Research on the Current Situation and Future Development Trends of Direct Air Capture Technology

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Abstract. Global warming is getting worse over time, and it seems like world governments are still fairly reluctant to fully commit to a carbon neutrality plan. Vast amounts of research have been published demonstrating that CO2 emissions into the atmosphere greatly contributes to global warming, so much attention has been given toward ideas promising to reduce CO2 in the atmosphere. One idea that has been proposed to help achieve carbon neutrality is Direct Air Capture technology (DAC). DAC has existed as a concept since 1999 and is currently still in development. This report examines the current state of DAC technology as well as the opportunities that the future could hold. It is found that current DAC technology is very inefficient and it is believed that further improvements are too slow to create a big difference in the near future. Energy input is expected to drop in the coming decades., but not by a significant number. Future DAC technology seems to hold potential, with costs seeming to point to a better direction than modern technology. It is evident that the proper way to move forward in the future is to look toward other avenues of research while continuing to develop DAC technology.

Keywords: Direct Air Capture, Global warming, CO_2 emission.

1. Introduction

The world has been greatly affected by a climate crisis for decades [1]. One major contributor to global warming is the emission of CO_2, which could raise global temperatures through the trapping of heat that comes with its buildup. One of the main reasons behind these emissions is the wide usage of carbon-emitting fuels such as fossil fuels, which has led to a movement in many countries to pursue a transition toward "clean" energy (energy that doesn't emit any CO_2). However, recent projections [1] indicate that global emissions of CO_2 have continually increased despite efforts to pivot towards a clean energy policy. Thus, a hot topic of discussion has surrounded certain technologies that promise to remove CO_2 from the atmosphere.

One such method suggested to accomplish this is Direct Air Capture (DAC) technology. Generally, DAC involves using physical or chemical processes to remove CO_2 from the surrounding air. The isolated CO_2 is then stored in a remote location or transformed into other substances such as synthetic materials or carbon-neutral fuels. It is important to note, however, that DAC is still an emerging technology that has only been developed for a number of years. Currently, a few key manufacturers are operating certain DAC technologies in plants and funding from various governments could develop the potential of the technology in the future. As of August 2023, the Biden Administration recently pledged 1.2 billion dollars in investment into DAC technology [3]. According to the International Energy Agency, 0.01 Mt of CO_2 are currently being removed from the air each year [4]. To put this into perspective, global emissions of CO_2 hovered around 33.6 billion metric tons of CO_2 in 2019 [5]. This number is over 3 million times greater than the number given for DAC removal. Being such a new technology, there could very well be a massive improvement in efficiency. The current costs of DAC also don't paint a clear picture of the viability of DAC in the future. Estimates range wildly from source to source; for example, Carbon Engineering, a major DAC manufacturer, has put the cost of their technology at one plant at \$94-\$232 per ton of CO_2. Another DAC manufacturer, Climeworks, has put the cost at around \$600 per ton of CO_2 [6]. Therefore, pinpointing the specific needs and requirements of DAC would produce faulty results with current statistics and information.

Ultimately, the main goal of this report is to see the viability of DAC in the future and how significant it could be in mitigation to climate change. The importance of finding the significance of a burgeoning technology early could greatly help guide the thinking and policy that will come in the future. Knowing whether to invest in DAC or to look towards focusing on other avenues of research would be vital to working towards carbon neutrality, which seems to be growing as a major issue every year. Other objectives that are worked through in this paper are assessing the potential of various DAC technologies and generally how the technology as a whole is becoming more efficient based on current projections. Various roadblocks to the growth of DAC, as well as limitations of the technology, will also be considered when analyzing the viability of DAC.

2. Current State of DAC

Right now, the 2 most significant DAC technologies are liquid solvent and solid sorbent approaches, which are being conducted in a handful of plants currently existing in the world.

