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Research Paper

The Future of Direct Air Capture (DAC): A Cost Benefit Analysis of a Proposed DAC Plant

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Abstract
As climate change becomes an increasingly severe issue, ways of mitigating this problem have been devised. Direct air capture (DAC) is an effective approach to potentially fight against climate change by directly withdrawing carbon dioxide (CO_2) from the atmosphere. According to the Sixth Assessment Report (AR6) of Intergovernmental Panel on Climate Change (IPCC), carbon capture and storage, which includes DAC and bioenergy capture and storage, is "a critical decarbonization strategy in most mitigation pathways." [36] Current DAC technologies normally uses a contractor unit filled with chemical sorbents that can capture CO_2 molecules directly from the atmosphere. The captured CO_2 molecules can then be released through the regeneration process, which releases high purity carbon dioxide from the sorbents by heating and pressurizing the unit. The released CO_2 molecules can be utilized or stored, such as producing synthetic oil or converting to solid form for safekeeping. This study investigates the costs and benefits of a proposed DAC plant capable of capturing a million tons of CO_2 annually. An introduction of relevant DAC technology is provided, with flow charts illustrating each process. A comprehensive list of potential costs and benefits are also listed with monetary estimation, as well as the rationales behind these data. At the end is a discussion of the results drawn from the cost-benefit data, as well as a conclusion regarding the feasibility of deploying a similar plant in the US.

Keywords
Climate Change, Carbon Capture, Direct Air Capture (DAC), Global Warming, Geothermal Power, Mitigation of Climate Change, Carbon Capture and Storage (CCS), Carbon Capture and Utilization (CCU), Synthetic Direct Air Carbon Capture and Storage (SDACC), Carbon Dioxide (CO_2), Cost Benefit Analysis

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I. Introduction

Climate change is one of the most controversial and hotly debated topics globally. Countries like China, the United States, Russia, India, and Japan are the uppermost contributors to the emission of carbon dioxide, the predominant greenhouse gas that leads to climate change. For instance, China produces 27% of the world greenhouse gases, the United States produces 11%, and India produces 6.6%. The rate of CO_2 emissions globally has increased an average of 90% since the 1970s, mainly due to the increasing use of coal-based electrical generation. [1]

As a result of continuing increases in the release of carbon emissions into the atmosphere, scientists from all countries are searching for ways to mitigate carbon emissions and consequent climate change. For example, new ways of transportation like electric vehicles, the movement of utilities from coal-powered electrical plants to generating energy supply through renewable energy sources such as solar, wind, biomass, and, more recently, nuclear energy as well as transitioning industrial production facilities to implement carbon capture technologies have emerged in the recent years as potentially viable solutions. Also, numerous corporations including airlines, technology, as well as oil and gas companies are aiming to be carbon neutral in the near future. Major international corporations, including United Airlines, Microsoft, ExxonMobil, and Stripe have invested in carbon capturing technology in order to achieve their state carbon-neutral goals.

There are several types of carbon capture technologies. One of them is to install devices in a power or heat generating facility that removes carbon dioxide from ventilation systems, and either store them underground (CCS, carbon capture and storage) or use them for industrial purposes (CCU, carbon capture and utilization). Synthetic direct air carbon capture and storage (SDACCS), or simply Direct Air Capture (DAC) is another type of technology that captures and utilizes carbon dioxide. It employs chemicals to remove CO2 directly from air through a series of chemical reactions. As mentioned in a report by Mark Z. Jacobson, the Intergovernmental Panel on Climate Change (IPCC) states that ‘‘capture, utilization, and storage ’’(CCS/U) can help reduce 75–90% of global CO2 emissions and that it is ‘‘technically proven at various scale." They also identify DAC as a viable method of limiting warming to 1.5 degrees Celsius. This climate goal is essential in "reducing extreme heat waves, droughts, water stress and extreme weather." [37]

The DAC systems developed by Canadian company Carbon Engineering, Swiss firm ClimeWorks, and US-based Global Thermostat, use large fans to circulate air into the sorbents. According to International Energy Agency (IEA), there are currently 19 direct air capture (DAC) plants operating worldwide, capturing more than 0.01 Mt CO_2 /year, and a 1Mt CO_2/ year capture plant is in advanced development in the United States. [4] According to Katie Lebling and other researchers, depending on the choice of technology, "the range of costs for DAC vary between $250 and $600 per Mt CO_2 today." With the support from policies and mature of the market, the cost of DAC would decline in the next decades, presumably $100-$150 per Mt CO_2 for the next 5-10 years according to [23].

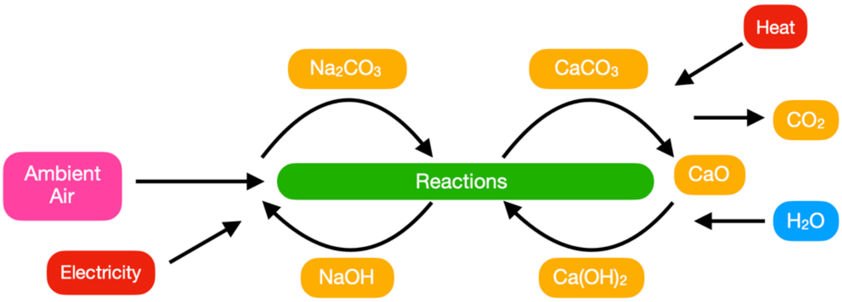

Figure 2: A Flowchart of High-Temperature Aqueous Absorption (Adopted from [18])

