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ARTICLE

Improving direct air capture with MechanicalTrees™ and membrane-based filters

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To combat the ever-increasing carbon dioxide emissions, the implementation of "carbon-negative" technologies, such as carbon capture and sequestration, is essential in the fight against climate change. Direct air capture (DAC), particularly membrane-based direct air (m-DAC) capture, has recently undergone extensive research and development, showing its potential as a revolutionary solution. Membrane-based systems provide many advantages over its solid and liquid sorbent counterparts due to its lower production costs, smaller footprint, and scalability. Thus, this article proposes the combination of a MechanicalTree™ and membrane-based filtering system as a cost-effective alternative to existing DAC technologies. While accounting for several variables, we provide a downsized experiment of our prototype and explain the rationale behind our methodology through a benefits-drawbacks and techno-economic framework. Essentially, m-DAC is able to provide equal, if not better, CO_2 capture rates/purity than solid and liquid systems at a significantly lower cost. Finally, current challenges and future research recommendations are presented.

BACKGROUND

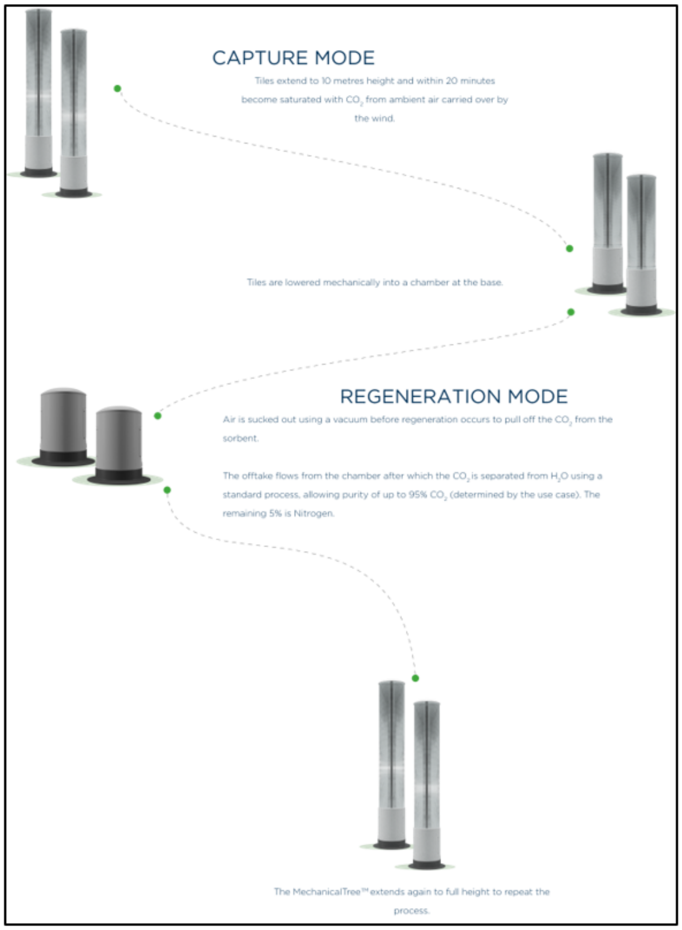
Climate change is described as the long-term changes in temperature and weather conditions (United Nations, n.d.), and is one of the biggest problems facing humanity today. Due to the immoderate burning of fossil fuels, the amount of carbon dioxide (CO_2) and other greenhouse gases in the atmosphere have been steadily increasing since the Industrial Age, trapping heat in the atmosphere and thereby contributing to global warming. Handling these enormous carbon emissions is challenging, with it suggested that global warming and climate change can only be reduced by introducing "carbon-negative" technologies that actively remove CO_2 from the atmosphere (Erans et al., 2022).