2.1. Liquid Solvent Technology

Liquid solvent technology involves taking in the ambient air and mixing it with a liquid solvent contained within the contraption. The air is mixed with alkaline solvents to separate the CO2 out, and calcium hydroxide Ca (OH)2 to form calcium carbonate CaCO3. Calcium carbonate is heated to further separate the CO2, which is then sent off for use. The remaining calcium oxide can be rehydrated with water to reform calcium hydroxide, thus making the process readily repeatable.

2.2. Solid Sorbent Technology

Solid sorbent technology, much like liquid technology, uses a contraption to suck in the ambient air. Instead of using a solvent to capture CO2, it uses a solid porous substance to capture and absorb it after the air is sucked in. The device is then shut off from the outside and a vacuum pump is used to suck the remaining air inside. Steam is administered inside as a heating method, which carries CO2 out into a condenser, where it is finally separated from the water and then shipped off for use. Regarding what happens to the CO2, it could either be stored in a carbon sink (usually deep underground in a natural formation) or transformed into other substances, like carbon-neutral fuels or synthetic materials.

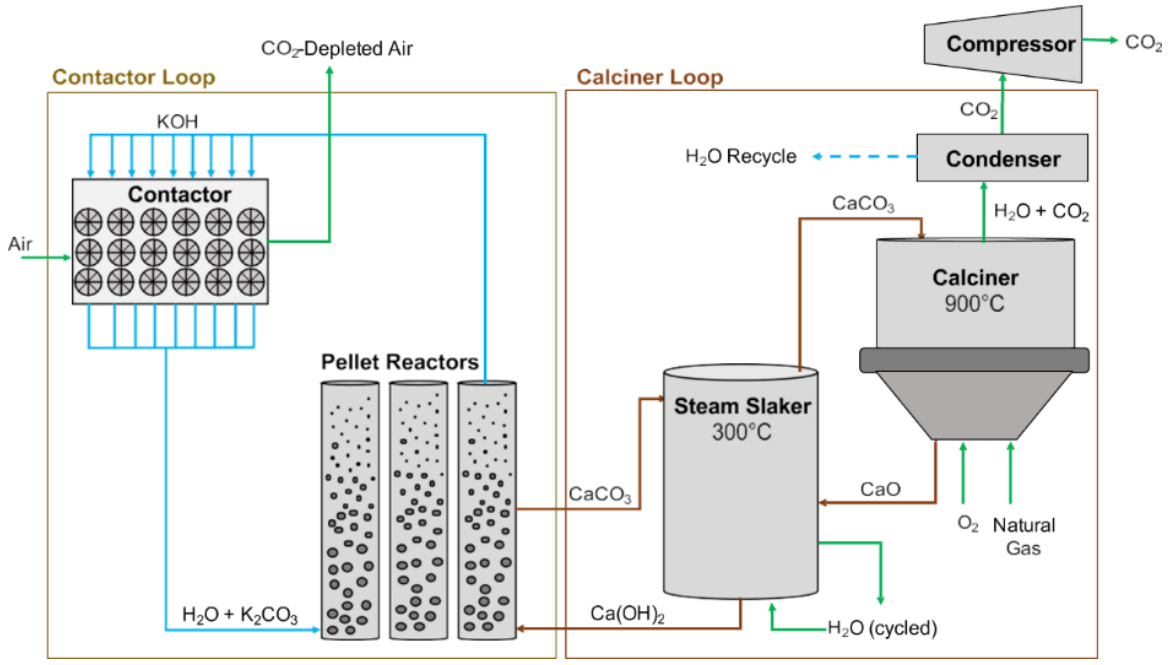


Figure 1. Diagram of the liquid solvent process [6]