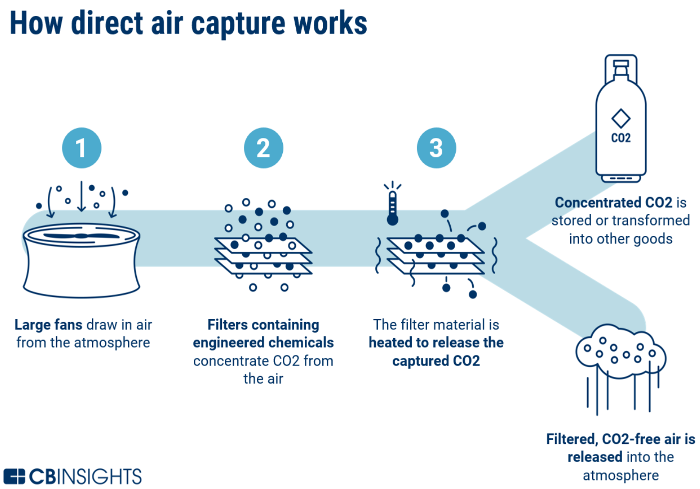

Figure 1: A Flowchart of DAC Processes from CB Insight Research [27]

This study aims to speculate the costs and benefits of establishing a direct carbon capture plant somewhere in the US that captures 1 million tons of CO_2 each year. The location is supposed to be a place with substantial CO_2 emissions, like the Houston area of Texas with a great number of oil refineries. [26]

1.1 Various Approaches to Direct Air Capture

The basic structure of a DAC module includes air intake units, filters with sorbent, and regeneration unit. The ambient air is first drawn into the air intake model, usually through a large fan. Then the air goes through the sorbent unit, in which CO_2 is being intercepted, and CO_2 free ambient air is released back to the atmosphere. For those absorbed CO_2, after the sorbent reaches its maximum capacity, a regeneration process is initiated through heating. As a result, the captured CO_2, along with water in the air, is released into a CO_2-water separation unit. Ultimately, the captured CO_2 gases is concentrated for transportation or storage, the water is released, and filters back to their normal intake pattern.

There are two major types of DAC technology. One such type is to uses a high-temperature (HT) aqueous solution. At first, ambient air is brought in contact with sodium hydroxide solution (NaOH) through air blowers or direct air flow. The CO_2 molecules within the pumped air react with NaOH, forming sodium carbonate (Na_2CO_3) (1). This process does not require any heat. This reacted liquid is then sent to the next process, known as regeneration. At here, Na_2CO_3 is mixed with calcium hydroxide ($Ca(OH)_2$), forming calcium carbonate ($CaCO_3$) and regenerating NaOH. (2) At the same time, $CaCO_3$ is warmed to 900˚ C to release CO_2, that is collected and stored or used. (3) Calcium oxide would also be released in this process, and it will later be mixed with water to regenerate $Ca(OH)_2$.(4) All of the processes mentioned above could happen simultaneously.

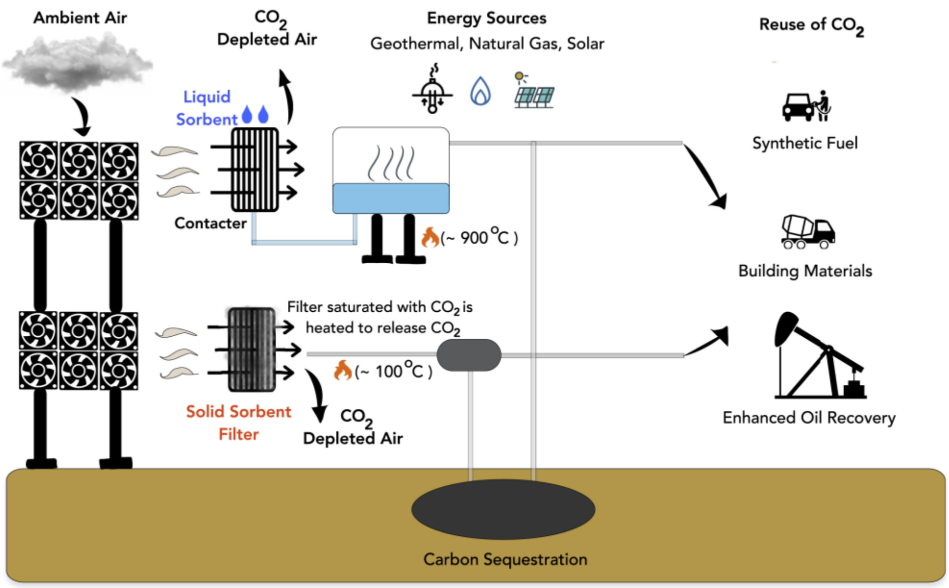

Figure 3: An Illustration of Both Liquid and Solid Sorbent Technologies
Source: [28]

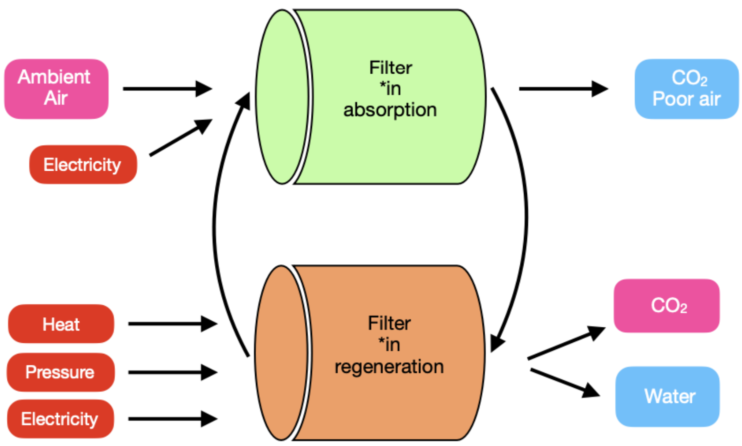

Figure 4: A Flowchart of LT Sorbent Absorption Technology
(Adopted from [18])

