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Economics of Direct Air Capture of Carbon Dioxide

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Executive Summary

This Masters Project was designed to review Direct Air Capture (DAC) technology's current positioning in the market and to pinpoint necessary augmentations to economics and policy that must take place in order to improve that positioning. The underlying problem DAC was designed to solve was climate change, which by economists' standards is considered an externality and not a challenge that directly impacts society's buying/selling behaviors. We recommend, with this paper, various ways the equation could hypothetically change for which the DAC solution becomes relevant. While the underpinning of our thesis is that improving environmental outcomes by capturing more carbon dioxide (CO2) emissions is advantageous for our planet's future, the critical reason for defining market conditions that demand DAC technologies is that concerns of climate change simply aren't enough to encourage the advancement of the space. Our approach to researching this question is to conduct literature reviews, interviews, and to analyze data sets to determine best fit solutions for stimulating demand for DAC technologies in the market.

The first two sections in the overview of this report provide an overview into the technology's mechanics and the system's associated costs. The two main types of DAC technologies make up the majority of the DAC market players and are detailed in this section. We note that the cost for CO2 capture via DAC varies greatly due to the number of companies still piloting their projects as opposed to those companies that have proven their business in the market. We often refer to the numbers provided by scientific research and the companies to provide comparisons of how successful the technology could be at these price points during our analysis.

In our overview, we also cover policy. We identified three main policies that could be applied to DAC technologies to improve their competitiveness against other systems of CO2 capture. The policies discussed are the federal Section 45Q tax credit, California's Low Carbon Fuel Standard (LCFS), and the Buy Clean California Act. We dissect their benefits and highlight how these policy tools can be applied to DAC.

The next section of this report covers the business case for CO2 and how DAC fits in the market landscape of CO2 suppliers. Starting with supply, the report outlines how organizations that use CO2 get their supply currently. We provide an overview of annual market supply volumes and the industrial sectors that emit the most CO2 that ultimately ends up being used in

other processes, sequestered, or just released out into the air. We use the numbers associated with cost of capturing these emissions as a relative comparison point for the cost of capture predicted by the DAC market players. We take a deep dive into a selection of DAC market players as part of our discussion on CO2 supply.

The next section under the business case for CO2 is on demand for CO2. Here we enumerate the many uses of CO2 in a variety of different end markets. We illustrate which end-uses are seeing growth in demand and how that growth could translate to opportunity for DAC companies. Before moving on to an analysis, we briefly highlight the discrepancy between CO2 supply and demand in a summary of our economic review.

Following our economic review, we dive into analysis of the opportunity for DAC companies in the CO2 markets. We determined the two main growth markets for CO2 that could take advantage of DAC's steady CO2 supply and government and policy incentives were enhanced oil recovery and methane fuel development. We conducted sensitivity analysis on the cost of CO2 capture from DAC in these two markets, applying policy incentives where relevant. This ultimately demonstrated that with the right alignment of policies, DAC CO2 capture could be competitive with other sources for CO2 when CO2 capture costs remained low. Since most of these DAC companies are not yet commercialized, there remains a lot of unknowns about how realistic these low CO2 prices will be in the future.

Before concluding the report, we discuss risks to the development of DAC businesses in CO2 markets. These risks relate to speed at which the market grows, the number of policies that are set in place for DAC companies to utilize, the access to energy resources needed to power DAC facilities, as well as the potential for true CO2 reduction as revealed by a life cycle analysis.

We conclude this report with a series of recommendations for DAC companies. We note the importance of policy in the success of DAC as well as selecting the appropriate "beachhead" target customer in order to catalyze growth potential. While there are still a lot of uncertainties in the realm of DAC development, we believe that DAC companies should focus on supplying CO2 for EOR before expanding into other markets in an effort to scale and create market efficiencies.

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Introduction

This Masters Project was designed to review direct air capture (DAC) technology's current positioning in the market and to pinpoint necessary augmentations to economics and policy that must take place in order to improve that positioning. The underlying problem DAC was designed to solve was climate change, which by some standards is considered an externality and not a challenge that directly impacts society's buying/selling behaviors (Beuttler, Wurzbacher and Charles 2019). For this reason, DAC businesses are pivoting to market their technology as a solution to carbon dioxide (CO2) supply. Instead of assuming a market for carbon credits, we recommend, with this paper, a market strategy where the DAC solution becomes economical and scalable under current policy conditions.

While the underpinning of our thesis is that improving environmental outcomes by capturing more CO2 emissions is advantageous for our planet's future, the critical reason for defining market conditions that demand DAC technologies is that concerns of climate change simply aren't enough to encourage the advancement of the space without a CO2 tax or other policy driven solution.

DAC Overview

There are multiple DAC technologies with differing designs that remove CO2 from the atmosphere. At a basic level, these DAC technologies all remove CO2 from air with fans that move ambient air through a system that uses solvents or filters to capture CO2 and form it into a solid. The solid can then be stored and later heated into a pure gaseous stream of carbon dioxide**.** This pure stream of CO2 has the potential to be feedstock for products like synthetic fuels, cements, chemicals, or plastics (Larsen, et al. May 2019).

