Redesigning Direct Air Capture using Renewable Energy

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Abstract

With the increasing global threat of climate change, the world is very seriously looking into rapid solutions to the problem. Among the major identified solutions—increase in energy efficiency, development of renewables and the development of carbon capture and storage/utilization technologies, the case of Direct Air Capture, is relatively new and needs much research. Being a technology that's still in its early stage, the cost of this technology is still very high but given the urgency of climate change, this needs to be corrected and brought down to easily deployable levels. Thus, this research looks to explore simple solutions to decrease the running cost of Direct Air Capture by using renewable energy. Using the reference as the Direct Air Capture plant of Carbon Engineering, this research proposes the replacement of the contactor fans and the calciner (the most energy-intensive parts of the process) with a solar updraft tower and a solar power tower respectively, to show that ideally, 0.219 GJ energy could be saved in the air contactors, and a maximum value of 4.05 GJ energy could be saved in the calciner, thus leading to an economically much viable process for Direct Air Capture.

***Key words** – climate change, direct air capture (DAC), carbon dioxide*

Introduction

Carbon Dioxide plays a significant role in the heat budget of the atmosphere (Hole, n.d.) (Fasihi, Efimova, & Breyer, 2019; Hole, n.d.). Since the very beginning of the planet, Carbon Dioxide and GHGs in general, have played a vital role in maintaining the temperature in the planet, thus keeping it habitable. But, with the increase in human intervention into natural process and cycles, and rapid burning of large quantities of fossil fuel, the level of CO_2 in our atmosphere has greatly increased, reaching dangerous levels. The planet has always regulated the balance of carbon dioxide in the atmosphere through natural sources and sinks like forests, surface, intermediate and deep waters of water bodies (Hole, n.d.). The ocean too, has always greatly buffered the immediate consequences of the rise in Carbon Dioxide levels, by acting as a huge sink. The level of Carbon Dioxide in the atmosphere today cannot be balanced merely by natural bodies. Thus, a method needs to be devised to bring the concentration of these GHGs in the atmosphere back to normal, to prevent any permanent damage from taking place.

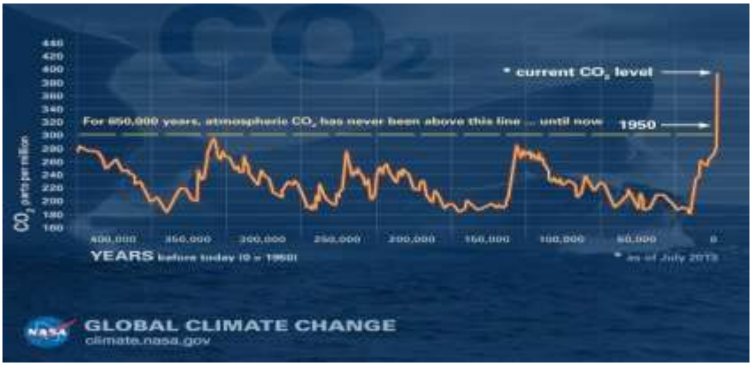


Fig. 1. Levels of CO_2 in the atmosphere (“Climate Change,” n.d.)

The recent data for concentration of CO_2 in the atmosphere reads 408.55ppm for September 2019 (“Earth’s CO2 Home Page,” n.d.). This concentration used to be around 280ppm for the pre-industrial era. Just comparing this data to the corresponding data in the previous year shows that September 2018 had a concentration of 405.59 ppm CO_2 in the atmosphere (“Earth’s CO_2 Home Page,” n.d.). This pace of increase of carbon concentration in our atmosphere is alarming.

Objectives of the Study

The purpose of this study was to explore and determine ways by which the current cost of direct air capture can be brought down. The research was performed with the objective of redesigning the existing general layout of Direct Air Capture used in Carbon Engineering using renewable source of energy, to investigate how the cost of direct air capture could be brought down.

Review of Literature

The Paris agreement aims to mitigate the effects of climate change by keeping the global rise in temperature well below 2°C and preferably even 1.5°C compared to pre-industrial era through the united effort of all the countries. To achieve this goal, the following three pillars have been set [4]:

1. Increase in energy efficiency
2. Increase in the use of low and zero-carbon sources of energy
3. Carbon capture and secure storage

Though the first two solutions to climate change have always been highly researched and worked upon (energy efficiency has always been prioritized, and the research and development of renewable sources of energy is at an all-time high); still, research into Carbon Capture and Utilization/ Storage is at a very young stage with only very few companies having recently started capturing CO_2 from the atmosphere in a large, commercial scale. Besides these companies, many have proposed novel and innovative solutions to capturing carbon from all their fields, but almost all of these remain only functional in laboratories or small demonstrative models, at max.