Formula:

(1) Absorption: $2NaOH + CO_2 \rightarrow Na_2CO_3 + H_2O$

(2) NaOH regeneration: $Na_2CO_3 + Ca(OH)_2 \rightarrow 2NaOH + CaCO_3$

(3) CO_2 release: $CaCO_3 + heat \rightarrow CaO + CO_2$

(4) $CaCO_3$ regeneration: $CaO + H_2O \rightarrow Ca(OH)_2$

This method that uses HT aqueous solution is mainly adopted by the Canadian DAC company Carbon Engineering. Though they currently deployed small plants in British Columbia, the company plans to build a new plant in Permian Basin, US, which would be capable of annual capture of 1 million tons of CO2. Nevertheless, given the high temperature demand in the regeneration process, this technique costs massive amount of energy. For example, according to an assessment from [18], even with recent technological advancements, Carbon Engineering's HT aqueous sorbent technology would generate 0.3 tons of CO_2 when capturing a ton of CO_2 (using natural gas as the power source).

Another predominant DAC technology is to use low-temperature solid sorbents. The first step is similar: facilitated by fans, ambient air is insufflated into the DAC unit with filters full of solid sorbents. These materials are usually amines, which are well known for their property of absorbing diluted CO_2 molecules. Then, CO_2 would chemically bond with the sorbent materials, and CO_2 poor air would eventually leave the system. When the filters become saturated, the regeneration process starts, while adsorption stops. The unit is heated to approximately 100° C and the pressure within the unit decreases (varies from technology). Water may also be outputted through the use of certain kind of solid sorbent technology (Climeworks).

The Swiss company Climeworks is famous for adopting LT solid sorbent technology. Their latest plant uses low-grade heat, like waste heat from nearby renewable electricity plant, and produces CO_2 of 99.9% purity. Nevertheless, a complete cycle of their system usually takes 4-6 hours. Other LT solid sorbent technology from companies like Global Thermostat reduces the cycle time to approximately 30 minutes. However, the cost is a requirement of saturated steam at sub-atmospheric pressure, which adds to the total energy costs of the overall process. [18]

Though further studies may lead to the inventions of newer sorbent or solute technologies, this study only evaluates the two predominant types of sorbent technologies. Based on the characteristics of each mentioned above, solid sorbent technology is preferred for this study. It has advantages of lower water and energy needs, potentially purer CO2 output, and minimal indirect CO2 output.

II. Table of Costs and Benefits

		Present	**10 years**	**20 years**
Cost	Land	US$745,000	—	—
	Transportation	US$115,500	US$37,500	US$15,000
	Installation of buildings (Capital Investment, capture/ storage facilities)	US$387,500,000	—	—
	Employment (Engineers, installation experts, maintenance experts, safety experts, etc.)	US$22,500,000	US$22,500,000	US$22,500,000
	Maintenance (equipments, filters, grounds, pipelines, etc.)	US$705,042,900	US$112,500,000	US$20,042,900
	Decommissioning (Recycling, Disposal, restoration of site, etc.)	US$8,500,000	US$8,500,000	US$8,500,000
	Accidents/Deaths	US$814,500	US$814,500	US$814,500
	Regulatory Compliance Cost	US$500,000	US$500,000	US$500,000
	Non-quantifiable (landscape, aesthetics, livability, congestion, etc.)	US$60,000	US$60,000	US$60,000
	Opportunity Cost	—	—	—
	Total Cost	US$1,125,777,900	US$144,912,000	US$52,432,400
Benefits	Investment capital	US$200,000,000	US$100,000,000	US$50,000,000

		Present	10 years	20 years
	Government Subsidies	US$35,000,000	US$5,625,000	US$750,000
	Revenue from customers (based on avg cost for a ton of carbon)	US$87,500,000	US$142,500,000	US$232,200,000
	Carbon Taxes Avoided (Based on the data of California)	US$34,596,000	US$56,350,000	US$91,790,000
	Fines/Penalties Avoided	TBD	TBD	TBD
	Non-quantifiable (social)	US$50,000,000	US$75,000,000	US$100,000,000
	Total Benefit	US$407,096,000	US$379,475,000	US$474,740,000
	Average Cost per ton of CO_2 captured	US$1,126	US$145	US$52
	Net Cash Flow	-US$718,681,900	US$234,563,000	US$422,307,600
	Discount Rate [38]	8%		
	Net Present Value (assume inflation rate)	-US$129,104,849	-US$361,188,019	US$108,648,054
	Cost benefit ratio (Total)	0.953		

III. Costs and Benefits explained:

3.1 Land cost:
According to the World Resources Institute [5], the land area requirement for a solid sorbent using geothermal power is 0.2 square kilometers, which is approximately 75 acres. According to Seidel [6], the average cost of rural land in Texas averaged $3,725 per acre in 2021.

According to the US Department of Energy [31], the average land use of a typical geothermal plant is around 1-8 acres per MW. Assuming the land use is 4 acres per MW, and the geothermal plant has a capacity of 25 MW, the land use is 4*30 = 120 acres.

Therefore, the land cost of the plant can be calculated by $3,725* 200 = $745,000

3.2 Transportation cost:
As approximated in the maintenance section, the efficiency of sorbents varies as relevant technology develops over time. Therefore, the need of sorbents for the three sections are:
Present: 1,000,000,000kg/130 = 7,700,000 kg = 7,700 t.
Near future (10 years later): 1,000,000,000kg/400 = 25,000,000 kg = 2,500 t
Long term (20 years later): 1,000,000,000kg/1000 = 1,000,000 kg = 1,000 t

We assume the transportation cost of the sorbent is the same with that of the coal. According to the U.S. Environmental Protection Agency, "in 2019, the average transportation cost of coal was $15.03 per ton." [9] Therefore, the costs are 7,700 t * 15 = $115,500, 2,500 t * 15 = $37,500, and 2,500 t * 15 = $15,000.