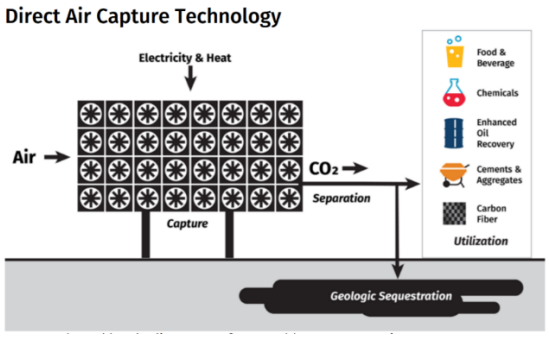

Figure 1 (Larsen, et al. May 2019)

Technology Overview

DAC units can be categorized into two design groups. These two groups are those that use liquid solvents to remove CO2 from ambient air and those that use solid sorbents to remove CO2 from ambient air. The liquid solvent DAC technology removes CO2 from ambient air in a two-step process that can be seen in **Figure 2**. In the first step, fans pull ambient air into an air contactor. The air contactor contains absorption columns that have been sprayed with a sodium hydroxide solvent. This sodium hydroxide solvent reacts with the CO2 in the ambient air to form a sodium carbonate solution. The second cycle occurs in the causticiser where the sodium carbonate solution reacts with calcium hydroxide to make a solid calcium carbonate. The solid is than heated in the calciner. The heat reacts with the solid calcium carbonate to form a concentrated stream of gaseous CO2 and calcium oxide that is then recycled back into the system (Fasihi, Efimova and Breyer 2019).

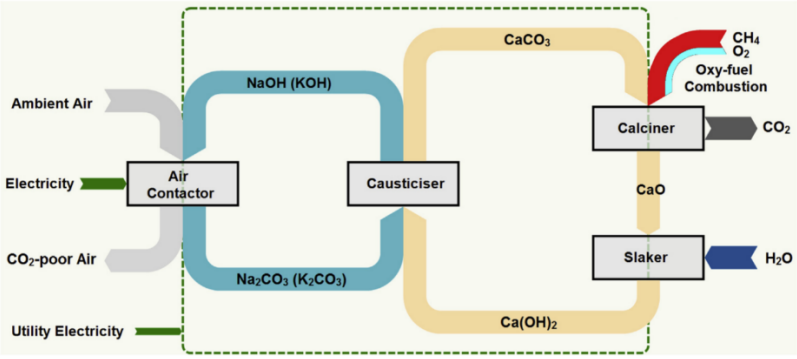

Figure 2 (Fasihi, Efimova and Breyer 2019)

The second type of technology uses solid sorbents to capture CO2. The configuration for this type of DAC technology can be seen in **Figure 3**. Fans pull air into an air contactor that has filters that bind to the CO2 in the air. These filters typically are made with amines that are effective at capturing low concentrations of CO2 (Fasihi, Efimova and Breyer 2019)**.** When the filters are saturated with CO2, the system is turned off and the unit is heated to release the captured CO2 from the filter. The released CO2 is then cooled and removed from the unit. Once the CO2 is out of the system, the system itself must be cooled in order to begin another cycle. The time it takes to cool the system depends on the type of filter that is used to adsorb the CO2 (Fasihi, Efimova and Breyer 2019).

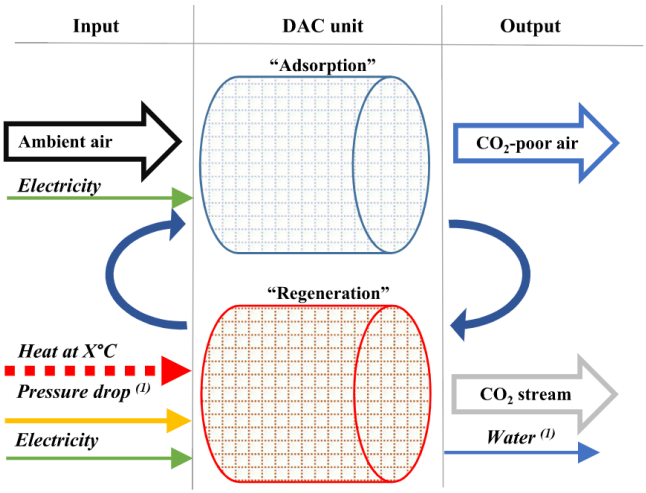

Figure 3 (Fasihi, Efimova and Breyer 2019)

DAC differs from carbon capture and storage (CCS) in that it does not need a concentrated CO2 stream to capture CO2. This means DAC can be sited anywhere which lowers the cost of transporting CO2. However, because the technology removes low concentrations of CO2 from ambient air, the energy required to remove one ton of CO2 from the atmosphere is high. There is also additional energy input needed to heat solid calcium carbonate into a gaseous carbon dioxide that can be sold into carbon dioxide markets. As a result, the high energy need of the technology introduces scale risk as widespread implementation of DAC would require large amounts of energy. Lastly, there are concerns around earthquakes and water quality when storing carbon underground (Institute for Carbon Removal Law and Policy 2018).