Even in the case of development of low and zero-carbon alternatives to fossil fuels, the development of the following key media is necessary (Jiang, Xiao, Kuznetsov, & Edwards, 2010):

1. Electric (battery) (This will require the upstream source of energy to be decarbonized first. Batteries are also further limited by their low net gravimetric and volumetric energy densities.)
2. Development of hydrogen combustion (Hydrogen, although ranking higher than batteries, is unlikely to compete with carbonaceous fuels.) Further, both these will require fundamental large-scale changes in energy infrastructure.
3. Biofuels (There are forecasts indicating a biomass limit, and biomass only will not be remotely enough in meeting the exceptional demands of transportation fuels.)

Reports like these conclude with the conversion of CO_2 back to carbonaceous fuels to be the only sustainable solution going forwards, highlighting even more the importance of carbon capture to keep the cycle going.

The capture of Carbon Dioxide from flue gas sources and exhausts is divided into the following three processes (Jiang et al., 2010):

1. Post-combustion capture
2. Pre-combustion capture
3. Oxy-fuel combustion

These three processes have varying degrees of efficiencies in the removal of CO_2 from exhaust gas streams. The average efficiencies of carbon capture in plants range from 50-94% (Leeson, Fennell, Shah, Petit, & Dowell, 2017). Further, the emissions from long distance transport like airplanes and other means of transportation like the millions of cars in streets all over the world cannot be captured using such devices (Fasihi et al., 2019). The use of conventional CO_2 capture technologies for the capture of emissions from small, widely distributed emitters like the transport sector, which in total account for 50% of the GHGs in the atmosphere, is near to impossible (Seipp, Williams, Kidder, & Custelcean, 2017). These facts thus substantiate the need of a CO_2 capture solution that capture CO_2 independent of location and origin.

Direct Air Capture

Direct air capture (DAC) is a branch of technologies developed to capture CO_2 from air (Isobe et al., n.d.). Compared to capturing CO_2 from flue gases and exhaust streams, capturing CO_2 from air directly is thermodynamically unfavorable. Thus, to make DAC feasible, the energy requirements must be minimized and the corresponding carbon capture maximized (Isobe et al., n.d.).

Although plants alone have sustained this operation for centuries, the increasing anthropogenic emissions is now too much for the plants to take in (Goeppert, Czaun, Surya Prakash, & Olah, 2012). Biologically, these measures can be enhanced through the increase in activities like afforestation and BECCS, but these pose the problem of taking up too much land and food, and other enhanced biological methods like ocean fertilization and enhanced weathering can greatly bring out adverse side effects like changing ocean pH and altering its chemistry (Kohler, Hartmann, & Wolf-Gladrow, 2010; Smith et al., 2016). Other BECCS options include biochar, soil carbon sequestration, etc., that can be applied to a whole portfolio of NETs for effective climate change mitigation (Fuss et al., 2018; Minx et al., 2018).

The first artificial application of capturing CO_2 from the ambient air was introduced in the 1930s for cryogenic applications, after which it was further adopted into manned closed systems such as submarines and space stations (Schellnhuber, 2011). These systems dated back to 1965, were not regeneratable, however (Isobe et al., n.d.).

Due to the very dilute concentration of CO_2 in the atmosphere (400ppm), chemical sorbents with strong binding characteristics became widely discussed and researched. An aqueous solution of strong bases like Sodium Hydroxide and Potassium Hydroxide is used in PSCC technologies and researchers are now investigating its applicability to DAC technologies. An analysis was carried out for the physical and economic limits for BECCS and aqueous sorbent DAC, and it was concluded that the second option was more feasible in the long term (Keith, Ha-Duong, & Stolaroff, 2006). However, the requirement for high-grade (900°C) heat for aqueous solution-based DAC could increase the costs and require a dedicated source for heat, instead of just being able to utilize waste heat (Fasihi et al., 2019). Many researches have worked on improving this system through steps like minimization of energy usage in the air contactor, modifications in contactor packing, etc. (Stolaroff, Keith, & Lowry, 2008). After many theoretical and experimental research in the field in the field of chemical and process engineering, reference (Keith, Holmes, St. Angelo, & Heidel, 2018) provided for the first time, a technical paper for a plant for capture of 1Mt CO_2/year using potassium hydroxide (KOH) based on a real pilot plant.

