Direct Air Capture Technology: An Investigation of Net Carbon Impacts

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In recent years, Direct Air Capture (DAC) has been emerging as a promising negative emission technology, primarily due to its flexibility of location and capability to absorb CO2, generated from non-localized sources. This study evaluates the two variants of DAC i.e. DAC-1 utilizing liquid solvents and DAC-2 using solid sorbents, in terms of overall emissions generated as a result of the process of CO2 removal from atmosphere. It was found that majority of overall emissions generated during the life cycle of DAC, may be attributed to the operational phase. The operational emissions were then classified into three major steps i.e. CO2 capture, CO2 separation and compression. The impact of the choice of energy source on generated emissions was then analyzed in the cases of both DAC-1 and DAC-2, separately for the three classifications. Both the variants were found to be reasonably efficient in terms of net CO2 removed from atmosphere, provided the energy requirements are sourced from renewable energy resources. Additionally, we analyzed the secondary impacts in terms of land use requirements and water loss during the process.

As of 2020, the current CO_2 levels in the earth's atmosphere have reached 412 ppm, denoting a rise of over 47% from the preindustrial levels of 280 ppm [1]. The more practical implications of this rise in atmospheric CO_2 may be visualized in terms of increase in Earth's average temperature. This carries serious implications in terms of, but not limited to sea level rise and modified meteorological and ecological patterns. In order to limit the global temperature rise within 2^0C, the atmospheric CO_2 levels need to be maintained below 450 ppm. Considering the upsurge in global greenhouse emissions during last few decades and the expected continued dominance of fossil fuels in the coming years, the pathway of removing CO_2 from atmosphere is increasingly becoming more relevant [3]. In their review of 1.5 °C consistent emission reduction pathways, IPCC projected the use of carbon dioxide removal (CDR) in the order of 100–1000 Gt CO_2 removed over the 21st century [2]. Currently, one prominent CDR technology in use is the Carbon Capture and Storage (CCS), where CO_2 is collected from large industrial point sources, then transported and stored in underground geological formations. Though the technology has proven to be effective in terms of capturing CO_2, it is only limited to large industrial sources in terms of applications. Greenhouse emissions from these industrial sources account for about 36% of global greenhouse emissions, thus limiting the application potential of CCS. In recent years, Direct Air Capture (DAC) has been emerging as a potential technology capable of absorbing CO_2 from non-localized sources such as agriculture, air and marine transport. Additionally, DAC benefits from its inherent flexibility of location, which can reduce the transportation infrastructure requirements and also has the capability to extract CO_2 at desired purity and concentration for commodity markets.

The aforementioned technologies and more specifically DAC, require a significant amount of energy in order to accomplish this process of extracting CO_2 from air, resulting in generation of its own greenhouse emissions in this process. Furthermore, the overall emissions from the process also include embodied emissions from the construction, maintenance and demolition of the required infrastructure. This study aims to evaluate the CO_2 emissions produced within different parts of the DAC process and present a realistic picture of the overall carbon capture efficiency of the process. This warrants a comparison of the amount of CO_2 captured with the amount of CO_2 generated in the process of capturing, which is analyzed under different scenarios of fossil based and renewable energy sources.

Studies conducted in the last decade regarding the practical feasibility of the DAC technology have primarily concentrated on the cost aspect of the process [14][15]. The cost estimates from these studies range from \$100 to \$ 1000/t CO_2 [12]. It is worth noting that these estimates represent the cost per ton of captured CO_2 and not per ton of CO_2 removed from atmosphere. In order to cover this gap, several studies have worked on evaluating the emissions generated in the DAC process, so that the process evaluation matrices can be based on the amount of CO_2 removed from atmosphere. In the absence of published information, majority of studies in this context have focused on emissions associated with operational requirements, typically calculated based on thermodynamic principles and reaction enthalpies instead of practical prototypes [16][17][18]. However, a few studies like Liu et al. (2020) examined the overall emissions of the DAC-1 technology paired with Fischer-Tropsch synthesis (FTS) to produce transportation fuels [19]. They estimated 0.51 g CO_2 produced per gram of CO_2 captured and concluded this number to be heavily dependent of the emission factors of the electricity used. Similarly, de Jong et al (2020) calculated the life cycle carbon efficiency of the DAC-1 process and found the results between 10% to 93% for the pessimistic and optimistic scenarios respectively [10]. This study aims build up on the analysis provided by different authors, to provide a comprehensive picture of the emissions generated within different steps of the two variants of DAC technology.

