Removing Carbon Dioxide from the Atmosphere: Scientific, Technological and Societal Challenges

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Over 150 years of fossil fuel combustion has increased the global atmospheric carbon dioxide (CO_2) concentration from approximately 280 ppm in pre-industrial times to almost 400 ppm today. Due to the strong link between the rising atmospheric CO_2 concentration and global climate change, we now live in a "carbon-constrained" world, with a strong push from scientists, engineers, segments of the public, and scientifically literate policy-makers for rapid development of alternative energy sources. However, the coupling of growing population and the ever-increasing global standard of living means that increased energy demand will continue. Although a worldwide effort is focused on development and deployment of renewable energy technologies, the pace of development is outpaced by the growth of energy demand. For this reason, fossil energy will continue to supply the preponderance of global energy for generations.

Given continued reliance on fossil energy, global CO_2 emissions will keep rising, hastening climate change. Today, CO_2 emissions from fossil fuel combustion are associated with three broad categories, (i) electricity production from coal or gas-fired power plants (ca. 33-50% of total), (ii) land, air or sea transportation (ca. 33% of total), and (iii) other industrial uses. To date, global climate and energy strategies addressing anthropogenic emissions have focused on capturing the CO_2 emitted from the world's largest point sources – coal-fired power plants. This can be done in a variety of ways, for example by modification of existing plants to capture the CO_2 produced (i.e. post-combustion capture or PCC), or by designing new plants that allow for more efficient CO_2 capture. However, it should be noted that these approaches, even if widely adopted, would only address the 33-50% of CO_2 emissions associated with large point sources.

CO_2 Capture from Point Sources Cannot Address Mobile Emissions

The most difficult CO_2 emissions to address are those associated with transportation. On-board CO_2 capture from mobile sources such as automobiles and airplanes is currently impractical. While the electrification of passenger vehicles is (very slowly) shifting some energy use for transportation to large electricity-generating point sources, some mobile CO_2 sources, such as planes, will likely never be electrified. Thus, alternative technologies for addressing CO_2 emissions from mobile sources are needed.

Direct Capture of CO_2 from Air or "Air Capture"

In 1999, Klaus Lackner first proposed the widespread development and deployment of devices that extract CO_2 directly from the atmosphere as a way to address global CO_2 emissions and climate change (Lackner et al.). Although initially considered as an alternative to capture from large point sources, the direct capture of CO_2 from the air, or "air capture," is now generally considered a complimentary technology to point source capture. The implementation of these two technologies together could allow long-term use of fossil energy while slowing or mitigating the impacts of anthropogenic CO_2 emissions on climate change. Furthermore, unlike other climate mitigation options—often described as geo-engineering, whereby humans tinker with the

planet to influence climate—CO_2 capture from air can be viewed as a potentially safer option, a form of traditional pollution control.

So why have we not widely implemented PCC and air capture broadly? Because today, in the absence of a price on emitted carbon, there is no incentive for the private sector to adopt such technologies. A recent study published by the US Department of Energy suggests that 90% of the coal-fired powerplants in the US could implement PCC at a cost of approximately $60 / ton CO_2 captured (Nichols, 2011). However, as an emerging technology, there are far fewer detailed technoeconomic descriptions of air capture processes, with the limited reports to date offering a wide array of estimated costs. Some studies of air capture processes based on CO_2 absorption using basic alkaline hydroxide solutions suggested costs of $500-1000 / ton CO_2 (House et al.), whereas a more recent evaluation of a second-generation technology based on use of supported amine adsorbents suggests costs closer to $100 / ton CO_2 (Kulkarni and Sholl).

The Technical Challenge of Air Capture

Most gas separation processes considered for air capture are based on CO_2-absorbing liquids or CO_2-adsorbing solids, with the overall process passing through cyclical stages of adsorption and desorption, as shown in Figure 1. This overall approach is common and is employed in a variety of scalable gas separation technologies currently practiced today. However, direct capture of CO_2 from the air has a unique challenge associated with the ultra-dilute nature of CO_2 (ca. 400 ppm) in the atmosphere, compared to most large scale gas separation processes. Despite this unique challenge, air capture also has some key advantages over PCC, for example the ability to locate the capture process anywhere in the world, due the fact that the ambient air is largely uniform in composition. This allows for siting processes at locations appropriate for CO_2 use or sequestration, negating the need for transport of concentrated CO_2 in pipelines over long distances.