There have also been many researches in the field of carbon capture using solid absorbents and adsorbents, employing processes like TSA and MSA for capture and more efficient regeneration of the sorbent material requiring low-grade heat that can be more easily available (“About Global Thermostat,” n.d.; Kulkarni & Sholl, 2012; Sinha, Darunte, Jones, Realff, & Kawajiri, 2017).

More radical methods have also been suggested for DAC. There have been solutions suggesting electrochemical capture of CO_2 (Eisaman et al., n.d.) and then solutions introducing novel nanofilter materials that can capture CO_2 from the atmosphere at costs as low as around 18USD per ton CO_2 captured. The many solutions brought forward in solving this global crisis also range from biological mutants for accelerated carbon uptake in green plants (e.g, mutations in Rubisco), to catalysis of hydroxylation and solvation into the ocean, to even using aerosols to block out the sun, preventing the amount of radiation entering the planet in the first place. Now while all of them may not seem feasible at a large scale and only be limited as theoretically feasible solutions, many do hold large potential in solving the planet’s carbon crisis. The return of the planet to its natural condition is not possible without the collective action of all these remedies. Artificial processes like catalytic conversion of CO_2 into all valuable higher alcohols, via a process run at low temperature in the liquid state are promising if the required energy can be derived directly from the sun by having the catalyst supported on a photoactive carrier such as titanium dioxide. Furthermore, many sorbents like Dimethyl ester of polyethylene glycol, cold methanol, MEA, DEA, MDEA, ammonia, Hot potassium carbonate etc. have also been well-researched for the purpose.

Still, most carbon capture options are expensive and energy intensive, thus causing them to be unusable. The reason why capturing CO_2 from the atmosphere is so difficult is that it is chemically inert (Sullivan, Krist, & Guard, 1993). This is one of the major reasons behind the difficulty in solving this problem.

Other Direct Air Capture models have been discussed in the methodology section of the report.

Renewable Energy in Direct air Capture

Since Direct Air Capture of CO_2 from the atmosphere takes place with the help of a high amount of energy, many reports have discussed using renewable sources of energy in fulfilling the energy demands of the process. Since this report focuses on Solar Energy for the fulfillment of the process, a literature review in the field of solar thermal has been carried out and given below:

Solar Thermal Energy

Solar thermal energy is being used all around the world using various technologies. The attraction to the source is justified by it being free of cost and relatively dependable for many parts of the world.

Solar Updraft Towers

Solar updraft towers use solar radiation to create a convection-driven updraft current. Air is heated in a greenhouse-like structure and directed up a chimney or tower, where the buoyancy-based pressure difference drives the air across a turbine or array of turbines. The simplicity of solar updraft towers, their lack of moving parts and expensive materials, and their ability to utilize diffuse or indirect solar radiation present a contrast to other solar-thermal technologies.

The solar updraft tower's three essential elements – solar air collector, chimney/tower, and wind turbines – have thus been familiar for centuries but are combined now in a novel way. Air is heated by solar radiation under a low circular transparent roof open at the periphery; the roof and the natural ground below form an air collector. In the middle of the roof is a vertical tower with large air inlets at its base. The joint between the roof and the tower base is airtight. As hot air is lighter than cold air it rises up the tower. Suction from the tower then draws in more hot air from the collector, and cold air comes in from the outer perimeter. Thus, solar radiation causes a constant updraft in the tower. The energy contained in the updraft is converted into mechanical energy by pressure-staged turbines at the base of the tower, and into electrical energy by conventional generators. Continuous 24-hour operation can be achieved by placing tight water-filled tubes or bags under the roof. The water heats up during daytime and releases its heat at night. These tubes are filled only once, no further water is needed. This design of an updraft wind turbine has been used in this project with modification to fulfill the necessities of a direct air capture system.