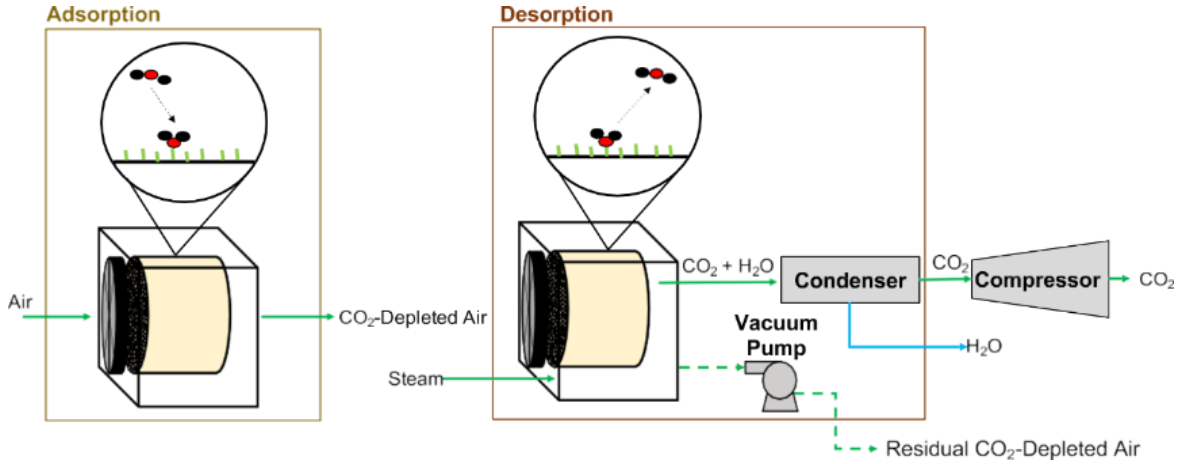


Figure 2. Diagram of the solid sorbent process [6]

2.3. The Current Costs of DAC

The costs of the technology need to be put into heavy consideration to gauge the current state of DAC. Overall, estimated costs range from $126-$780 per ton of CO2, which shows just how muddled the full extent of knowledge on DAC is currently. There is no conclusive estimate, as many sources will attach costs that seem completely removed from each other. When handling lower projections, it seems like the future of DAC is looking quite bright. However, higher projections seem to suggest that there is still a long way to go before this technology could possibly be viable. In fact, it could be far too late simply waiting for DAC to become more cost-efficient based on these projections. Another massive problem is the energy input required by the technology. According to a survey of experts, the median estimate of energy input in 2020 required for liquid and solid DAC was around 10 GJ/tCO2 and 8 GJ/tCO2 respectively. The same survey estimated that both technologies would only drop 2 GJ/tCO2 in energy input by 2050 [2]. It's a necessity to use renewable energy to power DAC, considering how it could be detrimental to input vast amounts of energy from carbon-emitting fuels, which ultimately negates the whole purpose of carbon removal. The state of renewable energy right now would not greatly facilitate mass usage of DAC, so it may take a while before the industry could start seamlessly adopting and integrating the technology into its plans for carbon neutrality. Overall, it's far too early to judge the potential of DAC based on what there is now, as the very idea of DAC has only existed since 1999. World governments are also only starting to wake up to the potential that could arise from DAC. According to the International Energy Forum, in 2020, 4 billion dollars of investment were pumped into DAC development [7]. Once investment starts pouring in, faster progress in the field could promise greater optimism regarding carbon removal. From here, it seems more optimal to focus on the future of DAC and potential methods that could drive down the costs and hopefully incentivize more investment.

3. Future of DAC

Looking beyond current DAC technology, speculation can be aimed towards potential ideas that are surfacing currently that could come into fruition in the coming decades. Some of the discussed technologies in this section are metal-organic frameworks and artificial trees.

3.1. Artificial Trees

One idea that has been proposed is a method using "artificial trees". These trees consist of plastic resins that would theoretically be able to remove carbon. Pale-colored plastic is embedded with tiny pieces of resin (measuring in micrometers) which immediately starts to remove CO_2 from the air. This is achieved when the resin reacts with CO_2 to form bicarbonate HCO^-_3, a type of salt. Water can be applied to free the CO_2 from the resin to free CO_2 from the device. According to Scientific American, this process is more powerful than if normal plants based on relative humidity. However,