Technology Cost

The cost of DAC technology in academic research ranges from $100 to $1000 per ton of CO2 sequestered (Institute for Carbon Removal Law and Policy 2018). This variance is understandable since there is large variation in DAC design and there are few plants in operation. For example, assumptions around design efficiencies, energy consumption and scale can impact the cost of sequestering CO2. These differences can be seen in **Figure 4** which has cost and technology information from three DAC companies.

Company	DAC Technology	Filter Type	Heating Temperature for CO2 release (℃)	Cost ($/tonne CO2)
Carbon Engineering	Liquid Solvent	NA	900	$110-275[1]
Climeworks	Solid Sorbent	amine-based	100	$600[2]
Global Thermostat	Solid Sorbent	amine-based	85-95	$90[3]
Infinitree	Solid Sorbent	Ion-exchange sorbent	-	-
Skytree	Solid Sorbent	Porous plastic beads with benzyl amines	-	-

Figure 4 (Fasihi, Efimova and Breyer 2019)

Policy

Policy can significantly speed up the adoption of a new technology by lowering costs. Unfortunately, federal R&D funding for the technology has been small. As of May 2019, $11 million total in federal dollars has been spent on DAC R&D (Larsen, et al. May 2019). However, there are two policies in the United States that explicitly benefit DAC technology and one policy that could potentially benefit DAC. These policies are the federal Section 45Q tax credit, California's Low Carbon Fuel Standard (LCFS), and the Buy Clean California Act (Larsen, et al. May 2019).

The federal Section 45Q tax credit is a carbon sequestration credit that applies to carbon capture projects that capture at least 100,000 tons of CO2 per year. These projects can claim credits for 12 years and must begin construction by 2024. The credit amount depends on the end use of the captured CO2. If the captured CO2 is used for feedstock for qualifying materials or enhanced oil recovery (EOR), the credit is $35 for every net ton of CO2 sequestered (Larsen, et al. May 2019). If the captured CO2 is permanently sequestered in geologic formations, the credit is $50 for every net ton of CO2 sequestered (Huffman and Sensoli 2020). The Internal Revenue Service (IRS) has given little guidance on lifecycle accounting and hasn't provided a definition

[1] (Keith, et al. 2018)
[2] (Gertner 2019)
[3] (Soltoff 2019)

of permanent geologic storage so it is likely that many projects that could benefit from the tax credit will not begin construction before 2024 (Larsen, et al. May 2019).

California's LCFS has set a carbon emissions intensity standard for transportation fuels over their lifecycle that fuel providers in the state must meet (SRECTrade, Inc. 2020). Fuel providers can meet this standard by lowering the carbon intensity of their fuel or by purchasing credits. Credits are generated when a fuel provider exceeds the carbon emissions intensity standard set by LCFS. Credits have a ceiling of $200 per tonne of CO2 (California Air Resources Board 2020). Currently, LCFS lists DAC as a technology eligible for credits if the CO2 captured is permanently stored for 100 years anywhere in the world and is eligible for project-based crediting where the project would get one credit for every metric ton of CO2 sequestered (Townsend and Havercroft 2019). DAC derived CO2 fuels, after undergoing a lifecycle assessment, can also to generate credits by selling those fuels in the California market (Sandalow, et al. 2018).

The Buy Clean California Act will set CO2 lifecycle standards for construction materials that California state agencies must adhere to when procuring construction materials. These standards are expected to be put in place in 2021. DAC could benefit if it is defined as an eligible technology under this policy (Larsen, et al. May 2019).

Business Case for CO2

The problem DAC primarily aims to solve is climate change by removing CO2 out of the air. Currently, there is not a financial cost or "tangible burden" associated with the release of CO2 into the atmosphere so the target customer or demand for such a technology, from an economic perspective, doesn't exist. Instead of positioning this technology as a solution for climate change, we believe it can be positioned to fulfill another purpose: On-site raw material sourcing. Like solar panels, DAC systems can be installed directly into manufacturing facilities, and can provide valuable source material for production or even power resource. Several industries use CO2 in their products or as part of product development. These include, green houses, soda production, oil and gas ground extraction, algae production, and plastics and carbon fiber manufacturing (Roberts 2019). These companies can use DAC as a powerful tool to propel their businesses forward while demonstrating a commitment to environmental sustainability and carbon neutrality. For example, Occidental Petroleum's CEO has committed to carbon neutrality

goals for the company and has partnered with Carbon Engineering to build a DAC plant with capacity to capture 500,000 tonnes of CO2 per year to help meet that goal (Rathi, Quartz 2019).