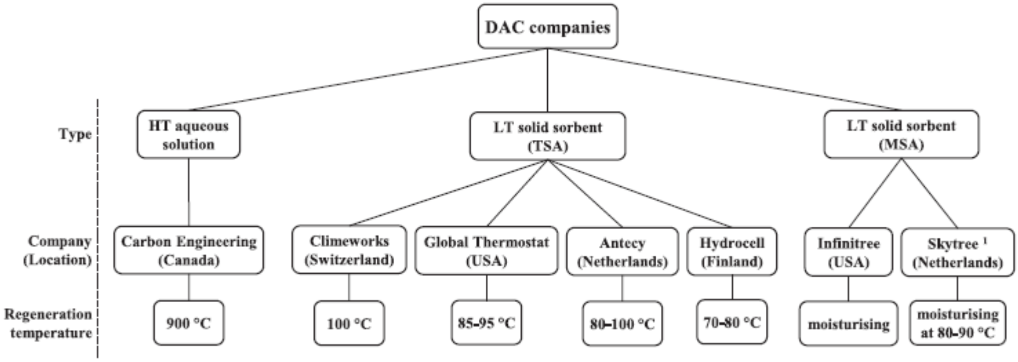
Concentrated solar power towers

Concentrated solar power (CSP) systems generate electricity by using computer-controlled mirrors (known as heliostats) in a large area to reflect and focus sunlight onto a small area to create intense heat to vaporize water. The water steam then drives turbines connected to electrical power generators.

Molten salt tanks can be used to storage thermal energy absorbed during the day to allows CSP plants to continue to generate electricity even after sunset.

Applicability in the DAC Scenario

Basic air capture models consist primarily of an air contactor, a sorbent material, and a regeneration module. The materials and assemblies adopted for these purposes vary greatly with the method employed for DAC. The variation of those technologies can be seen below in Fig. 2 :



(1) electrostatic absorption and moisturising desorption

Fig. 2. Companies active in the field of CO_2 DAC and methods employed (Fasihi et al., 2019)

High Temperature (HT) aqueous solution

High Temperature (HT) aqueous solution process consists of two cycles taking place simultaneously, as illustrated in the figure below in Fig. 3:

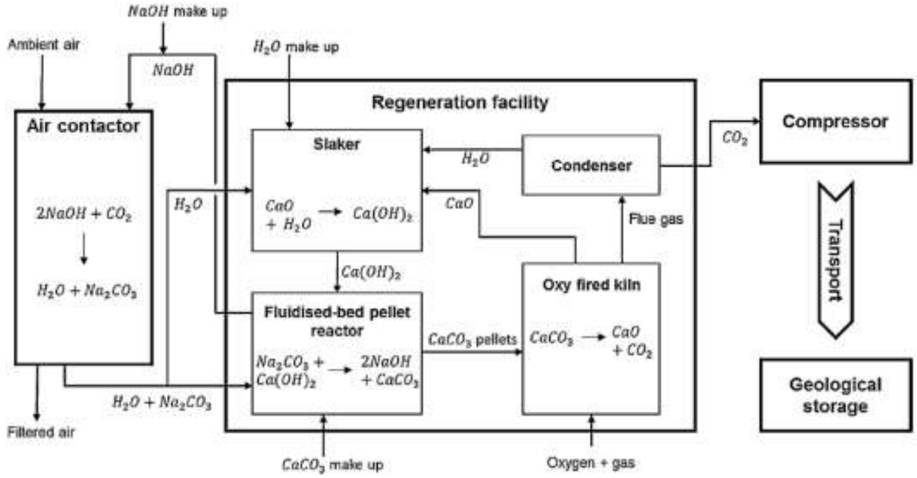


Fig. 3. Schematic Representation of a DAC Facility (Fasihi et al., 2019)

In the first cycle (to the left), air is brought in contact with the sorbent solution (in packing wetted with sorbent, or with sprayed sorbent), where the air flow is maintained either by natural draft or with the aid of fans (Fasihi et al., 2019). In this process, the CO_2 react with the strong hydroxide sorbent (-OH) forming a carbonate salt (-CO3) of the metal in the hydroxide, and liberating water.

This absorption takes place in room temperature and pressure and the air remaining after the carbon dioxide has been stripped off it, is released back to the atmosphere (Fasihi et al., 2019). The CO_2 in the air is already removed in this step of the process. The remainder of the process (the second cycle) focuses on the regeneration of the sorbent solution, while retrieving pure Carbon Dioxide from the carbonate salt.

Thus, in the second cycle, the carbonate salt is reacted with calcium hydroxide (Ca(OH)2) solution, thus regenerating the sorbent and precipitating solid calcium carbonate ($CaCO_3$).
The next step and the most energy intensive step in the process is the retrieval of the captured CO_2 for safe storage/ conversion to other useful products (Fasihi et al., 2019).