3.3 Installation cost：
According to Sigurdardottir and Rathi [12], the cost for constructing the Orca plant from the Swiss company Climeworks is US $10-15 million. This facility can capture 4000 tons CO2 each year. The facility we build for this scenario can be able to 1 million tons CO2 annually, which is 250 times of the Orca plant.
We assume the cost of our plant is 25 times that of the Orca facility because of its large scale. Therefore, the cost for construction is approximately $312,500,000. (312.5 million)

As mentioned in the land cost part, a geothermal power plant of 30 MW capacity also needs to be established. According to US Department of Energy [32], the initial cost of the geothermal plant is around $2500 per installed kW in the U.S. Therefore, the cost of the power plant can be estimated by:

$2500 * 30MW * 1000 kW = $75,000,000

And the total installation cost is:

$75,000,000 + $312,500,000 = $387,500,000

3.4 Employment cost:

According to an analysis from the Rhodium Group, "a typical direct air capture (DAC) plant requires 278 workers to maintain and operate the facility once it is constructed." [13] We assume that the requirements for DAC employees are similar to those of traditional power plants. According to Career Explorer [14], "the average salary for a power plant operator in the United States is around $80,850 per year." Therefore, the total cost would be 278* $80,850 = $22,500,000.

We also assume that the number of employees would decrease 15% in a decade as the total efficiency of the plant would increase, due to the requirement of fewer raw materials required for future operations. Nevertheless, the increase in efficiency also comes with salary increases over time, a similar 15%. Therefore, the costs for the near future and long term remain unchanged, which is $22,500,000 for both time periods.

3.5 Maintenance cost:

For sorbents, according to Husk and Wenz [7], "the current sorbent technologies capture around 130 kg CO_2 captured/kg sorbent over its useful life." For the near future, as related technology develops, sorbent efficiency will also be improved. Therefore, "anywhere between 220 and 580 kg CO2 captured/kg sorbent material in its useable lifetime." [7] Taking the mean value between the two numbers, we assume 400 kg of CO2 can be captured per kilogram of sorbent. For the long term, Husk and Wenz [7] assumed that over 1,000 kg CO2 can be captured per sorbent. The cost for each kg of sorbent is ranging from $15 to $100. [8] We assume that cost for the present is $90/kg, $45/kg for the near future, and $20 for the long term.

Therefore, the cost of sorbents can be approximated by:
Present: $90*1,000,000,000kg/130 = $700,000,000 = $700/ton CO2
Near future: $45*1,000,000,000kg/400 = $112,500,000 = $113/ton CO2
Long term: $15*1,000,000,000kg/1000 = $15,000,000 = $15/ton CO2

Because there is no information related to the costs of maintaining facilities within the facility, we assume that 0.1% of the installation cost is spent annually for maintenance of the units.
$312,500,000 * 0.1% = $312,500

For electricity costs, since solid sorbent, which only requires approximately 100 degrees Celsius heat, is assumed to be used in this facility; moreover, waste heat the geothermal power plant can be utilized. According to Mahdi Fasihi and other researchers [18], for two kinds of solid sorbent DAC technologies, their average electricity usage is ranged between 160-300 kWh per ton of CO_2 captured, mainly for facilities like circulating fans and air pumps. Taking the mean value, the usage of 230 kWh per ton of CO_2 is assumed. For the 1 million capacity, the total annual electricity usage is:

230 * 1,000,000 = 230,000,000 kWh = 230,000 MWh

The electricity usage for office areas is also considered: 25,000 kWh of power is assumed to be used each year. (equivalent to a medium business according to [10]) Thus, the total electricity demand is:

230,000,000 kWh + 25,000 kWh = 230,025,000 kWh = 230,025 MWh.

Since the geothermal plant has a capacity of 30 MW, along with a 90% efficiency according to US Department of Energy [32], its electricity output can be calculated by:

30MW * 24 * 365 * 0.9 = 236,520 MWh

With a operating and maintaining cost of $0.02 per kWh[32], the total annual operating cost for electricity plant is:

236,520 MWh * 1,000 * $0.02 = $4,730,400

For water cost, as mentioned by Mahdi Fasihi and other researchers [18], solid DAC systems usually do not require water input. They might even output water during the regeneration process. Therefore, there is only little or no cost of water, and we will not provide a value for this potential cost.

With all information mentioned above, the total maintenance costs are:
Present: $700,000,000 + $4,730,400 + $312,500 = $705,042,900
10 years: $112,500,000 + $4,730,400 + $312,500 = $117,542,900
20 years: $15,000,000 + $4,730,400 + $312,500 = $20,042,900

3.6 Decommissioning cost:
According to [15], the average cost for transporting and storing CO2 in countries like the US can be assumed by $10 per ton. Assuming that 35% of the CO2 captured can be sold as food-grade, 50% of them stored, and the rest 15% would loss during the processes of converting/transporting. Therefore, the cost for transportation and storage of CO2 is estimated to be approximately $8,500,000.

3.7 Accidents/Deaths
A common way of estimating the costs of accidents is buying the workers' compensation insurances. According to Kimberlee Leonard [25], the price can be calculated by the formula to determine business premium base costs:

Premium = (Payroll / $100) x classification code rate x experience modification rate (EMR)

Because there is no specific code designated for direct air capture, in order to get the number, we use the code for a similar industry. According to [24], the classification code 4635 "is assigned to the manufacture and storage of carbonic acid gas and carbon dioxide, including the manufacture of dry ice." For 4636, the rate per $100 of Renumeration is $3.62[24].

