Prospects for direct air capture

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The target of limiting the temperature rise to 2°C, as agreed upon in the Paris Agreement, requires maintaining atmospheric CO_2 levels below 450ppm. Since 1850, CO_2 concentration in air has rapidly increased from around 280ppm to over 410ppm. To realize 2°C temperature control target, carbon neutrality needs to be achieved between 2050 and 2070, which means net zero carbon dioxide emissions are achieved when anthropogenic CO_2 emissions are balanced globally by anthropogenic CO_2 removals over a specified period. However, the rapid increase in CO_2 concentration in the atmosphere caused by the utilization of fossil fuels in human life has brought great challenges to the realization of carbon neutrality. Negative emission technologies are necessary and can ensure that global net zero greenhouse gas emissions can be achieved even if some sectors or regions are net emitters.

Direct Air Capture (DAC) is a technology designed to extract carbon dioxide (CO_2) directly from the atmosphere, subsequently sequestering the captured CO_2 underground or repurposing it to prevent re-emission into the atmosphere. This process achieves a net-negative CO_2 emission effect, contributing to climate change mitigation. The concept of DAC was originally proposed by Lachner from Los Alamos National Laboratory to mitigate the climate change. As it is initially designed for capturing CO_2 from air, DAC is thought to be especially adapted for CO_2 capture near the small distributed or mobile CO_2 emission sources. Due to the extremely low CO_2 concentration in air, the feasibility of DAC causes controversy continuously since the birth of its concept. But due to the urgency of mitigating greenhouse gas emissions, huge CO_2 emissions into atmosphere continuousely and the success of real applications, DAC is getting more focus recently.

STATE OF THE ART OF DAC

In comparison to CO_2 capture from stationary sources, coastal blue carbon, and terrestrial carbon removal, DAC technologies offer the advantage of not being geographically restricted and can be employed to address CO_2 emissions in the vicinity of mobile sources. Currently, the DAC process typically comprises three main components: an air capture module, an absorbent or adsorbent regeneration module, and a CO_2 storage module, as illustrated in Figure 1. In the air capture module, most of the CO_2 in the air is adsorbed by solid adsorption materials or absorbed by liquid absorbents. Subsequently, in the absorbent or adsorbent regeneration modules, materials or solvents will be regenerated by heating or pressure/temperature swing adsorption. Also, the saturated sorbents/solvents can also be regenerated by moisture swing/pH swing. In CO_2 storage module, the collected CO_2 is fed into the storage tanks after compression. Compared with the CO_2 partial pressure of 12kPa in the flue gas from a coal power plant, the CO_2 partial pressure in air is only 40Pa. Thus membrane separation and cryogenic separation methods for DAC are restricted by the requirements to membrane area or equipment volume. Solution absorption and solid adsorption have become the mainstream processes for DAC due to their better adaptability to low partial pressure CO_2. Alkaline solution is typically used in the solution absorption process, and solid adsorbents mainly include alkali/alkaline-earth metal-based adsorbents, metal-organic frameworks (MOFs) type adsorbents, amine-based adsorbents, and moisture-swing adsorbents. Through more than 20 years of continuous development, many companies and research institutions have focused on scaling up laboratory achievements, and gradually build DAC demonstrations for commercial use through small-scale, prototype, and pilot tests. Carbon Engineering and Climeworks companies are early starters for research and development of DAC and they have built commercial scale demonstrations. Carbon Engineering and its partner companies plan to build the first large-scale commercial plant in 2024 to capture up to 1 Mt CO_2 per year for enhancing oil recovery.[1] Carbfix built the world's largest DAC/enhanced weathering system in 2017 and in 2021 entered into a groundbreaking agreement with Climeworks to build a 4,000 t/a capture plant at the ON POWER geothermal park in Iceland.[1] Zhejiang University has developed a small-scale DAC (30 kg/d), which adopts a variable humidity regener-