METHODOLOGY

DAC System Description

The entire technological process for DAC may be subdivided into four major components i.e. CO_2 capture, CO_2 Separation, Transportation and Sequestration/ Utilization. CO_2 capture represents the process of extracting CO_2 from the ambient air, either by chemical absorption using liquid solvents or by physical adsorption using solid sorbents. Based on the choice of CO_2 capture mechanism used in the process, the DAC technology may be classified as DAC-1, which uses liquid solvents and DAC-2, that uses solid sorbents. This collected CO_2 is then separated from the absorbent/ adsorbent, to prepare the same for the next cycle. Once the CO_2 is separated, it is prepared and transported, typically using pipelines and finally stored in the underground geological formations for sequestration. Alternatively, the captured CO_2 may also be prepared for commodity utilization such as greenhouse farming and beverage carbonation, and transported to the utilization facility accordingly. The details of aforementioned sub-processes are provided ahead.

CO2 Capture:

Due to low concentration of CO_2 in the ambient air (~400 ppm), the CO_2 capture process requires a substantial amount of air to be passed through the capturing solution/ material. This requires large infrastructure with multiple fans operating in parallel, to provide the airflow over packaged materials that houses the absorbent. The setup is called the 'Air Contactor'. One such cost-optimized air contactor design has been presented by 'Carbon Engineering', that utilizes the DAC-1 variant of the technology [4]. This system, that is designed to capture 1 Mt CO_2/ year, consist of a total of 10 air contactors. Each air contactor unit houses 4 rows of 40 modules measuring 5m in height and width, and 8.6 m in depth. With the inlet air velocity of 1.5 m/s and assuming 75% CO_2 capture efficiency, contactor area of 38,000 m^2 is required to capture 1 Mt CO_2/year, under this configuration. Each module consists of PVC-based packaging material over which a strong hydroxide sorbent is introduced from the top which interacts with the incoming ambient air in a perpendicular flow orientation.

Similar to DAC-1, DAC-2 employs a similar method where the ambient air is blown through packaged solid adsorbent contained within the air contactor. In certain applications, the adsorber (air contactor) itself is switched to the desorption mode. This eliminates the infrastructure requirements associated with the construction of a separate desorption facility, but in turn makes the air contactor design more complicated due the associated sealing requirements. This step of CO_2 capture is fundamentally similar for both variations of the technology. The operational energy consumption for this phase may primarily be attributed to the required fan energy which in turn is governed by the pressure drop through the contactor. In addition to this, the DAC-1 variant also uses pumping energy to transport the solvent thorough the system.

CO2 Separation:

This sub-process of CO_2 separation refers to the extraction of CO_2 from the absorbent material/solution, essentially preparing the absorbent for the next cycle, and is accomplished within the 'Regeneration facility'. Due to the high stability of CO_2 and its affinity towards the absorbent, this step tends to be most energy intensive. The underlying processes and their subsequent energy requirements vary by the choice of DAC variant used i.e. DAC-1 or DAC-2. In case of DAC-1, the process is called 'Regeneration', where the chemical solvent containing CO_2 is passed through a series of chemical reactions that result in concentrated stream of CO_2 separate from the chemical solvent. One good example of such a process is the Pelletized version of Kraft process, as described by Holmes et al. (2013) [5]. This process requires the dried $CaCO_3$ pellets to be heated to a temperature of approximately 900^0 C, consequently resulting in significant thermal energy requirement. Whereas in case of DAC-2, the process is more commonly called 'Desorption'. In such applications, CO_2 is typically separated by heating (Temperature Swing adsorption) or a combination of heat and vacuum (Temperature/ Vacuum swing adsorption) to release CO_2 from the physically bound state with the solid sorbent. Alternatively, a humidity swing approach is also being developed by a few commercial designs. The process involves heating the sorbent to a temperature of $120\text{-}140^0$ C and account for the majority of energy requirements in the process. The sorbent is then cooled before it is fed back to the air contactor.