Supply: How Do they get their CO2 Now?

Fundamentally, CO2 is an abundant byproduct from man-made and natural processes. Therefore, CO2 can be captured at a source or not. A company can take emissions from a point source, move the CO2 to a factory where it can be turned into another product, and then sold to an end market. Alternatively, a DAC facility, where CO2 is taken directly from the air, can ship directly to end-markets. The big difference here to note is that DAC supply is not restricted by one particular point source and therefore a non-negligible cost is removed from the equation of moving supply to market. Here we will talk about industrial sources of CO2 as well as the DAC companies supplying end markets.

Companies that use CO2 as part of their manufacturing processes or products generally source from companies that produce CO2 in the form of exhaust from their industrial burners. CO2 emitted from existing processes varies in quantity and concentration, thus there is a cost associated with purifying and capturing these CO2 streams. Using the "potential sources of Waste CO2" table adopted from [Economics of carbon dioxide capture and utilization – a supply and demand perspective] (Naims 2016), we created **Figure 5** showing volumes of CO2 emissions of the 8 largest emission sources and the total volume of emissions for all sources. Coal and gas fired power plants produce the largest volume of CO2 emission. Global trends indicate a decrease in coal power production and an increase in natural gas power production. CO2 emissions from natural gas power production are more diffused (less concentrated) than CO2 emissions from coal, and therefore we predict that there will be an increase in CO2 capture costs from industrial point sources.

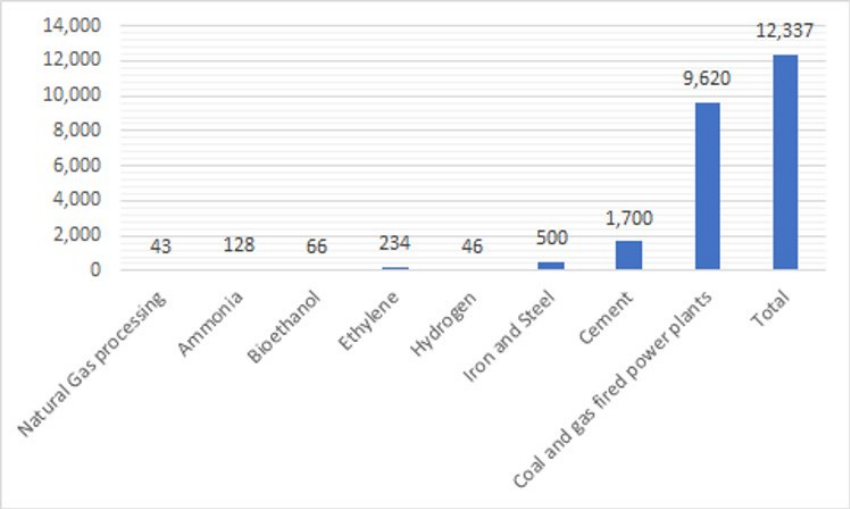

Figure 5 (IEA 2019)

The process of direct air capture includes purification of the CO2 stream. DAC provides businesses that use CO2 as a resource a consistent supply of this raw material without concern for purification, logistical matters, or dependencies on the output rate of other industries.

DAC Market Players

There are at least 5 companies working to commercialize DAC and many more in the pipeline (National Academies of Sciences, Engineering, and Medicine 2019). This section will take an in-depth look at various players in the space.

Climeworks[4]

Climeworks is a Swiss company that was founded in 2010 after its founders built and tested a DAC prototype model. Climeworks builds modular CO2 capture plants that can be located anywhere. Climeworks also commissioned the build of the world's first commercial scale DAC plant in 2017. For the smaller units, it could cost somewhere between $600 to $1000 per metric ton of CO2 captured to run these machines since they are energy intensive (Gertner 2019).

The first plant was built in Zurich and the CO2 from this particular plant was fed into a greenhouse in order to boost plant growth. This particular plant is capable of capturing 900

[4] https://www.climeworks.com/

metric tons of CO2 annually. The company's second plant is in Iceland and its captured emissions are injected into the earth. This plant captures approximately 50 metric tons annually.

Climeworks most recent plant was erected in Troia, Italy. This plant can capture about 150 metric tons of CO2 per year and these emissions will be converted into methane to power trucks (Rathi, Quartz 2018). Given the cost to build and operate these plants, and the small market for the technology, Climeworks has yet to prove its economic value. The distinct use cases for each plant demonstrates the versatility of CO2 as a commodity.

Climeworks also has a "subscription service" for individuals to contribute funds on a monthly basis to the company in exchange for offsetting a percent of an individual's global average travel footprint (Climeworks n.d.). It is unclear if this financing is a significant revenue stream for the company.