The experience modification rate (EMR) is a number based on a company's claim history. [25] Since DAC is a new industry with no accident records, we assume EMR is 1 in this calculation.

As mentioned in Employment Cost section, the annual employment costs are $22,500,000 for all terms. Therefore, the total annual premium is ($22,500,000/100) * $3.62 * 1 = $814,500

Since there is no data related to accident rate of DAC plants, the cost of compensation for individual worker is left to be determined.

3.8 Regulatory Compliance Cost:
Based on insufficient information, this cost is recognized as To Be Determined. We assume that the government and related authorities would support carbon capture and environmental protective businesses, so the costs of regulatory costs is relatively low.

In our case, we assume the regulatory compliance cost for two regulatory experts and associated reporting costs to federal and state agencies totals $500,000 per annum.

3.9 Non-quantifiable (landscape, aesthetics, and livability):
For these costs, we assume that the outlook of the facility would decrease the land value of surrounding areas (50% of the area of the plant) by 50%. Since the area for this facility is approximately 75 acres, so the surrounding area would be 38 acres, and the decreased value is $3,160*38/2 = $60,000.

For livability costs especially, since the plant would likely be located in somewhere with little population, this aspect is not specifically accessed.

3.10 Opportunity Cost:
A nuclear power plant could be an alternative to our DAC facility, in which nuclear energy reduces CO2 emission significantly. In fact, according to World Nuclear Association[29], a nuclear plant doesn't generate any CO_2 during its operation, and its total emission is equivalent to 12g per kilowatt hour, only 1.46% compared to that of coal plants and 2.45% of compared to that of natural gas plants. However, a new nuclear power plant has significant construction and operating costs, including the costs of emergency shutdowns.

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The opportunity cost question is what are the total carbon emissions avoided through the building of a new nuclear plant (of a specific size and generating capacity) and what those total benefits are valued at versus the costs of building and operating a new nuclear power plant over the same time period.

According to a study from synapse energy[30], the total cost of construction is between $6 billion and $9 billion for each 1,100 MW nuclear power plant. The amount of carbon emission reduced when compared with a traditional coal plant can be calculated by:
1,100,000 KWh * 12g / 1.46% / 1,000 = 904,109 tons

This amount is approximately equivalent to 1 million tons. Given that the total cost of this DAC plant for the present is approximately 1 billion dollars, the cost of this nuclear plant is significantly higher. Furthermore, the estimation of 6-9 billion dollars is from a 2008 study [30], and the cost for nuclear power plant in the present remarkably increased.

Therefore, we can conclude that there is not a significant opportunity cost in constructing this particular DAC project relative to investing in a new Nuclear Power Plant that provides benefits in terms of avoided carbon atmospheric emissions.

3.11 Investments:
According to Erin E. Smith [16], both Climeworks and Carbon Engineering received over $100 million in investments from government and the private sector. Since this hypothetical plant can process over 1 Million tonnes of CO2, we assume that the investment is doubled. As time goes, the investments would be 50% and 25% as compared to the initial years.

3.12 Government Subsidies:
Governments around the world is heavily investing into DAC for curbing climate change. For example, the US Department of Energy(DOE) announced a subsidy plan of DAC of $3.5 billion[33]. Nevertheless, there is no plan for specific plants, because all government announcements are relatively general at this early stage. Therefore, we assume that 5% of the sorbent cost will be subsidized for all of the three terms because of the declining price trends.

Present: $700,000,000*0.05 = $35,000,000
10 years: $112,500,000*0.05 = $5,625,000
20 years: $15,000,000*0.05 = $750,000

3.13 Carbon Taxes Avoided:
Beyond the 1 million tons saved by direct air capturing, the geothermal electricity module would also save CO_2 emissions. This can be calculated by using the relative reduction when compared with an alternative power source— natural gas in this situation. According to [28], the average gCO_2 emission from geothermal plants is 38 gCO_2 per kWh, which is 7.76% of that of a natural gas plant. Therefore, the amount of reduced emission saved by the integrated geothermal power plant can be calculated by:
236,520,000 kWh * 38g / 7.76% / 1000 = 116,000 ton
Because there is no definite carbon price for the United States as a whole, we calculate this price using California's rate. According to world bank, as of April 1, 2022, the price of a metric ton of carbon is US$31. [17] The source also mentions that its price would rise 5% annually plus inflation. Leaving inflation for the overall discount rate part, the carbon taxes avoided are:
Present: $31* (1 million + 116,000) = $34,596,000.
10 years: $31 * (1.05^10) * (1 million + 116,000) = approximately $56,350,000.
20 years: $31 * (1.05^20) * (1 million + 116,000) = approximately $91,790,000.

3.14 Revenue from customers:
There are a variety of ways that carbon dioxide can be sold and utilized. According to [19], a ton of food-grade CO2 costs €80-150 per ton back to 2015. Given that the cost of CO2 is rising in recent years[20], we suppose that a ton of food-grade CO2 currently costs $250. Since the DAC plant would produce 99.9% purity CO2, and FDA's food CO2 requirement is the same[21], the captured CO2 can be directly sold to, for example, companies producing carbonated beverages. Assuming that 35% of the total CO2 production can be sold to beverage factories nearby, and the cost of transportation is added to the decommissioning, around $87,500,000 can be collected

annually. For the future, we assume the cost would rise 5% annually plus inflation (to be calculated later). Therefore, the revenues for 10 years and 20 years later are approximately $142,500,000, and $232,200,000 respectively.