Carbon capture, utilization, and sequestration (CCUS) is an emerging technology that aims to combat this issue. There are two types of carbon capture: point-source capture (PSC) and direct air capture (DAC). PSC plants are located near point sources, or significant emitters of CO_2 (e.g. fossil fuel plants and mineral production sites), and process carbon before it enters the atmosphere (National Energy Technology Laboratory, n.d.). DAC involves sucking existing CO_2 directly from air with large fans, which can theoretically take place anywhere (Erans et al., 2022). Further, PSC is the primary method of CCUS as carbon capture is efficient and relatively straightforward near point sources. DAC, in contrast, is less popular and experiencing difficulties achieving the same level of success due to the innate nature of the technology's purpose - removing CO_2 directly from the atmosphere. Air is composed of many different gases: nitrogen (78%), oxygen (21%), argon (0.9), CO_2 (0.04%), and other gases (e.g. hydrogen, neon). This abysmally low concentration of CO_2 (0.04% or 400 ppm) in the air creates problems for DAC technologies. Most notably, extracting and separating this CO_2 from the atmosphere requires significant energy and resources, ultimately increasing the capital and operational costs. To reduce production costs and advance global scalability, new technologies must be developed to improve the efficiency of existing processes.

INTRODUCTION

We propose to enhance DAC through the combination of a MechanicalTree™ (MT) and membrane-based filtering system - both of which are powered by nuclear energy. First, Dr. Klaus Lackner, the scientist who initially suggested and pioneered the DAC mechanism, presented the MT as a novel invention that passively collects CO_2 by relying on wind to deliver ambient air, meaning no energy input is required - as shown in Figure 1 (Carbon Collect, n.d.).

Second, existing literature demonstrates a conflicted view on the use of membrane-based DAC systems (m-DAC), with some researchers doubting their effectiveness, while others arguing that they have the greatest potential and are the most cost-effective solution (Ozkan, 2021; Fujikawa et al., 2020; Fujikawa & Selyanchyn, 2022). Membrane filters have only been largely considered for PSC processes with minimal studies conducted to determine their definite effectiveness (Castro-Muñoz et al., 2022; Erans et al., 2022). Therefore, this article aims to predict and compare the cost-effectiveness of our prototype to its conventional counterparts through a localized simulation and techno-economic analysis. We believe the MT will passively collect the same amount of CO_2 as conventional fans, and the m-DAC will express a higher degree of efficiency than solid and liquid sorbent systems.



CAPTURE MODE

Tiles extend to 10 metres height and within 20 minutes become saturated with CO_2 from ambient air carried over by the wind.

Tiles are lowered mechanically into a chamber at the base.

REGENERATION MODE

Air is sucked out using a vacuum before regeneration occurs to pull off the CO_2 from the sorbent.

The offtake flows from the chamber after which the CO_2 is separated from H_2O using a standard process, allowing purity of up to 95% CO_2 (determined by the use case). The remaining 5% is Nitrogen.

The MechanicalTree™ extends again to full height to repeat the process.

Figure 1: An infographic showing the mechanisms of the MT in detail. The MT collects CO_2 from the ambient air before shrinking down to “drop off” the gas mixture to the filtering system; it then rises back up to repeat the process. Compared to the conventionally-used large fans that actively push air through a filter, MTs are able to capture air passively, which ultimately lowers the energy threshold to run the plant. From “MechanicalTrees^{TM}”, by Carbon Collect, n.d. (https://mechanicaltrees.com/mechanicaltrees/)

METHODOLOGY

To simulate the ideal scenario, we will restrict our model to an individual plant and assume several variables (location, elevation, temperature, and energy source) due to the high degree of uncertainty associated with DAC estimation. First, the plant will be located in a busy, urban area (e.g. downtown Toronto) where the CO_2 concentration is ~1000 ppm (Seppanen et al., 1999), which reduces the system’s energy requirement for air capture. Second, the plant will operate on flat terrain with a relatively low elevation point as CO_2 gathers in richer concentrations there; it is considerably denser than other gases found in the air (Murphy, 2022). Third, the temperature will affect the model’s performance, especially the membrane filter, but this only occurs at extreme temperatures (i.e. very hot or cold). It is, therefore, reasonable to assume a room temperature of 24°C. Fourth, because DAC systems require a substantial amount of energy to function, we intend to use a nuclear plant to power our system because nuclear energy is difficult to transport.