Carbon Engineering[5]

Carbon Engineering is a Canadian based company with a pilot plant in Squamish, Canada. This pilot plant can capture up to 1 ton of CO2 per day and will capture approximately 500,000 metric tons of CO2 each year (Rathi, Quartz 2019). Similar to Climeworks, Carbon Engineering has documented geological storage and "clean" transportation fuels as use cases for their captured emissions. Carbon Engineering's founder believes that his technology could capture CO2 for around $100 to $250 per ton, but the company has not yet commercialized their product (Keith, et al. 2018), (Chalmin 2019).

Global Thermostat[6]

Global Thermostat was founded in 2010 with the intention of "turning CO2 from a global liability into an opportunity for global prosperity". They have now built 2 functioning demonstration plants and have a partnership with ExxonMobile to advance their business. The company claims to have some of the lowest CO2 capture costs in the industry, boasting and estimated capture cost of $55/tonne of CO2 (Soltoff 2019). This estimate includes the $35/tonne tax credit policy. It is unclear if this will be the true going rate of CO2 capture for Global Thermostat because they are not fully commercialized and only running pilot operations.

[5] https://carbonengineering.com/
[6] https://globalthermostat.com/

Skytree[7]

Skytree is a unique DAC player because they do not run any DAC plant facilities. The company was founded in 2014 with the mission of "up-cycling carbon" and to be an integral part of the circular economy. Instead of developing large industrial plants to capture CO2, they apply their technology to smaller modules that help in particular environments. Their first product is the Stomata, a tool utilizing DAC processes to improve air quality in vehicles.

Infinitree[8]

Infinitree's customer is commercial greenhouses. The CO2 captured by their technology is used in these greenhouses to enhance photosynthetic rate and increase plant yields[9]. Their technology that removes CO2 from ambient air is a filter that absorbs CO2 when dry and will release the CO2 when wet[10]. This technology requires little to no energy to release CO2 from a solid state which could be promising for the DAC landscape. However, the technology is proprietary and nothing is publicly published about the cost or scalability of this filter.

Demand: Who needs CO2?

There are many applications for CO2 aside from sequestration. These such applications can be split into two broad categories, as illustrated in **Figure 6**. Direct use of CO2 refers to the direct use of CO2 in carbonation of food and beverages as well as the use of CO2 for EOR. Chemical or biological transformation of CO2 refers to development of new substances and materials such as plastics, CO2 in cement, creation of methane fuels as well as development of urea used in farming practices.

[7] https://www.skytree.eu/direct-air-capture/

[8] http://www.infinitreellc.com/

[9] http://www.infinitreellc.com/#about

[10] http://www.infinitreellc.com/technology

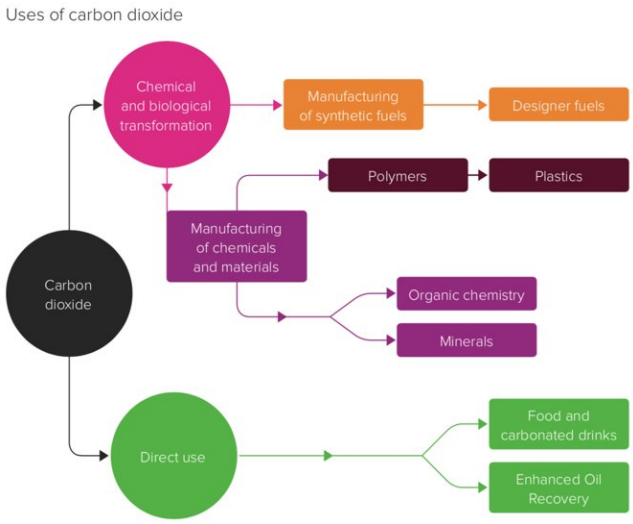

Figure 6 (Roberts 2019)

The IEA projected that around 250 million tonnes of CO2 would be demanded in 2020 as seen in **Figure 7**. The vast majority of CO2 captured for industrial use is used in the creation of urea while EOR makes up the second largest consumer. Only about 6% of CO2 captured and used will be used in food and beverage. We believe that there is an opportunity for the consumption of CO2 in EOR to increase dramatically over the coming years.

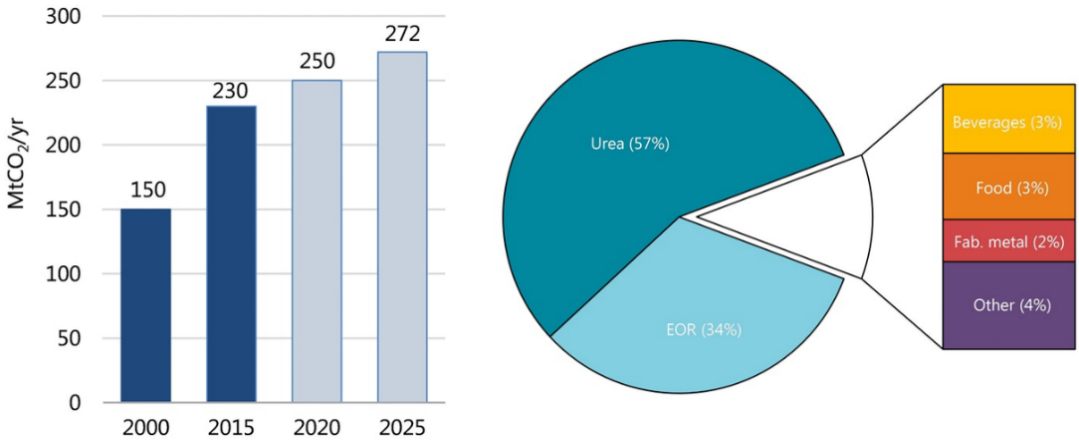

Figure 7 (IEA 2019)

