[13] "Negative Emissions Technologies and Reliable Sequestration", National Academies of Science, Engineering and Medicine (2019)

meeting the challenge of climate change. Growth creates new uses for captured CO_2 and a larger built infrastructure in which carbon can be sequestered. The value created in using CO_2 to make materials will be large; for comparison**, at $50 per tonne of CO_2, the cost of the removed carbon is equivalent to the carbon in a barrel of oil that costs $20 per barrel.**

10. **The economic opportunity for carbon-to-value/carbontech is huge**: The US total available market (TAM) is $1.07 trillion per year, and global TAM is $5.91 trillion per year. The total available market includes all revenue from products that could feasibly be made from carbontech materials or conversion processes. The largest segment today is fuels, which composes 85% of the U.S. market and 66% of the global market. The top three global markets in value include fuels ($3.82 trillion), building materials ($1.37 trillion), and plastics ($0.41 trillion).[14]

11. **The current highest market price for CO_2 is $1,000 per tonne in some island nations where the CO_2 is imported by ISO containers,** but this is not a big market. The US average is around $150 per tonne (liquid food and beverage grade). 98% of the CO_2 is purchased by industrial gas companies, purified, liquified and supplied to the industrial merchant customers as liquid bulk CO_2 (Mobilization Carbon-to-Value Report). These high costs suggest there are immediate markets for DAC-sourced CO_2 at costs well above $100 per tonne, if logistical and other issues can be overcome.

Financing and public policy

12. **To address the threat of climate change, one needs a different carbon accounting to accurately value carbon dioxide removal over emissions reduction**. In the future, the extraction of fossil carbon needs to be matched by carbon removal, and past carbon emissions will have to be removed as well. The accounting and incentive structures necessary for stabilizing CO_2 in the atmosphere at a safe level still need to be developed and go well beyond dealing with offsets and carbon taxes (Mobilization Policy Report).

13. Trillions of dollars of capital will need to be mobilized into carbon capture projects. **The good news is that there is ample capital available looking for long-dated stable returns** since there is a global asset-liability mismatch: long-dated liabilities with inadequate supply of long-dated assets. The other good news is that there are many financing structures that have already been invented but merely need adaptation to provide capital for mobilizing DAC (Mobilization Finance Report).

[14] Carbontech: A Trillion Dollar Opportunity, Nov 2018, https://carbon180.medium.com/

14. **Multiple pro-DAC policies already exist that can be leveraged and built upon to achieve mobilization goals**. US federal and state governments and other national and regional governments have a suite of tools in place that support CCS already, which can be leveraged directly or built upon to facilitate the necessary support (Mobilization Policy Report). The successful and creative utilization and transformative yield of these policies will build momentum for future support and intervention at different phases of DAC market development over time. Prime existing policies include: Federal 45Q tax credit, DOE Title XVII loan program office, R&D programs, FEED study support, ARPA-E program, and California Low Carbon Fuel Standard (LCSF).

15. **Rapid DAC plant deployment by 2025 must be prioritized, regardless of application**, if ultimate cost and scale targets are to be realized in the longer term. The next five years represent a critical window for achieving DAC technical evolution, learning curve advancement, and business model innovation and discovery, and must culminate with a fully commercial DAC industry, capable of scaling at volumes and at speeds that correspond to climate needs. As a core strategic consideration for mobilization, a focus on achieving rapid, near-term capacity gains by any and all means possible should be prioritized. It follows that mobilization over the next period should be sector opportunistic and application agnostic in pursuit of this capacity deployment objective.

16. **Past government interventions to spur technology advancement are numerous and instructive.** There is a wealth of past and current examples of national governments strategically intervening to spark and accelerate innovative technologies whose success and proliferation are judged to be in the national interest. Examples that were initiated during periods of pervasive economic distress and uncertainty on par with what is now being experienced in the COVID era also hold important lessons that should be absorbed and modeled. Specific cases that fall into this latter category include: Success US Department of Defense technology development ecosystem; Success - Solar scale-up initiatives under ARRA; Cautionary tale - Carbon Capture and Sequestration support under ARRA and ARPA-E. However, none are cases where economic distress was combined with a threat to national security. The most recent example is World War Two where US mobilization to build ships and armament followed by the Marshall Plan is widely credited with removing the last vestiges of the Depression and unleashing economic prosperity that produced a prosperous middle class in the United States. More generally the "Marshall Plan" of enabling REME globally will stimulate global economic prosperity.