Transportation:

The transportation step can be further classified into CO_2 transportation and the preparation for transportation which refers to the compression of CO_2, to the desired pressure. The emissions associated with this step vary significantly based on the desired compression pressure and the choice of transportation mode which is essentially governed by the final goal of sequestration or utilization. This step is independent of the variant of DAC used and is similar to other negative carbon technologies such as CCS. The results presented in the current study are based on the scenario of CO_2 transport via pipelines to the end goal of geological sequestration.

Sequestration/ Utilization:
The last step of the process refers to the injection of compressed CO_2 into underground geological formation for storage. To accomplish this final step, CO_2 is typically compressed into a supercritical fluid and then injected into a geological formation that is deep enough (typically 1 km or more) for the CO_2 to stay as a supercritical fluid. In addition to conventional geological storage, certain processes such as Enhanced Oil Recovery (EOR) are also being employed in industrial applications, where CO_2 storage is achieved with an additional benefit of increased oil extraction. Alternatively, various utilization processes such as CO_2 use for greenhouse farming, beverage carbonation and Fischer Tropsch Fuel production also present financially viable opportunities for CO_2 utilization. However, one might argue that CO_2 stored in products and fuels is eventually released back into the atmosphere and thus cannot be considered an ideal end goal for CO_2 capture. Similar to the transportation step, since this process only deals with the collected CO_2, it also is independent of the process variations used upstream i.e DAC-1/ DAC-2.

ANALYSIS

The study has been formulated based on a DAC system with a capacity of 1 Mt CO_2/ year and an assumed lifetime of 20 years. The emissions analysis of the different sub-processes of the two variations of DAC technology are based on the information provided by the published pilot plant designs. For the case of DAC-1, the energy, material and infrastructure requirements are obtained from the conceptual design presented by Keith and Holmes (2018) for a 1 Mt pilot plant which is currently under development. The infrastructure requirements and associated emissions for DAC-1 are based on the analysis performed by Dejong et al. [10]. Due to insufficient published data regarding the construction requirements of the regeneration facility, only the emissions associated with air contactor have been included in the analysis.

Similarly, In the absence of published information on the DAC-2 pilot plants, the energy balances are obtained from the National Academy of Sciences (NAS) study which evaluated the process energy requirements based on the methodology proposed by Realff and Kawajiri [7][13]. The analysis of the transportation and sequestration steps is based on the 3 Mt CCS system, examined by Konreef at al. (2008) [8]. The emission factors for different fuel sources are obtained from the National Renewable Energy Laboratory (NREL) study on greenhouse emissions for energy generation (2013) [9].

RESULTS

First of all, we start the analysis by comparing the CO_2 emissions generated in construction and demolition, during the process and in the final transport and sequestration steps, for the two variations of DAC technology. Figure 1 shows the distribution of emissions in terms of the three abovementioned segments. The embodied emissions are represented by construction and

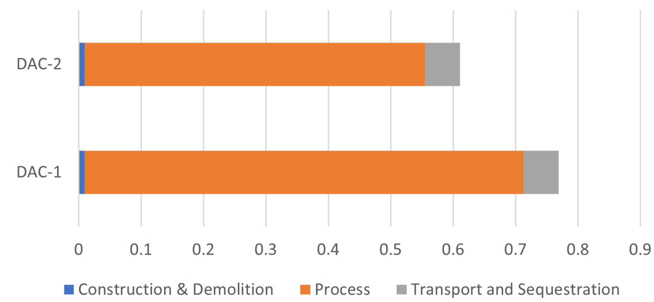


Figure 1: CO_2 emissions for the 2 variants of DAC Technology

demolition of the infrastructure and operational emissions are represented by the process emissions. The emissions associated with transportation and sequestration are presented separately as these are solely contingent upon the final goal of the process, rather than the variant of technology employed.