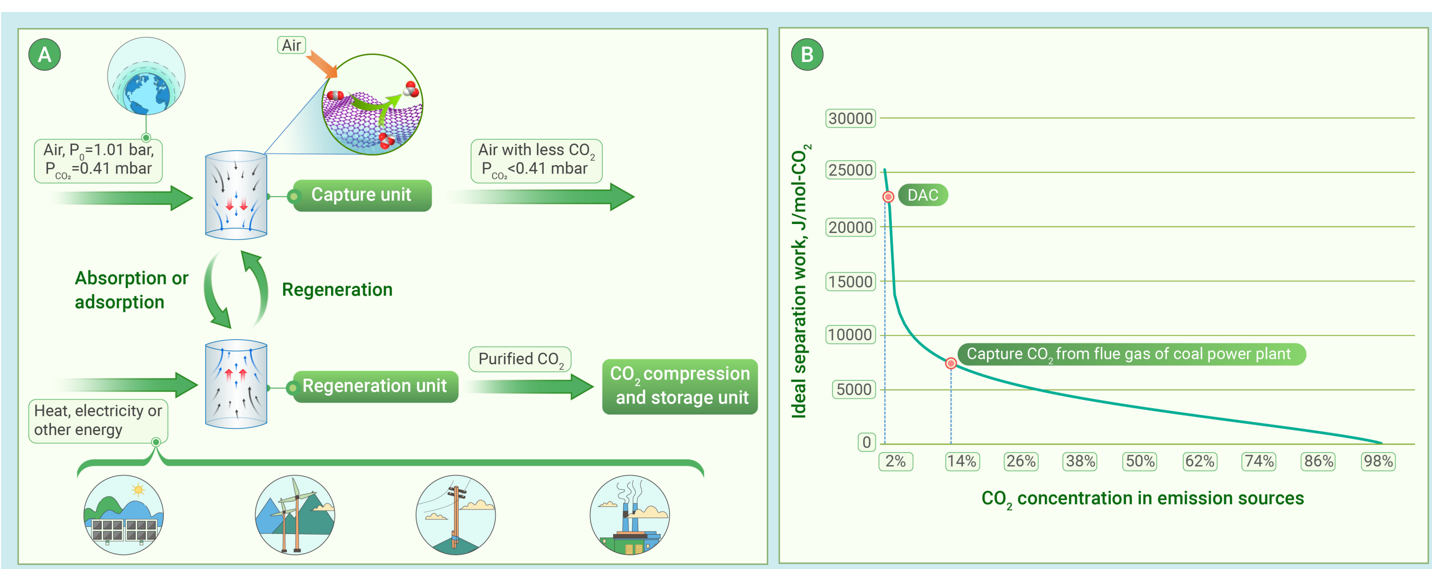

Figure 1. DAC concept, cost and its ideal energy consumption Now some pilot and commercial scale demonstrations are available for DAC. Heat and electricity requirements of capturing per ton CO_2 are 2118-2780 kWh and 440-494 kWh for DAC-alkaline solution method, and are 1400-2777 kWh and 218-694 kWh for DAC-adsorption method. The cost of DAC is 94-232 $/ton-$CO_2$ for alkaline solution and 300-600 $/ton-$CO_2$ for adsorption method.[2-5] As a contrast, cost of CO_2 capture or avoidance is 30-40 $/ton, 15-85 $/ton, 50-200 $/ton, 5-50 $/ton for coal power plant, biomass energy power plant, mineralization and efflorescence, and afforestation and reforestation, respectively.[2-5]

ation process to realize an integrated equipment and process for efficiently capturing, concentrating, and supplying CO_2 from an air source to agricultural greenhouses.[2]