Recommendations

1. **Both public and private support should be provided for the equivalent of the Apollo mission of landing a person on the moon in 10 years to demonstrate the performance and scalability of DAC technology. This should be started as soon as possible, with the objective of installing one million tonnes per year of DAC capacity by 2022 and 8 million tonnes by 2025 and lowering the cost of DAC to between $50 and $100 per tonne. This program would cost under 10 billion dollars over 5 years and form the basis for the rapid future growth to keep CO_2 concentrations under control.**

2. **A global organization should be established to coordinate this effort to scale up DAC capacity.** It should be given the explicit mandate to support achieving 45 billion tonnes per year of DAC capacity over the next 20 years. This organization could be similar to national space agencies such as NASA and ISRO; global research partnerships such as CGIAR; or an intergovernmental organization such as IRENA. Special efforts should be made to develop a DAC industry in energy-poor regions. A Marshall Plan equivalent would be very helpful in enabling the needed infrastructure to be built and would create greater demand for materials that could use products made from CO_2 from the air creating increased sequestration capability.

3. **National governments should consider financing DAC mobilization using an approach similar to the War Bonds approach that allowed broad participation in financing World War Two.** This would allow a large share of the general population to directly support the response to climate change by funding the construction of DAC machines and renewable energy facilities, green hydrogen capability and carbon-to-value capability to produce the materials and energy we need to drive economic growth and transition to a Renewable Energy and Materials Economy.

4. **National governments should consider activating the industrial base normally reserved for national defense and military hardware production to support DAC scale-up.** This could also include support by defense ministries for R&D on atmospheric CO_2 to carbon-to-value technologies, which may include the development of battlefield fuel from atmospheric CO_2 and hydrogen from water and renewable energy.

5. **National governments should consider implementing procurement policies to directly buy products, fuels and materials made from atmospheric CO_2 where feasible.** They should also consider directly purchasing the removal and sequestration of atmospheric CO_2 to cancel out their own emissions at a national level.

6. **National governments should consider implementing a carbon policy that imposes increasing fees for extracting forms of carbon (including coal, oil and gas) from geological formations, which could be offset through equivalent amounts of carbon removal and sequestration.** Governments should establish appropriate monitoring and verification systems to oversee and validate this.

7. **Private-public partnerships should be developed as well as industry-wide efforts to advance the scale of DAC capacity and the associated supply chain capacity. Government has a crucial role to play in mobilizing industry and by encouraging, supporting and enabling cooperation within various industrial sectors.** Mobilization policy strategy should be segmented into a 2-phase timetable that accounts for (a) the immediate near-term needs of a nascent industry that still has critical R&D, commercial/market development, and public acceptance challenges to overcome; and (b) the indispensable, long-term climate mitigation role that DAC must meet by scaling-up at an unprecedented rate.

8. **The planning for a global mobilization effort should proceed in parallel with the demonstration program because one cannot afford the delay of doing it in series**. The demonstration program should establish a target of $100 per tonne, which is both achievable given the conclusions of the 2019 US National Academies study[15], and impactful given the likely range of carbon prices in the near future.

9. **National governments should establish new programs in universities and vocational and trade schools to train people for the many jobs that DAC mobilization will create.** Some of these will be minor adaptations of existing job categories, while others will be relatively novel.

[15] "Negative Emissions Technologies and Reliable Sequestration", National Academies of Science, Engineering and Medicine (2019)

Conclusion

The world faces an enormous, unprecedented challenge in responding to the growing climate crisis. Every moment of delay increases the severity of the consequences of inaction and makes the necessary response more difficult. However, there is still a path for successfully managing this crisis, restoring balance to the global climate system, and ensuring renewed economic prosperity across the globe. We can follow this path by urgently and immediately mobilizing for the aggressive scale-up of DAC technology along with continuing to grow the markets for renewable energy and green hydrogen. Through rapid action, the deployment of DAC will reduce excess atmospheric CO_2, drive down technology costs for the future, create large numbers of near-term jobs, and usher in a new foundation for global industry based on air-sourced carbon, renewable energy, and green hydrogen. We can realize this vision if we choose to act now.

Climeworks on the roof of the waste incinerator plant in Hinwil, Switzerland

QANM

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About Elk Coast Institute

The Elk Coast Institute recognizes Direct Air Capture as a necessity to prevent the catastrophic consequences of climate change and to turn the threat into an opportunity simultaneously. The Institute is mobilizing for Direct Air Capture by providing workshops, market analysis and education to stakeholders. The focus is to provide a vision for the future of Climate Stability, and how we can get there through mobilization and a coherent plan.

Turning a Threat into an Opportunity