3.15 Non-quantifiable benefit:
The most obvious non-quantifiable benefit from DAC is its overall help for protecting the world environment. As used by a number of researchers, social cost is an appropriate measure for this non-quantifiable improvement. According to [22], a report from the Environmental Defense Fund, "The current central estimate of the social cost of carbon is over $50 per ton in today's dollars." They also mentioned that this is an underestimate of the per ton social costs. We use $50 for benefits in the present, $75 and $100 for the future as the world gets warmer. Therefore, for now the total non-quantifiable benefit is $50,000,000, $75,000,000 and $1,000,000,000 for the future, respectively.

3.16 Cost Benefit Ratio (CBR)
Cost benefit ratio is a numerical indicator of the relationship between the cost and the benefit of a project. It is calculated by dividing the sum of expected benefits from the project and the expected costs of the project. If the value is greater than 1 (or 1.33 from another source), the project is likely to be profitable, vice versa. [39]

Generally speaking, to move forward with a project, the CBR should be close to 1.33. The CBR for this specific project, however, is only 0.953, which is below 1 and 1.33. While this project has estimated costs higher than expected benefits; nevertheless, 0.953 is very close to 1. Therefore, it is foreseeable that the project eventually will break-even or more, especially with the likelihood of escalating negative climate conditions, the growing availability of additional government subsidies, private investments in more efficient carbon capture technology, and significantly increasing carbon taxes.

IV. Discussion

This cost-benefit study used a combination of data from similar projects and hypothetical data to determine the costs and benefits of different aspects of the project.

The costs for building and operating a DAC plant in the present are high. Consequently, the cost-benefit ratio is calculated as below 1, which signifies that the project might provide benefits that exceed costs.

The net present value is also estimated as negative for the present and near future (10 years). The total cost, which includes construction and operating costs, is approximately 1 billion for the present. The average cost of each ton CO_2 captured is estimated as $1125. According to Hiyori Yoshida [35], the cost for capturing a ton of CO_2 using Climeworks' plant is around $600-$800, which is relatively close to the estimation used in this study. Moreover, this cost could remarkably decline as time goes— to $144 for the near future and $52 for the long future— which is in accordance with estimations from other sources.

As shown in the figure below, the primary cost of this proposed DAC plant is on maintenance, which consists of 63% for the present, and 78% for the 10 years term. This extremely high cost is due to the low efficiency of the sorbents. However, as the efficiency and costs of sorbent decrease due to technological improvements, this cost will remarkably drop.

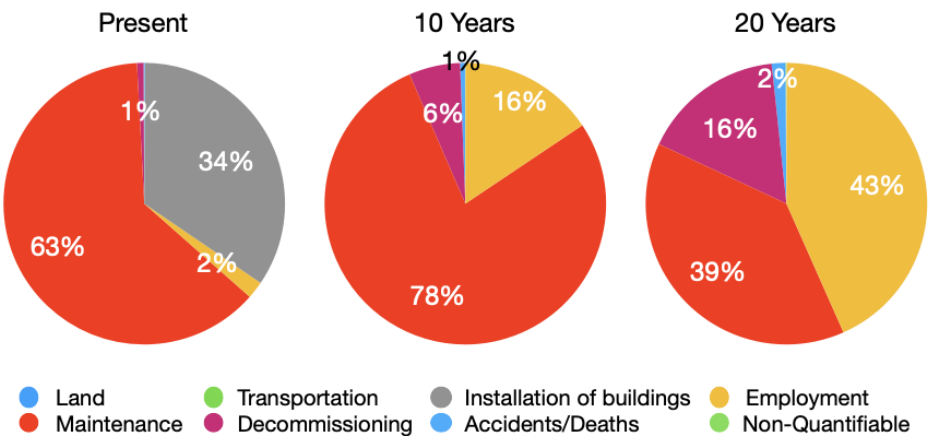

Figure 5: Cost Distribution of the Proposed DAC Plant— 3 Periods

As shown below, the benefits also show divergence over time. Investment capital played an important role in the benefits of the project, which consists of half the income for the present. As time goes, the amount of investments may decline, and this contributed to the change. The portion of revenue from customers and carbon taxes also becomes larger over time.

It is also important to note that this analysis uses an annual carbon tax increase of 5% for calculations . For example, an article from Carbon Market Watch [34] mentioned that "increase of around 130% over prices in early 2021, and more than a 200% increase since early 2020." As a result, the revenue from selling carbon credits might be significantly higher than the estimated (which assumes 5% annual increase.)

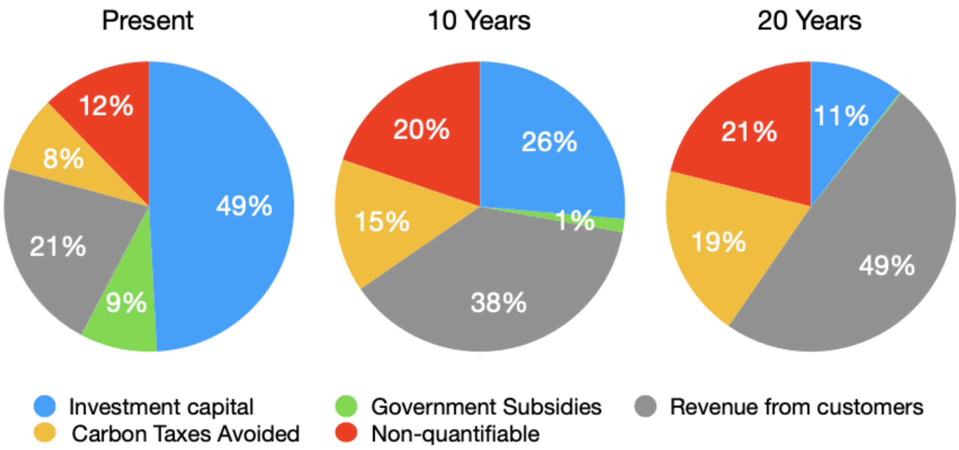

Figure 6: Benefit Distribution of the Proposed DAC Plant— 3 Periods

Another way to address the problem of high cost might be deploying a smaller scale plant. As mentioned in the cost-benefit explanation section, as relevant technological innovations occur, sorbent efficiency will also be improved. This means that while achieving the goal of capturing 1 million tons CO2 in the near future, sorbent costs of the present term can be reduced through deploying less sorbent materials and carbon capturing units.