As is evident from figure 1, the majority of greenhouse emissions in the entire process may be associated with the operational phase of the DAC technology. The operation emissions account for approximately 85% of the overall emissions generated in both DAC-1 and DAC-2. It can be noted that the process emissions in case of DAC-1 are significantly higher than in case of DAC-2. This difference is due to the higher thermal energy requirements in the DAC-1 regeneration step which will be explained in detail in the next section. The transportation and sequestration emissions are considered to be same in case of both the DAC variants as this process is independent of the methods employed for the downstream steps of CO_2 capture and separation. The emissions associated with construction and demolition in case of DAC-1 are based upon the pilot plant data provided by Keith et al. (2018) [6]. Due to the absence of any published data on the DAC-2 pilot plants, the embodied emissions for this variant are considered to be analogous to DAC-1, due to the similar infrastructure requirements. However, is has been suggested in literature that DAC-2 requires more frequent maintenance and replacement of industrially sourced sorbent material which may lead to higher embodied emissions in this case.

Since it is evident from figure 1 that majority of the overall emissions in the process are emitted during the operational phase, the process emissions are analyzed in detail. Two scenarios i.e. baseline and optimized scenario are compared for both DAC-1 and DAC-2, the details of which are provided in table-1.

Figure 2 presents a comparative analysis of the 2 variations of DAC, subdivided into the processes of CO_2 capture, separation and compression for transport. The first observation to be made here is the distribution of emissions within different steps of the process phase. The maximum proportion of CO_2 emissions are generated within regeneration step. This is due the significant thermal energy requirement of this step which

Scenario	Baseline	Optimized	
Technology	DAC-1 & DAC-2	DAC-1	DAC-2
Heat Requirements	NG	NG	Waste Inceneration[2]
Electricity Requirements	Avg. US Grid	PV	PV
Heat Regeneration	None	Significant[1]	Negligible

Table 1: Description of baseline and optimized scenarios. NG: Natural Gas; PV: Photovoltaic (Solar energy); [1] Based on Keith et al. (2018); [2] Based on the process used by 'Climeworks'.

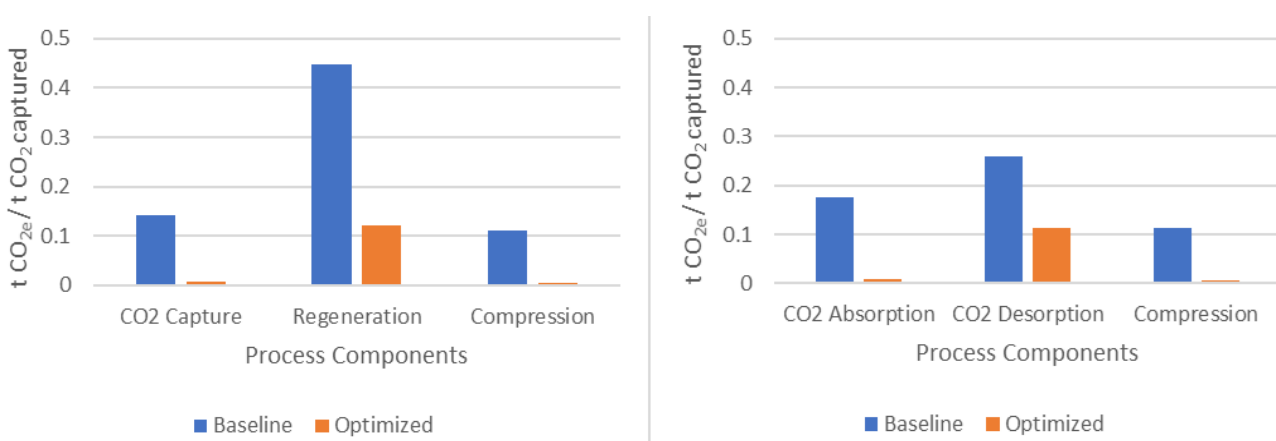
is consistent in the cases of both DAC-1 and DAC-2. It should be noted that the emissions associated with the regeneration step for DAC-1 are higher than the desorption emissions, in case of DAC-2. This difference is directly proportional to the energy requirements in both cases and is justified by the fact that DAC-1 requires substantially higher amount of thermal energy to accomplish this step. The second largest contributor to the process emissions is the CO_2 capture step, where the emissions may be attributed to the energy required for fans and pumps. The compression related emissions are calculated based on a 15 MPa output CO_2 stream for transportation via pipelines. These emissions are same for both DAC-1 and DAC-2, and are solely contingent upon the compression pressure to be achieved. The compression pressure is governed by the choice of downstream steps of sequestration or utilization