In a 2018 GreenBiz Article (Sweet 2018), the author points out a number of novel uses for CO2 that may gain traction over the coming years. These products include carbon nanotubes/fiber that can be used as a light-weight alternative to metals, plastics, concretes, and coatings, and bio-

composite foamed plastics. The volume of CO2 used in material production is projected to grow about 27% in the next ten years while the volume of CO2 used in fuel production will increase by 60% (Naims 2016). Fuel development and material development are therefore also areas with great potential for increased CO2 demand.

In summary, research indicates that there is a global supply of around 12,000 million metric tonnes of CO2 and a demand of only around 250 million metric tonnes. It is important to note that the supply isn't all being used for industrial processes; some CO2 is captured and sequestered. In our analysis and recommendations section, we will explore opportunities for market demand growth that encourages the development of DAC industries.

Market Recommendations

Currently, DAC derived CO2 is not cost effective without policy incentives. As a result, DAC companies should prioritize industries that have policy support for DAC derived CO2 to allow them to scale and drive down costs.

Policy Analysis

Policy can help drive innovation and lower technology costs. Historically, the United States has supported energy infrastructure through tax incentives in the tax code (Solar Energy Industries Association n.d.). We believe that federal tax policy for DAC is the best path for the technology to scale and gain market share. At the federal level, policy around R&D programs and tax incentives would benefit DAC. Greater R&D spending on DAC technologies can advance DAC technology efficiency to improve performance. Tax incentives for constructing and operating DAC plants can speed up DAC adoption by lowering costs. Analysis done by the Rhodium Group shows that there has been a positive correlation between technology deployment and tax support for both wind and solar technology (See **Figure 8**). (Larsen, et al. May 2019). Section 45Q of the tax code does provide tax support for DAC but only through 2024 and only for DAC units that capture at least 100,000 tons of CO2 per year. The short timeline may not be enough time for DAC to benefit from the tax support and scale like wind and solar. The minimum capture threshold must also be lowered or eliminated in order for DAC to scale like other renewable technology. For example, the production tax credit for wind does not have a minimum threshold to qualify for tax support (NC Clean Energy Technology Center 2018).

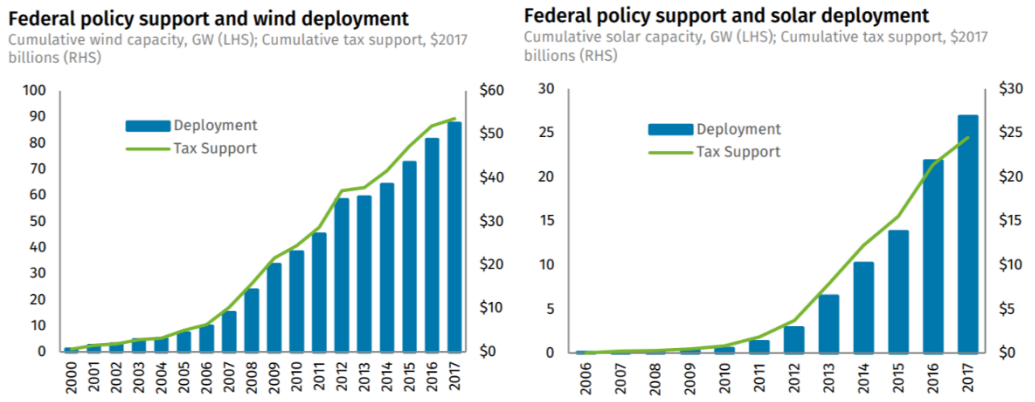

Figure 8 (Larsen, et al. May 2019)

A carbon tax in the US could also help scale DAC technology by incentivizing high CO2 polluters to pay for DAC to remove CO2 from the atmosphere. Assuming that a carbon tax would require carbon to be permanently sequestered in order to offset carbon emissions and an investor would rather pay to sequester one ton CO2 than pay a tax to emit one ton of CO2, the carbon tax would have to be between $110 and $275 to incentivize DAC investment today. This assumes DAC technology would cost between $110 and $275 per tonne of CO2 sequestered. If instead the carbon tax would allow DAC-CO2 to be used to supply CO2 markets where the CO2 used contributes emissions reductions, the carbon tax would have to be higher assuming that not all the CO2 used in these products would be permanently sequestered. Lifecycle analyses of different products that can utilize CO2 must be conducted in order to better understand the CO2 sequestration potential of these products. Regardless, given that carbon taxes around the world are averaging around $20 per tonne, this policy avenue is not realistic (Funke and Mattauch 2018).