The products thus released from the reaction- calcium oxide (CaO) and CO_2, are thus sent for the regeneration of calcium hydroxide and for storage/ utilization purposes respectively (Fasihi et al., 2019).

The chemical reactions described above are listed below (considering NaOH as the sorbent in the process):

Contactor	$2NaOH + CO_2 \rightarrow Na_2CO_3 + H_2O$
Causticizer	$Na_2CO_3 + Ca(OH)_2 \rightarrow 2.NaOH + CaCO_3$
Calciner	$CaCO_3 + heat \rightarrow CaO + CO_2$
Slaker	$CaO + H_2O \rightarrow Ca(OH)_2$

The energy requirement other than that required for the chemical reaction to take place, is for the fan to pass air through the contactor, spraying the sorbent and moving the reactants and products from one facility to another (Fasihi et al., 2019).

Results and Discussion

A schematic process of the Carbon Engineering plant has been shown below:

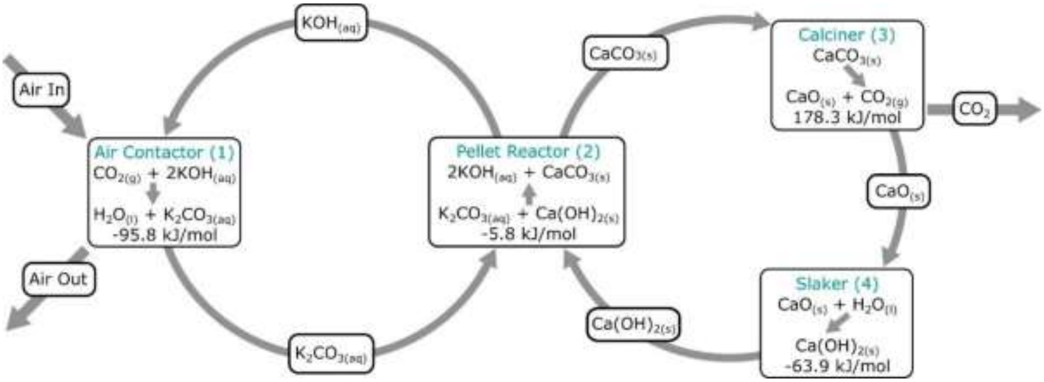


Fig.4. Calcium Cycle Recovery process employed in Carbon Engineering's plant (Keith et al., 2018)

The components of the system are described and assessed in detail below:

1. Air contactor

The contactor is one of the more energy intensive units in the process of Direct Air Capture. Currently, large fans are used to serve this purpose. The large fans serve the purpose of sucking in large volumes of air and providing the necessary pressure difference required to pass the air through the gas-sorbent contactor. In this report, in order to economize the process, a solar thermal solution to the problem has been introduced.

Using a solar updraft tower to create the required pressure difference to pass the ambient air through the packing, has been investigated below:

System Design:

There is 0.04% CO_2 by default in air.

Ignoring losses, to remove 1Mt CO_2 per year, the total mass of air to be processed:
$\dot{M}CO_2 = 10^9$ kg / year

$\dot{M}_{air} = 2.5 \text{ X } 10^{12}$ kg air / year

Density of air: $\rho_{air} = 1.183$ kg/m^3 at 25℃

Thus, volume of air to be processed in a year

$\dot{V}_{air} = 2.04 \text{ X } 10^{12}$ m^3 / year

The number of days of operation in a year is assumed to be 300 days and the hours of operation in a day is 10 hours/day.

The volumetric flow required in the contactor

$$\dot{v}_{air} = \frac{Vair}{300.10.60.60} \qquad (1a)$$

$$= 188964.4747 \text{ m}^3/\text{s}$$

The corresponding mass flow rate in the contactor
$\dot{m}_{air} = 231481.5$ kg/s

(Keith et al., 2018) has provided the following data in his research, which we can extract as:

a) Economically optimized velocity of air through contactor
   $v_o = 1.4$ m/s

b) Optimum pressure-drop in the packing
   $\Delta p_d = 9.7$ Pa/m at 1.4 m/s

c) Optimum air travel depth in packing

$l_p = 7$ m

From this, we can calculate the total pressure drop in packing as

$\Delta p_{tot} = \Delta p_d \, . \, l_p$

$= 67.9$ Pa

d) packing sp. surface for optimized material

$\rho_{packing} = 210 \ m^2/m^3$

Using the volumetric air flow rate ($\dot{v}_{air}$) and the optimum velocity of air through the contactor (v_o), we can calculate the total face area for air flow as