In terms of comparison between the baseline and the optimized scenario, a significant reduction in emissions generated in all the three steps may be observed. The overall process emissions reduce by 55% in DAC-1 and by 42% in DAC-2. The primary reason for this drop in generated emissions may be attributed to the lower emission factors associated with the use of renewable energy to source the thermal and electrical requirements of the process. Furthermore, it is to be noted that the reduction in case of DAC-1 is higher than in case of DAC-2. This is prominently due to the much higher emission reduction achieved in the regeneration step of DAC-1. The reason behind this significant reduction may be attributed to the assumption of significant heat regeneration, as proposed by Keith et al. (2018) for the DAC-1 pilot plant design [6].

The analysis presented here points to the relevance of the choice of source energy and its impacts on the overall emissions of the process. A similar trend was observed in the case of emissions associated with transportation and sequestration where the use of renewable energy (PV) to supply the electrical requirements, resulted in a significant improvement in the carbon efficiency of the process.

Secondary Impacts:

In addition to the CO_2 emissions generated in the process, we analyzed the secondary impacts of the DAC technology in terms of its land use requirements and water loss. The results are presented in comparison to the natural negative emission methodology of afforestation. Figure 3 shows the land area requirements by the 2 variations of DAC compared to afforestation. It can be noted from the figure that the direct area requirements of both versions of the DAC technology are negligible in comparison to afforestation, based on a capture capacity 1 Mt CO_2/ year. The direct area refers to



2a: DAC-1

2b: DAC-2

Figure 2: CO_2 emissions in baseline vs optimized scenarios for the 2 variants of DAC.

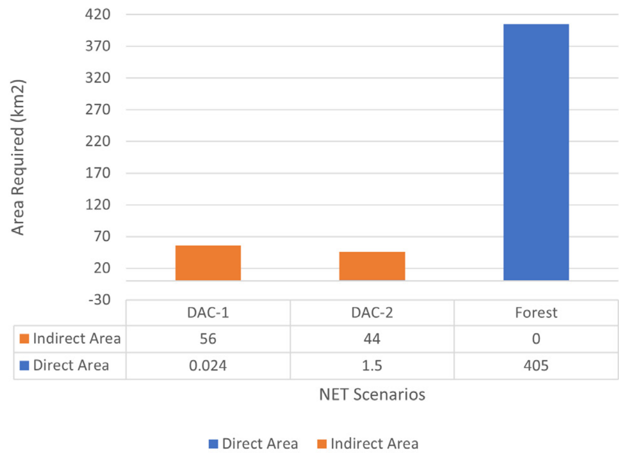


Figure 3: Land area requirements for removing 1 Mt CO_2/year

the area required by air contactor and the regeneration facility. However, there exist certain indirect area requirements which can be realized as the area required for the on-site power island and the CO_2 depleted region which needs to be included in the overall area requirement. Incorporating the indirect area requirements, the overall area required for DAC-1 and DAC-2 plants was calculated to be 56 km^2 and 44 km^2 respectively. This requirement in both cases is significantly lower than afforestation, that requires approximately 405 km^2 to capture 1 Mt CO_2/ year. Similarly, the water loss in case of DAC-1 (~8.2 Mt/year) and DAC-2 (~1.2 Mt/yearr) was found to be negligible in comparison to the scenario of a forest (3028 Mt/year) with same goal. An important note to be made is that the water loss calculations presented here are based on a 65% RH atmospheric condition and could increase up to four-fold if the RH is reduced to 50%, as suggested by Stolaroff et al. [11].