V. Conclusion

In conclusion, this study is a comprehensive cost-benefit analysis(CBA) of the emerging technology that manages climate change— direct air capture (DAC). A suppositional DAC plant, located somewhere in the US, that is capable of capturing 1 million metric tons of CO_2 is the basis of this study. The plant uses electricity and heat from its integrated geothermal power plant, cutting down its emission to free. A broad list of all potential aspects of costs and benefits are listed, with monetary estimations based on both existent and proposed data. The rationales behind all numbers listed are also listed in the explanation part under the cost-analysis table, with detailed explanations and calculation processes.

The result of this study is that this type of DAC plant has costs higher than its calculated benefits, with a cost benefit ratio (CBR) of 0.953. This means that the plant is a marginally beneficial investment, given a long period of 30 years incorporated in this CBA.

The plant would cost enormous amount of money to build and operate, especially in the present or near future, where both construction costs and material costs are huge— a billion US dollars to build and operate in the present. Nevertheless, the CBR value 0.953 is extremely close to 1.00 (or 1.33), which means that the plant is not far away from break-even. As stated above, it would recover costs with more government subsidies, investments, and higher returns from selling carbon credits.

It is also important to notice that this study is evaluating a highly immature industry. The DAC technology is still experimental, with only a handful carbon capture facilities actually operating, where they only capture limited amount of CO_2. Because of this, as more DAC plants start to operate, additional relevant data, including construction costs, operating costs, maintenance costs, and overall operating efficiency will become available. New data will enable CBA to be more accurate in its estimates of costs and benefits from DAC technology.

Furthermore, non-quantifiable costs or benefits such as landscape aesthetics and health cannot be easily estimated. The impacts bought on these aspects are more subtle and indirect. The project is certainly beneficial to the country or the world as a whole, for its effect of mitigating climate warming caused by greenhouse gases, but no monetary benefits can be concluded from this.

Overall, this study is successful at providing an approximate estimation of costs and benefits of the proposed direct air capture plant, though with a relatively large margin of error. This study is beneficial for potential decision makers or investigators interested in learning about the latency of deploying a DAC plant for directly extracting CO_2 from the atmosphere.

As DAC technology develops, or even new kinds of them invents, it is foreseeable that deploying a DAC plant would be break-even or so far as to be profitable. DAC is an obvious future technological trend on managing climate change, with great potential due to its immediacy at limiting CO_2.

Bibliography

[1]. International Energy Agency. (2022, March 8). Global CO2 emissions rebounded to their highest level in history in 2021 - News. IEA. Retrieved August 8, 2022, from https://www.iea.org/news/global-co2-emissions-rebounded-to-their-highest-level-in-history-in-2021

[2]. Jacobson, M. Z. (2019). The health and climate impacts of carbon capture and direct air capture. Energy & Environmental Science, 12(12), 3567-3574

[3]. Gambhir, A., & Tavoni, M. (2019). Direct air carbon capture and sequestration: how it works and how it could contribute to climate-change mitigation. One Earth, 1(4), 405-409.

[4]. Budinis, S. (2021, November). Direct Air Capture – Analysis. IEA. Retrieved August 8, 2022, from https://www.iea.org/reports/direct-air-capture

[5]. World Resources Institute. (2021, February 3). Direct Air Capture: Resource Considerations and Costs for Carbon Removal. Impakter. Retrieved August 10, 2022, from https://impakter.com/direct-air-capture-resource-considerations-and-costs-for-carbon-removal/

[6]. Seidel, S. (2022, February 3). How Much Does an Acre of Land Cost in Texas in 2022? Southern Green Builders. Retrieved August 11, 2022, from https://info.southerngreenbuilders.com/blog/acre-of-land-cost-in-texas

[7]. Husk, J. C. (2022). Inside-Out: Driving Down Direct Air Capture Costs With High-Efficiency Adsorbents. Frontiers. Retrieved August 11, 2022, from https://www.frontiersin.org/articles/10.3389/fclim.2021.787500/full

[8]. Sinha, A., & Realff, M. J. (2019). A parametric study of the techno-economics of direct CO2 air capture systems using solid adsorbents. AIChE Journal, 65(7), e16607.

[9]. West, B. (2020, May 12). Coal transportation rates in the United States decreased for the fifth consecutive year. EIA. Retrieved August 12, 2022, from https://www.eia.gov/todayinenergy/detail.php?id=43695

[10]. Money Supermarket. (n.d.). Business Energy Bills. Retrieved August 12, 2022, from https://www.moneysupermarket.com/gas-and-electricity/business-energy/a/business-gas-electricity-average-bills/

[11]. EnergyBot. (2020, June 8). Electricity and Energy Rates By State. Retrieved August 8, 2022, from https://www.energybot.com/electricity-rates-by-state.html

[12]. Sigurdardottir, R., & Rathi, A. (2021, September 8). World's Largest Carbon-Sucking Plant Starts Making Tiny Dent in Emissions. Bloomburg. Retrieved August 8, 2022, from https://www.bloomberg.com/tosv2.html?vid=&uuid=7526e055-2c5a-11ed-b086-717359644f5a&url=L25ld3MvZmVhdHVyZXMvMjAyMS0wOS0wOC9pbnNpZGUtdGhlLXdvcmxkLXMtbGFyZ2VzdC1kaXJlY3QtY2FyYm9uLWNhcHR1cmUtcGxhbnQ=

[13]. Larsen, J., Herndon, W., & Hiltbrand, G. (2020). Capturing New Jobs: The Employment Opportunities Associated with Scale-Up of Direct Air Capture (DAC) Technology in the US. Rhodium Group, available at.