$A_{tot} = 134974.62 \ m^2$

To provide this surface area for air contact with sorbent, the volume of packing material required is

$$V_{packing} = A_{tot} \, / \, \rho_{packing} \tag{1b}$$

$$= 642.73 \ m^3$$

Using the optimum depth of packing, the face area of the packing can be determined by

$$A_{packing} = V_{packing} \, / \, l_p \tag{1c}$$

$$= 91.82 \ m^2$$

This face area of the packing is equal to the area of the cross-section of the tower

$$A_{tower} = \pi \, . \, (r_{tower})^2 \tag{1d}$$

Thus, $r_{tower} = 5.40$ m

Now,

Power output of solar chimney can be calculated as the product of solar input and the efficiency of the plant.

$$P = \dot{Q}_{solar} \, . \, \eta_{plant} \tag{1e}$$

The solar energy input $\dot{Q}_{solar}$ into the system can be written as the product of global horizontal radiation G_h and collector area A_{coll}.

$$\dot{Q}_{solar} = G_h \, . \, A_{coll} \qquad (1f)$$

The pressure difference created between the base (the collector) and the top of the chimney, can be divided into a static and a dynamic component, neglecting friction losses,

$$\Delta p_{tot} = \Delta p_s + \Delta p_d \qquad (1g)$$

The static pressure difference drops at the base of the packing, the dynamic component describes the kinetic energy of the airflow

With the total pressure difference and the volume flow of the air at $\Delta p_s = 0$ the power P_{tot} contained in the flow is now:

$$P_{tot} = \Delta p_{tot} \, . \, v_{tower,max} \, . \, A_{coll} \qquad (1h)$$

Using equations above, with plant efficiency (η_{plant}) set to 90% and global horizontal radiation (G_h) set to 1000W/m^2,

$V_{tower,max} = 13.25$m/s

The total kinetic energy of the flow can be written as

$$P_{tot} = 0.5 \, . \, \dot{m} \, (v_{tower,max})^2 \qquad (1i)$$

Thus, the area of the collector can be determined as

$$A_{coll} = 0.5 \, . \, \dot{m} \, . \, v_{tower,max} \, / \, \Delta p_{tot} \qquad (1j)$$

$$= 22593.65 \text{ m}^2$$

Thus, radius of collector,

$$r_{coll} = (A_{coll} \, / \, \pi)^{0.5} \qquad (1k)$$

$$= 84.78 \text{ m}$$

Using the Boussinesq approximation, the speed reached by free convection currents can be expressed as

$$V_{tower,max} = (2 \,.\, g.\, H_{tower} \,.\, \Delta T/T_0)^{0.5} \qquad (1l)$$

$$= 642.73 \text{ m}^3$$

From experimental observations conducted inside a solar coffee dryer (project carried out by the author) it was observed that a temperature difference of 25K° can be obtained on a sunny day for a similar setup. For a ΔT=25 K°,

H_{tower} = 90 m

Simulation:

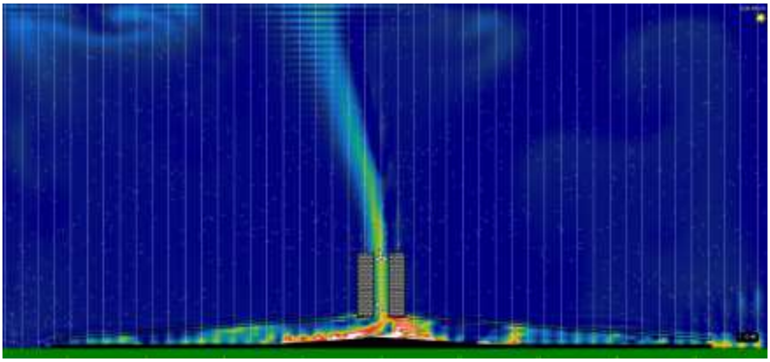


Fig. 5. A computer simulation of the updraft tower with optimized height to replace the contactor fan (2D simulation only for visual conception)