DISCUSSION

As is evident from the results, the choice of source energy proves to be the most important factor that governs the carbon capture efficiency of the process. Based on the optimized case scenarios presented above, the overall carbon capture efficiency of the DAC process was calculated to be around 85% for both DAC-1 and DAC-2. This can be translated as the DAC process generates 0.15 t CO_2, in order to capture 1 t CO_2. However, in the baseline scenarios utilizing fossil-based energy sources, the overall efficiency was found be approximately 30% for DAC-1 and 44% for DAC-2. These results indicate that if the DAC process is accomplished using the fossil fuel-based energy, the overall efficiency renders the process somewhat impractical. Thus, using low-carbon energy generation sources is the most beneficial factor towards the effectiveness of DAC. However, if this low carbon energy is better used as direct supply to limit future emissions, is a subject for another study. Our analysis also suggests that the majority of overall emissions from the process may be attributed to the process phase due to significant operational energy requirements. Furthermore, due to the calculated distribution of emissions between process and transportation phases, the availability of renewable energy proves to a more important factor towards determining the ideal location for a DAC plant, than nearness to the storage site.

In both the cases of DAC-1 and DAC-2, the thermal energy requirements dominate over the electricity requirements due to the heat required to address the strong binding chemistry of CO_2. That being said, DAC-1 typically requires high thermal input (900^0 C) for solvent regeneration, which is relatively harder to be substituted by renewable energy sources. However, the system proposed by Keith et al. based on heat generation by natural gas, claims to capture the majority of CO_2 produced in the process. DAC-2 holds the advantage in this context, since the regeneration only requires heating to relatively lower temperatures (<150^0 C). This requirement is more likely to be achieved by renewable energy sources. As an example, 'Climeworks', a Switzerland based DAC company is using waste heat incineration to supply the majority of thermal requirements of the process.

Another important distinction to be made here is that the liquid solvent used in DAC-1 is typically generated as a part of the process. Whereas the solid sorbent required in case of DAC-2 needs to be sourced externally. DAC-1, being based on chemical reactions, was also noted to be advantageous in terms of lower risk from air pollutants. DAC-2 on the other hand, suffers from much higher risk from air pollutants as they can negatively impact the affinity of CO_2 towards sorbent media.

Lastly, in terms of practical adaptation, the commercial development of DAC has been gaining momentum in the past decade with multiple privately funded companies utilizing the two variants of the DAC technology. One of the leading DAC-1 based company 'Carbon Engineering' is using aqueous hydroxide solutions that react with CO_2 to precipitate a carbonate salt. In terms of DAC-2 based commercial development, few of the designs are utilizing amine based solid sorbents to capture CO_2, with others considering different kinds of structured solid sorbents under development. As of June 2020, there are currently 15 DAC plants operating around the world, capturing more than 9000 t CO_2/year, with an additional 1 Mt CO_2/year plant currently under development in United States [20].

CONCLUSION

This study evaluated the overall emissions from different parts of the two variants of DAC technology. The operational phase was found to dominate the emissions generated throughout the life cycle of the process with the regeneration/ desorption step accounting for the maximum energy use and consequently maximum CO_2 emissions. Both the variants i.e. DAC-1 and DAC-2 were found to be reasonably efficient, provided that the required thermal and electrical energy requirements are sourced from low-carbon emitting sources. Both these variants were found to be viable options to tackle the global greenhouse emissions, but the required scale of implementation is massive. This makes DAC best suited as a complementary mitigation strategy which should ideally be applied in conjunction with continuing efforts towards minimizing the anthropogenic greenhouse emissions.

ENDNOTES

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