[14]. https://www.careerexplorer.com/careers/power-plant-operator/salary/

[15]. Smith, E., Morris, J., Kheshgi, H., Teletzke, G., Herzog, H., & Paltsev, S. (2021). The cost of CO2 transport and storage in global integrated assessment modeling. International Journal of Greenhouse Gas Control, 109, 103367.

[16]. International Energy Forum. (2022, June 13). Major Investors Back "Direct Air Capture" CO2 Technology. https://www.ief.org/news/major-investors-back-direct-air-capture-co2-technology

[17]. World Bank. (n.d.). Carbon Pricing Dashboard | Up-to-date overview of carbon pricing initiatives. https://carbonpricingdashboard.worldbank.org/map_data

[18]. Fasihi, M., Efimova, O., & Breyer, C. (2019). Techno-economic assessment of CO2 direct air capture plants. Journal of cleaner production, 224, 957-980.

[19]. https://www.sintef.no/globalassets/project/cemcap2/12112017-fact-sheet-co2-food.pdf

[20]. Faulconbridge, G., Holton, K., & Davey, J. (2021, September 22). Britain tells its food industry to prepare for CO2 price shock. Reuters. https://www.reuters.com/world/uk/uk-pay-tens-millions-get-carbon-dioxide-pumping-again-2021-09-22/

[21]. CO2 METER. (2019, October 6). Why the Grade of CO2 Gas you are Using is Important. https://www.co2meter.com/blogs/news/co2-purity-grade-oxygen-purity-grade-charts

[22]. Environmental Defense Fund. (n.d.). The true cost of carbon pollution. https://www.edf.org/true-cost-carbon-pollution

[23]. Lebling, K. (2022, May 2). 6 Things to Know About Direct Air Capture. World Resources Institute. https://www.wri.org/insights/direct-air-capture-resource-considerations-and-costs-carbon-removal

[24]. https://www.workcompassociates.com/class-codes/4635

[25]. Leonard, K. (2022, January 4). Texas Workers ’Compensation: Laws, Costs & Providers. Fit Small Business. https://fitsmallbusiness.com/texas-workers-compensation-insurance/

[26]. Grist. (2021, April 30). This machine in Texas could suck up companies ’carbon emissions — if they pay. https://grist.org/technology/this-machine-in-texas-could-suck-up-companies-carbon-emissions-if-they-pay/

[27]. CB Insights. (2021, August 13). Direct Air Capture Explained: The Buzzy New Carbon Reduction Tech Gaining Exec Attention. CB Insights Research. https://www.cbinsights.com/research/direct-air-capture-corporate-carbon-reduction/

[28]. Ozkan, M., Nayak, S. P., Ruiz, A. D., & Jiang, W. (2022). Current status and pillars of direct air capture technologies. Iscience, 103990.

[29]. World Nuclear Association. (n.d.). Nuclear energy and climate change - World Nuclear Association. https://world-nuclear.org/nuclear-essentials/how-can-nuclear-combat-climate-change.aspx

[30]. https://www.synapse-energy.com/sites/default/files/SynapsePaper.2008-07.0.Nuclear-Plant-Construction-Costs.A0022_0.pdf

[31]. Geothermal Technologies Office. (n.d.). Geothermal Power Plants — Minimizing Land Use and Impact. Energy.Gov. https://www.energy.gov/eere/geothermal/geothermal-power-plants-minimizing-land-use-and-impact

[32]. GEOTHERMAL TECHNOLOGIES OFFICE. (n.d.). Geothermal FAQs. Energy.Gov. https://www.energy.gov/eere/geothermal/geothermal-faqs

[33]. Segal, M. (2022, May 20). DOE Launches $3.5 Billion Direct Air Carbon Capture Program. ESG Today. https://www.esgtoday.com/doe-launches-3-5-billion-direct-air-carbon-capture-program/

[34]. Ruggiero, A. (2022, March 2). Higher carbon prices: Is speculation truly to blame? Carbon Market Watch. https://carbonmarketwatch.org/2022/03/02/higher-carbon-prices-is-speculation-truly-to-blame/

[35]. Baptie, Z. L. (2021, September 13). Direct Air Capture: Costs, Benefits, and the Future. Risk Management and Decision Processes Center. https://riskcenter.wharton.upenn.edu/lab-notes/directaircapture/

[36]. de Coninck, H., Revi, A., Babiker, M., Bertoldi, P., Buckeridge, M., Cartwright, A., ... & Sugiyama, T. (2018). Strengthening and implementing the global response. In Global warming of 1.5 C: Summary for policy makers (pp. 313-443). IPCC-The Intergovernmental Panel on Climate Change.

[37]. Fendt, L. (2021, June 22). Why did the IPCC choose 2° C as the goal for limiting global warming? MIT Climate Portal. https://climate.mit.edu/ask-mit/why-did-ipcc-choose-2deg-c-goal-limiting-global-warming

[38]. Ori, J. (2019, August 8). The Cap Rate and Discount Rate. GlobeSt. https://www.globest.com/2019/08/08/the-cap-rate-and-discount-rate/?slreturn=20220803101545

[39]. Hayes, A. (2022, March 29). How the Benefit-Cost Ratio (BCR) Works. Investopedia. https://www.investopedia.com/terms/b/bcr.asp