Next, we will introduce how our system works. First, the MT captures carbon via the natural movement of air. Sorbent tiles in the MT expand and retract to capture CO_2 from ambient air for <20 minutes (Carbon Collect, n.d.). Once saturated with air, the tiles are lowered underground into a chamber lined with a multistage membrane filter.

Inside, a vacuum pump will be present to facilitate the pressurized conditions and ensure the system’s integrity. Here, the parameters of the chamber (e.g. pressure ratio and stage cut) and the material of the membranes (i.e. composition, gas permeance and selectivity) are important and greatly impact the membrane’s performance (Fujikawa et al., 2020; Castro-Muñoz et al., 2022). Our system will follow Fujikawa et al.’s (2020) four-stage model and their simulation parameters: CO_2 concentration = 300 ppm in retentate gas at every stage, 101.3 kPa of feed pressure and a work vacuum of 5 kPa at the permeate, and a pressure ratio of 30. For the membrane material, we will use an ultrathin freestanding siloxane nanomembrane achieved by Fujikawa and his colleagues in another study (Fujikawa et al., 2019), which has an impressive CO_2 permeance of 40,000 GPU and selectivity of 70, but is currently not commercially available. In summary, as the air enters the chamber, the membranes filter the gas mixture via several mechanisms, such as molecular sieving through its nanopores, Knudsen-diffusion, and viscous (or Poiseuille) flow (Castro-Muñoz et al., 2020). At the first stage, the membrane module isolates one or two gases from the air mixture (e.g. N2) before passing it to the next module. Subsequent modules will continue isolating gases until CO_2 remains. Finally, the CO_2 will be compressed in pressurized vessels using capillary action. Once in an aqueous state, it can either be repurposed or stored depending on its purity level.

RESULTS & DISCUSSION

We will start by justifying our two most important control variables: location and the use of nuclear energy to produce electricity. As mentioned previously, because the energy requirement decreases significantly as the feed concentration (i.e. amount of CO_2 in air) increases (Fujikawa & Selyanchyn, 2022), m-DAC will be most cost-effective in areas with higher CO_2 concentrations than 400 ppm, such as office spaces (~1000 ppm) (Seppanen et al., 1999). We then chose nuclear energy as our primary source of fuel for this plant due to its cost, environmental friendliness, and convenience. Although renewables may be considered an ideal source, many are intermittent and periodically available, so their capacity factors are insufficient to power this plant (Michaelides & Michaelides, 2020). However, nuclear fusion (the process by which nuclear energy is produced) has a low generation cost, meaning nuclear power plants can exhibit higher capacity factors (Liang et al., 2022). Moreover, the total unit cost of nuclear energy is 6.8 cents/kWh in Ontario, which is cheaper compared to conventional natural gas (14 cents/kWh). Overall, this makes nuclear power an ideal candidate for its efficiency and cost-effectiveness over other energy sources.

For the choice of membrane material, we had many excellent options available from glassy and rubber polymers to amino polymers and other emerging membranes. Each type of material had its own strengths and weaknesses, but there were some overarching guidelines on how membrane modules should be constructed. High-performance membranes, which are favourable, should exhibit high gas permeance (>10,000 GPU), high CO_2 selectivity (> 30), and strong separation performance; the module itself should contain key parameters to maximize the CO_2 purity: high pressure ratio (>30) and low module stage cut (Castro-Muñoz et al., 2022; Fujikawa et al., 2020). For these reasons, we ultimately decided to pursue an ultrathin freestanding siloxane nanomembrane (permeance of 40,000 GPU and selectivity of 70) and follow the parameter suggestions of Fujikawa et al.'s simulation (2020).