CHALLENGES AND OPPERTUNITIES FOR DAC

The primary challenge confronting Direct Air Capture (DAC) technology is its elevated cost and energy consumption, with heat consumption ranging from 1400 to 2780 kWh and electricity consumption ranging from 218 to 694 kWh per ton of CO_2 captured. [2-5] The cost of capturing one ton CO_2 using DAC technology is approximately 97-600$. In 2018, Keith et al. calculated in detail based on pilot scale data that the cost of KOH solution absorbing air CO_2 was 94-232 $/t.[4] The cost reported by Climeworks company based on the operation of a commercial scale plant with a scale of 600-900 t/a CO_2 is 300-600 $/t, and it is anticipated that the investment cost can be reduced through scaling up.[5] The capture cost of the amine-based TVSA (vacuum temperature swing adsorption) method is expected to decrease to below 200 $/t in the short term.[5] Based on the prediction of the US National Academies of Sciences, the cost of DAC using solid adsorbents can be reduced to 88-228$/t CO_2 in the next decade.[2-3] The high energy consumption of DAC is primarily attributed to the low concentration of CO_2 in the atmosphere, which is only around 410 ppm and is much lower than that of stationary sources such as coal-fired power plants (10-14 percent CO_2 in the flue gas). In contrast, the heat consumption, electricity requirement, and cost for capturing one ton of CO_2 from a coal power plant are 600-620 kWh, 150-200 kWh, and $30-$40, respectively. From the thermodynamic perspective, the ideal separation energy consumption per unit of CO_2 using DAC technology is much higher than capturing CO_2 from the flue gas of coal-fired power plants. As shown in Figure 1, due to the low concentration of CO_2, the DAC technology requires a larger equipment when capturing the same amount of CO_2, further leading to the increased cost. Another significant factor contributing to the high cost of DAC is the absence of efficient and low-cost absorption/adsorption materials. Since CO_2 capture from air typically occurs at room temperature, physical adsorbents have poor adsorption capacity and selectivity. Chemisorption relies on chemical bonding forces for adsorption, and chemical adsorbent has a stronger capacity. But more energy will be consumed for CO_2 desorption to break the tight chemical bond. Therefore, the development of adsorbent materials with better performances (high adsorption capacity, high selectivity, better kinetics, lower regeneration energy, good chemical stability & mechanical stress etc.) is the key to the development of DAC. Additionally, the desorption process must be straightforward and energy-efficient, while the absorption/adsorption material should be capable of undergoing multiple cycles and economically viable.

Despite the extensive research and development efforts, Direct Air Capture (DAC) currently does not exhibit clear advantages in terms of energy consumption or cost compared to other CO2 mitigation technologies. After years of research and development, DAC technologies grows to be applicable in specific occasions. Despite extremely high energy consumption and cost limit further development of DAC, DAC may become one of the last CO_2 reduction technology when CO_2 concentration in atmosphere exceeds the limit of the Paris Agreement. Also, CO_2 emissions from stationary and mobile sources contribute to 60% and 40% of global emissions, respectively. The mobile sources are generally small scaled, distributed and numerous, and current technologies for stationary CO_2 emission sources such as power plants are unsuitable. DAC can be applied in these small distributed or mobile CO_2 emission sources due to its direct capturing CO_2 from air. DAC can be also equipped on the site of CO_2 storage and eliminates the extra CO_2 transportation, and provides a better technology solution for these emission sources. It is worth to be noted that these mobile sources also can utilize carbon free energy, and thus the competition of DAC is decided by its cost over the utilization of alternative energy. However, in some special sectors, e.g. some military applications where fossil fuel is irreplaceable and CO_2 needs to be removed, DAC has obvious competitiveness.

SUMMARY AND OUTLOOK

In conclusion, DAC, as a negative emission technology, will possibly play a certain role in carbon neutrality achievement. Despite initial doubts about its feasibility, continuous research and development spanning over two decades have led to some practical applications of DAC. However, the significant energy consumption and cost associated with DAC technologies, stemming from the low CO_2 partial pressure in the atmosphere, pose challenges for widespread large-scale implementation in the future. Decrease in energy consumption and cost of DAC depends on the development in adsorption/absorption materials with better performances (such as better selectivity, CO_2 working capacity, kinetics, regeneration energy, chemical stability, and mechanical stress), and is also decided by the improvements in processes and compact equipment. CO_2 regeneration driven by waste heat in industry, or the development of efficient gas-solid contactor and the accessibility of cheap and renewable energy sources could further reduce energy consumption and cost of DAC.[3] However, DAC's unique advantages in capturing CO_2 from air near mobile or small distributed emission sources underscore its application potential in specific scenarios. Additionally, given the ongoing debates and uncertainties surrounding emission reduction responsibilities, DAC could serve as a valuable tool if efforts to control temperature rise prove unsuccessful and irreversible. In such a scenario, DAC may represent one of the final solutions to mitigate the concentration of CO_2 in the atmosphere.

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DECLARATION OF INTERESTS

The authors declare no competing interests.