Another policy avenue would be to set CO2 standards or guidelines in markets that have demand for CO2 and can deliver CO2 reductions. For example, California is doing this in the Buy Clean California Act which could incentivize DAC by setting lifecycle standards for construction materials procured by California's state agencies. If implemented at the federal level or adopted in other states, DAC could benefit from these policies as it creates demand for DAC derived CO2 and regulatory agencies would get desired CO2 reductions. The market potential for DAC derived CO2 utilized in construction materials is 10 MtCO2/year according to the International Energy Agency (IEA 2019).

Target Markets

DAC companies should target industries that are economical for their business and allow them to scale in order to get experience in building and operating DAC plants. This will spur innovation and drive down costs through experience. Given that current policy supports DAC derived CO2 for carbon sequestration, EOR, and transportation fuels in California, DAC companies should target these sectors now to benefit from these policies.

In 2020, CO2 utilized in EOR has a market size of 85 MtCO2/yr that is projected to increase to 92 MtCO2/year in 2025 (IEA 2019). This market is large enough and has sufficient policy support to make it an attractive primary market for DAC companies. Analysis of the revenue streams for sequestering one tonne of CO2 for two DAC plants, a high cost and low-cost plant, can be seen in **Figure 9.** Costs in the two scenarios were chosen to reflect Carbon Engineering's projected costs for their technology since they have published a thorough analysis of what it would cost their technology to capture one tonne of CO2. Revenues come from policy credits and a CO2 price. Credits from Section 45Q and LCFS can be stacked in EOR (Townsend and Havercroft 2019). The section 45Q credit of $16.8 per tonne of CO2 is derived from assuming the plant will get a $35 credit for every ton of CO2 sequestered for 12 years and then normalized over useful life of the plant which is assumed to be 25 years. For this analysis, a conservative LCFS credit price of $85 per ton of CO2 sequestered is used from projections that the Rhodium Group has provided (Larsen, et al. May 2019). LCFS prices can reach $200 per ton of CO2 sequestered which would only make the economics of EOR more attractive (California Air Resources Board 2020). Additionally, an estimated CO2 price of $21.5 is assumed (Naims 2016). With these assumptions, the breakeven point is around $120 per tonne of CO2 which makes the low-cost scenario economical. The high cost scenario is not economical under current revenue assumptions and would remain uneconomical even with a LCFS credit price of $200 per tonne of CO2.

In this EOR market, there is also additional incentive for oil and gas companies to buy CO2 produced by DAC technology. Pending a rigorous lifecycle analysis, if CO2 utilized in EOR has been captured by a DAC technology, oil and gas companies can potentially produce carbon neutral or even carbon negative oil (McGlade 2019). With this potential for a more environmentally friendly product, oil and gas companies may be willing to pay a higher price for DAC derived CO2.

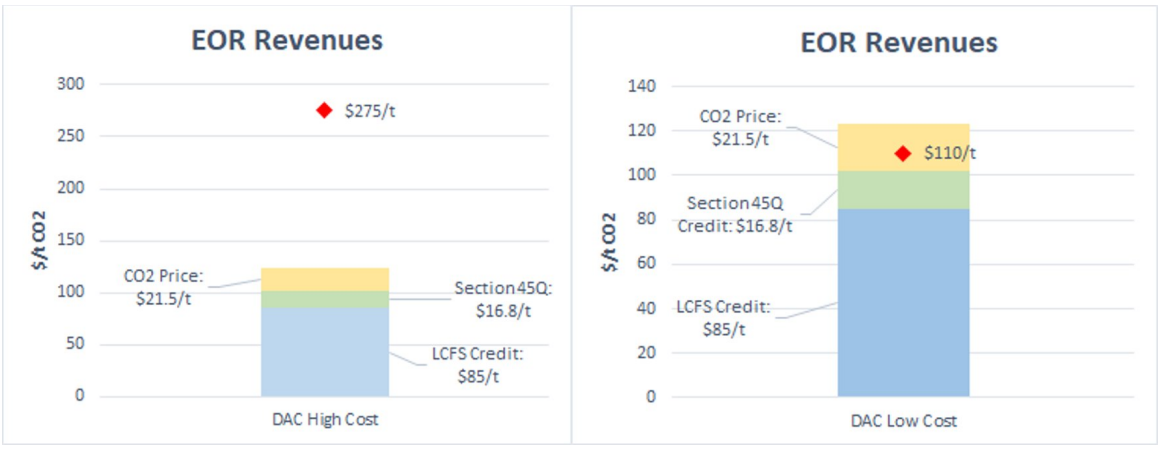

Figure 9: EOR Revenues for DAC High and Low Cost Scenarios

A secondary market that DAC companies should target, is the fuel market in California. In a similar analysis to the EOR market analysis, revenues from an LCFS credit and a CO2 price were compared in low and high technology cost scenarios for one ton of CO2. In the low-cost scenario, assuming an LCFS credit of $85 per tonne of CO2, the project is short of breaking even. With a LCFS price of $88.5 per tonne of CO2, the project would breakeven. The high cost scenario remains uneconomical regardless of LCFS price.