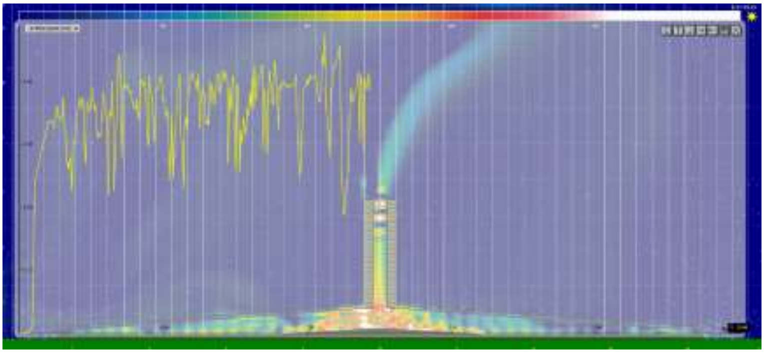


Fig. 6. Updraft Tower for contactor with an iterative result of the variation of air velocity (scaled 0.05X) in the tower with variation in height (2D simulation only for visual conception)

Thus, using a solar updraft tower can eliminate all the cost of using fans in current DAC plants.

Savings

Thus, for the air contactor units, replacement of the fans with a solar updraft tower will result in the following savings:

Operational Savings:

Energy used in Fans for air contactor = 61 kWh/ton CO_2 (Keith et al., 2018)
Energy used in the operation of the solar updraft tower = 0
Net Energy Savings
= 61 kWh/ton CO_2
= 0.2196 GJ/ton CO_2

Pellet Reactor

Carbonate ion is removed from solution by causticization in the pellet reactor. The fluidized bed reactor has been custom designed for this particular product and is not an energy intensive unit. Thus, a redesign prospect for the pellet reactor has been dropped.

Calciner

Currently, a Circulating Fluidized Bed CFB is used in the purpose of calcination. This part of the process is the most energy intensive one and thus, further research has been carried out for its possible replacement.

Solar Power Tower as a calciner

From previous researches, it has been known that a solar power tower can reach temperatures of 500 degrees Celsius or higher, thus allowing for a huge boost in energy savings, as compared to fossil fuels-based heating, where all the energy is required in heating to 900 degrees.

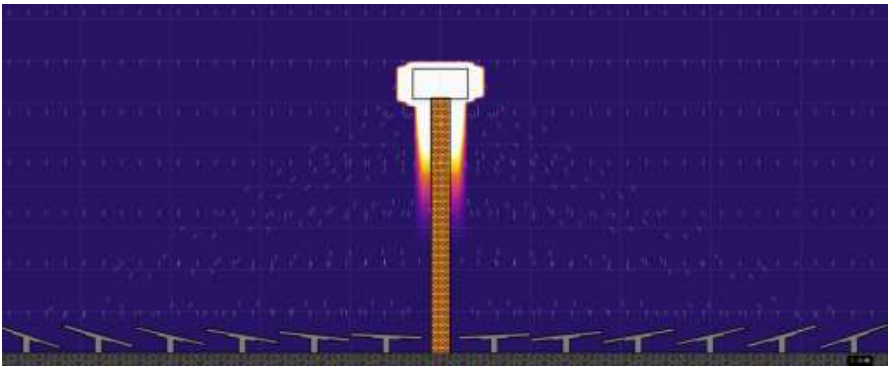


Fig. 7. 2-D Thermal simulation of the solar power tower (2D simulation only for visual conception)

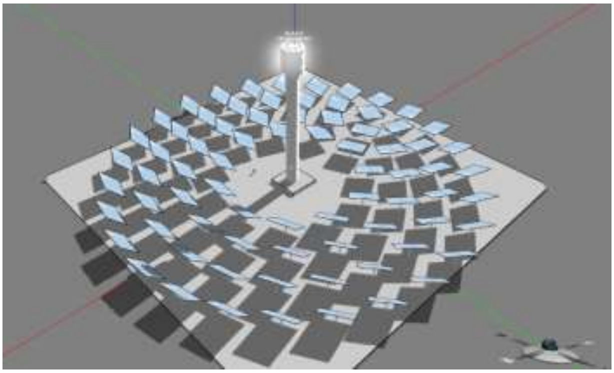


Fig. 8. A model of a solar power tower (Xie, Schimpf, Chao, Nourian, & Massicotte, 2018)

The only operational cost in this scenario is for the solar tracking mechanisms in heliostats.