Furthermore, it is important to mention that even with these ideal conditions, a two-stage process with commercially-available membranes could produce a maximum CO_2 purity of 50%, which is on par with existing solid DAC systems (Castel et al., 2021; Kiani et al., 2020). However, with the use of non-commercially available, high-performance materials (including our ultrathin membrane), CO_2 purity can reach levels of 98 - 99%. This means that the actual CO_2 purity of our prototype may be significantly higher above 50%.

We can further understand why m-DAC may be a more economically viable alternative than solid and liquid sorbents by comparing them from a techno-economic standpoint. In essence, m-DAC is able to provide equal, if not better, CO_2 capture rates/purity than solid and liquid systems at a significantly lower cost. For example, solid DAC systems require more energy and, therefore leads to a higher operating cost. The energy requirement of a solid-based DAC system is from \$0.02 - \$0.20/kWh (\$0.11/kWh on average) (Kiani et al., 2020), while m-DAC systems consume an average of \$0.039/kWh, making it extremely competitive among other DAC technologies (Fujikawa et al., 2020). Castro-Muñoz et al. (2022) confirmed this hypothesis and found that m-DAC only uses 0.5 - 0.6 MJ/kgCO_2, while solid and liquid systems require 2 - 3 and 4 - 6 MJ/kgCO_2, respectively. As a result, m-DAC may be a better alternative because it is

able to provide a better CO_2 capture ability (98 - 99%) at a significantly lower energy requirement (\$0.039 kWh and 0.5 - 0.6 MJ/kgCO_2). Finally, Table 1 below summarizes the key benefits of m-DAC over traditional sorbents.

CONCLUSION

In conclusion, m-DAC has immense potential to improve the outlook of carbon capture and the role it plays in actively removing CO_2 from the atmosphere. With high-performance materials, multistage operations, and ideal module conditions, m-DAC will become a powerful tool for many applications. While the ambitions are high and the implications are indeed profound, there is still much development to be done in determining "true" effectiveness based on realistic factors and applying the technology in real-world experiments. Although this is possibly due to the variability of m-DAC technology, there was a lack of research in finding a standard level of effectiveness (i.e. CO_2 capture rate or purity) and production cost for membrane capture systems, making it difficult to define how efficient m-DAC is in absolute terms. This in turn, made it challenging to directly compare m-DAC to its solid and liquid counterparts, which is why we resorted to a techno-economic analysis. Thus, future studies should aim to establish a common standard for CO_2 capture effectiveness and monetary requirement using realistic parameters.

Table 1: The five main advantages of m-DAC over conventional solid and liquid-based systems. These include a lower operational cost and energy requirement, a higher CO_2 capture percentage with high-performance materials, more potential for scalability, and a lower maintenance and risks of accidents.

	Solid and liquid-based systems	**Membrane-based systems**
Operational Cost	\$0.11/kWh (on average)	\$0.039/kWh
Energy Requirement	2 - 3 (solid); 4 - 6 (liquid) MJ/kgCO_2	0.5 - 0.6 MJ/kgCO_2
CO_2 Capture Purity	~50% (with current absorbent systems)	~98-99% (with high performance membranes)
Scalability	Require more infrastructure and energy to install; difficult for large-scale implementation (Kiani et al., 2020; Fujikawa & Selyanchyn, 2022)	Remote, small, and rapidly scalable (Fujikawa & Selyanchyn, 2022; Castro-Muñoz et al., 2022)
Maintenance	Liquid absorbents are vulnerable to dangerous accidents, such as liquid leaking, degradation, and equipment corrosion (Castro-Muñoz et al., 2022)	Simple to set up and operate; does not require any special chemicals or sorbents (Fujikawa et al., 2020; Ozkan, 2021)

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