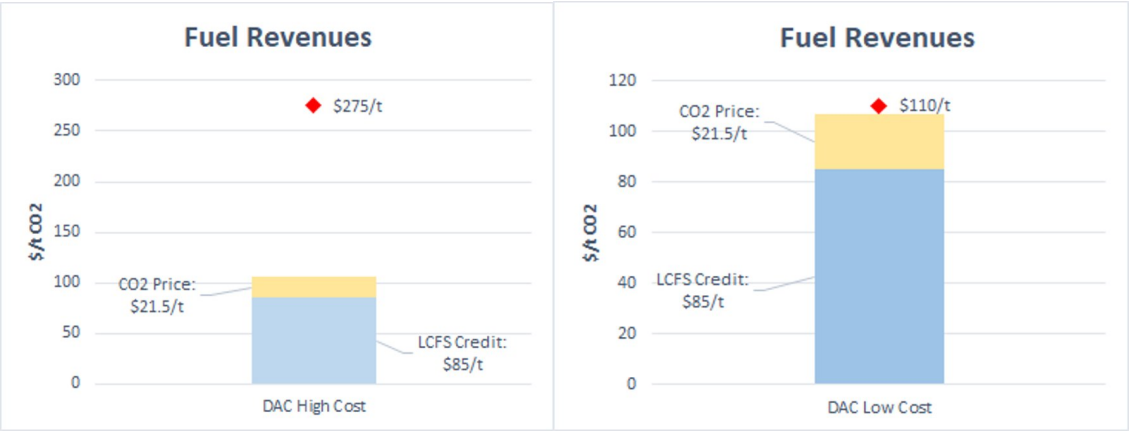

Figure 10: Fuel Revenues for DAC High and Low Cost Scenarios

Other Considerations

About 6 years ago, manufacturing of materials made up the greatest percentage of CO2 utilization over direct utilization and fuels (Naims 2016). Based on market projections, it is

possible that material manufacturing will continue to lead with fuel development overtaking direct utilization.

While capture of CO2 exhaust from coal power production provides the greatest CO2 capture at the lowest cost, this supply opportunity is quickly shrinking, leaving many cost neutral alternatives with a smaller capture rate. DAC may cost more but it is effectively the most stable supply of CO2 next to coal power exhaust, thus, a likely contender for CO2 market capture in the coming years.

Another way in which we could see growth of DAC technologies is through value-driven consumerism. In recent years, the average consumer has put increased importance on company level environmental and social stewardship. Many companies feel pressure to invest in something positive, especially those that are known for having a large environmental impact, such as airlines.

Companies like Climeworks are offering industry ways to offset their carbon production by investing in their technology. This could be considered more of a marketing ploy than a real opportunity for change and therefore less likely to have the same positive economic reaction that the growth in manufacturing using CO2 will have.

Risks

There are a number of potential risks facing DAC companies. Here we highlight those risks to be considered in further detail beyond the scope of this report. The first risk we note is that there does not appear to be any rigorous LCA analysis completed and published on DAC's markets. This needs to be done so that we can understand how much net carbon is truly removed from the air so that this impact can be articulated to consumers of the captured CO2 and so we can appropriately account for the costs of capturing one net tonne of CO2. Second, we must keep in mind that DAC requires significant energy input. If energy is not coming from renewable sources, DAC will reduce the net amount of carbon sequestered. Third, we do not know how fast market opportunities will arise and grow and whether or not these DAC companies can sustain themselves during that, potentially extended, period of time. Lastly, the economics of DAC relies heavily on policy and policy change that is yet to come.

Conclusion

The following three conditions need to be true for the economics of DAC adoption to make sense:

1. Policy must incentivize technological advancement and support technology deployment through tax incentives that better allow DAC to scale with a longer timeline and lower carbon capture thresholds.
2. Supply of CO2 from other resources, such as coal to power emissions needs to dwindle. This is a possibility because of greater efforts to reduce emissions from energy industry production.
3. Demand for use of CO2 in materials and fuels needs to increase. Per the reviewed research, there is a true opportunity for this to take place in the next 10 years.

We recommend that DAC companies take the following steps to enhance their economic opportunities:

1. Target enhanced oil recovery as a primary end-market for DAC CO2.
2. Target the methane fuel development market as a secondary end-market for DAC Co2.
3. Lobby for policy incentives that benefit DAC CO2 capture.
4. Back further research into materials development (such as polyurethane and other plastics).

Our hope is that this research will start a deeper conversation around DAC. This technology has the potential to revolutionize the way society views CO2 and greenhouse gas emissions.

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