Savings

Thus, for the calciner, replacement of the fossil-fueled heat source with a solar power tower will result in the following savings:

Operational Savings:

Energy used in circulating fluidized bed = 4.05 GJ/ton CO_2 (Keith et al., 2018)

Energy used in the operation of the solar power tower = energy used in the tracking mechanism for heliostats (minimum compared to the value above)

For static field of heliostats,

Energy used in the operation of the solar power tower = 0

Net energy savings (maximum value)

= 4.05 GJ/ton CO_2

Slaker

Similarly, for slaker also, the processing equipment is an energy- liberating one, and thus, the redesign prospect has been dropped.

Miscellaneous

Parabolic Trough for preheating

The system involved plenty of preheaters and pumps in between components. The function of these components can be achieved using a solar parabolic trough heater that performs very well functions in heating fluids to a moderate temperature.

Final Plant Layout

Thus, after all the calculations as given above, a new plant design for the direct air capture of CO_2 has been devised and a schematic design is given below:

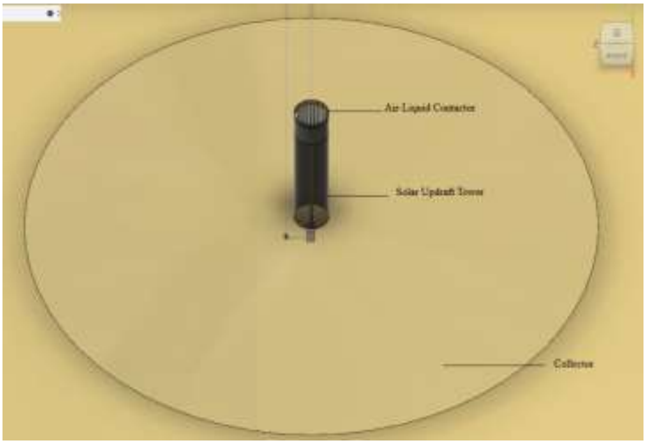


Fig. 9. Fusion 360 model of a Solar Updraft Tower with gas-liquid contactor packing

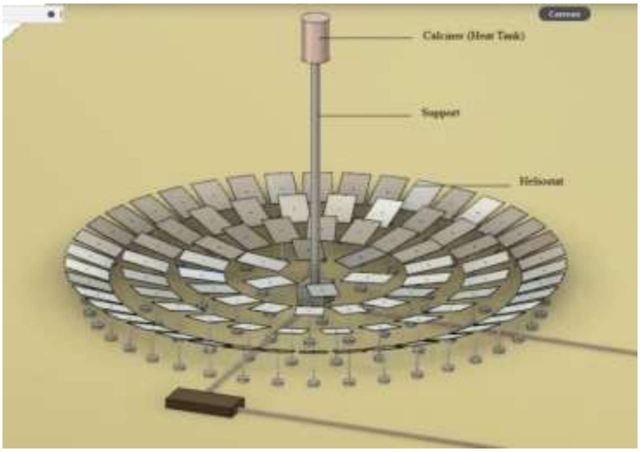


Fig. 10. Fusion 360 model of a Solar Power Tower to be used as a calciner

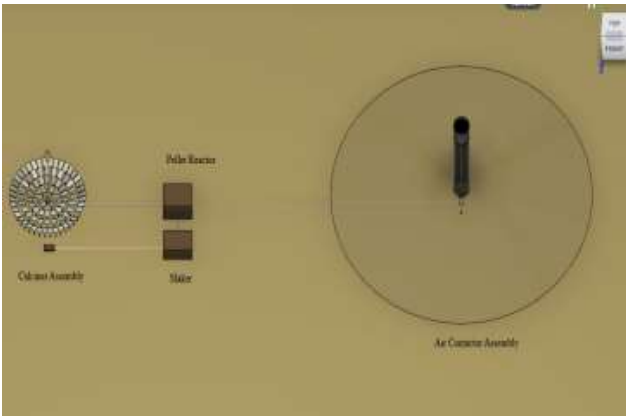


Fig. 11. Simple Fusion 360 model of a DAC plant running on renewable (solar thermal) energy

The units are far placed to ensure that the solar energy received by any of the collectors aren't obstructed significantly

Conclusion

Thus, it was concluded after the research that DAC plants can be redesigned using renewable energy and they would still function with the same efficiency, but with a much better economic efficiency. It was further concluded that 0.219 GJ energy can be saved in the air contactors and a maximum value of 4.05 GJ energy could be saved in the calciner. Thus, Solar thermal technologies can be developed in deserted areas and infertile lands, and thus put wasted land to use, while providing the important function of Carbon capture.

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