this process is extremely small-scale (the resin is extremely small and therefore can't be put into large-scale production) [8]. Expanding this technology further into a conceptual idea, Klaus Lackner, an experimenter with this technology at Columbia University, seeks to make these trees by spacing out tall vertical columns of discs coated with resin. Steam would then flush out the CO_2 into a separate location for future use. Lackner estimates that it would take 10 million of these trees would pull CO_2 concentrations in the atmosphere down by 0.5 ppm (parts per million) [8]. The current CO_2 concentration is around 400 ppm. Adding on, some other obstacles include the energy input needed for pumping and compressing CO_2 (which numbers around 1.1 MJ per kg) and the amount of water needed to sustain multiple cycles of carbon removal. Consideration of the cost of the resin itself proves more hopeful, as 1 kilogram of resin costs just $2.50. Overall, it's too early to call whether this technology could ultimately be at the forefront of DAC technology, with deployment seeming to be farther into the future.

3.2. Metal-Organic Frameworks

Another idea that has been proposed is the idea of using metal-organic frameworks in DAC technology. Metal-organic frameworks (MOFs) are solid materials that are porous and therefore can "soak up" gases like a sponge. One unique feature of these frameworks is the fact that they have vast surface areas, meaning that even a small number of them could soak up vast amounts of CO_2. In addition, the process itself doesn't require large temperature shifts, unlike some other technologies like solid DAC (which necessitates the use of steam and the aforementioned artificial trees) [9]. This could ultimately promise cost reductions that are so desperately demanded for DAC technologies. One paper saw a demonstration of MOF DACs and estimated that the regeneration energy on the lower end numbered around 1.6kWh/kg-CO_2, or around 11.5 GJ/tCO_2, showing how early it is to be hopeful about the efficacy of technology. The same paper estimated that the cost could number around \$35-\$350/tCO_2 based on the source of regeneration energy [10]. According to an article published in the US Department of Energy written by Julie Chao, one potential problem that could arise in DAC MOFs is the high cost to regenerate them (release the CO_2 to allow for further capture). Chao ultimately believes this technology is nearing commercial use, which could ultimately be a powerhouse in DAC technology considering its many advantages on paper [11]. Despite this, there is still a lot of optimization to be done, and time needed to see how MOFs will fare as a commercial technology.

4. Conclusion

The overall conclusion reached through analysis of DAC technology is that it is too early to call the extent of influence DAC could ultimately bring to the table in the future. It is suggested to start thinking about more realistic approaches to achieving carbon neutrality, incorporating clean energy and other methods foremost. One limitation is that current projections could be unreliable and even inaccurate (the cost projections from various sources serve as an example). Building off and putting too much trust in these projections could take away from realizing the future potential DAC could bring. Another limitation is that much of the development of DAC could come down to investment in the technology. As of writing this report, the Biden Administration in the US recently invested 1.2 billion dollars into DAC development and deployment. If DAC can get proper funding to help increase efficiency and turn concepts into reality, then a rapid scaling of growth in the industry could be foreseeable. An analysis of current DAC technology revealed that the two major DAC technologies (solid sorbent and liquid solvent technology) are far too expensive and inefficient to put a decent dent in the carbon concentrations in the air. However, they are still being improved upon and are both new technologies that have only come to fruition in the past few years. Looking toward potential DAC technologies that could start operations in the future, it was found that 2 potential technologies (metal-organic frameworks and artificial trees) exhibited certain strengths and potential. Artificial trees were found to be cheap to construct, as the resin used to remove carbon is extremely cheap. Metal-organic

frameworks (MOFs) are an extremely promising technology that could show itself to be useful in the future. This is due to its incredible efficiency largely due to its large surface area and gas “soaking” properties. Despite this, it is expected to have a large cost required for regeneration (allowing the MOFs to suck in CO2 again). The current conclusion is that it is too early to definitively say whether DAC could become significant in the future due to its relative infancy. Thus, it will be optimal to not put too much reliance on the growth of the technology and to manufacture an energy policy better suited to combat global warming with realistic projections for the future.

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