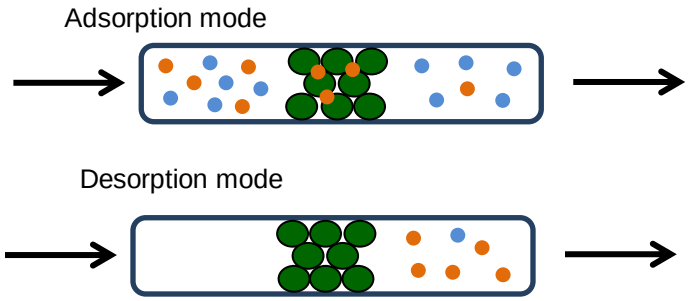

Figure 1: Gas separation processes based on adsorption onto solid are cyclical in nature, with an adsorption cycle (top) selectively removing some gas species (orange) by adsorption on a solid (green) yielding a purified exhaust, followed by a desorption cycle (bottom) liberating a concentrated product, most often induced by a pressure and/or temperature change.

Five important criteria can be outlined for any truly relevant air capture process. (1) Because of the low concentration of CO_2 in air, very large volumes of air must be moved through the process, about 125 times and 375 times more than for CO_2 capture from a natural gas fired or coal fired power plant, respectively, assuming an equivalent capture fraction. Thus, to prevent excessive energy requirements for gas movement, any air capture process must have very low pressure drops associated with flow through the process. (2) Also associated with the low ambient CO_2 concentration, air capture processes must employ materials/fluids with high CO_2

capture capacities, via use of materials with a very high density of adsorption sites and/or very strong CO_2-adsorbent interactions. (3) A practical air capture process must also have favorable adsorption kinetics to allow for short cycle times, as long cycle times would lead to impractical plant sizes associated with large inventories of adsorption media. (4) Because absorption and adsorption are exothermic processes, the removal of CO_2 from the capture media for concentration is endothermic and can require significant energy input. This regeneration energy must be provided at low cost, ideally in the form of low grade waste heat. (5) Finally, the process equipment and adsorption media must have a suitably long lifetime, as the above factors will make air capture a capital-intensive process with large plant sizes compared to many traditional gas separation processes.

Extraction of CO_2 from Air via Adsorption on Amines

A wide variety of CO_2-adsorbing materials have been considered for use in PCC processes. For air capture applications, the scope of materials can be dramatically decreased, as processes must operate near ambient temperature and pressure, and offer good adsorption capacities under ultra-dilute conditions. Supported amine materials, a class of solids functionalized with organic amine sites, are the only materials developed so far that offer large CO_2 capacities under air capture conditions and operate near ambient temperature. Several research groups have recently reported the suitability of such materials for CO_2 capture from ultra-dilute gases (Goeppert et al.).

As an example of a process that shows the potential to meet the five key requirements outlined above, one may consider a process based on supported amine adsorbents coated on the surface of a high surface area, structured contactor, such as a ceramic monolith. These contactors are already produced on a large scale for use in catalytic exhaust gas clean-up and offer a low-cost route to high surface areas with low pressure drops. These materials can be coated with amine adsorbents, and flow of air through the adsorbent lined channels at high velocity allows for rapid CO_2 adsorption kinetics. Desorption is achieved by flowing low grade saturated steam (70-105 ºC) through the monoliths and over the adsorbent layer, providing both a thermal and concentration driving force for desorption. Steam in this temperature range can be obtained as low grade waste heat from a variety of industrial processes, or produced via solar-thermal heating at low cost. The concentrated CO_2 product can be obtained from the steam/CO_2 mixture via condensation or compression. Finally, the robust nature of the monolith contactor offers promise for long-term stability of adsorbent materials. The above description is only a single process possibility, and undoubtedly there are other promising approaches as well.

Outlook for Air Capture

While the scientific and technological possibilities surrounding development of practical processes for CO_2 extraction from air appear promising, future development of such technologies hinges on an array of social and political complexities. While almost $7 billion federal dollars have been spent to date on research and development on carbon capture from large point sources, the total federal investment for CO_2 capture from air may be as little as $300K. Given this fact, essentially all investment in air capture technologies in the US has been private, and thus, in the absence of a carbon tax, initial deployments of air capture technologies will be focused on delivering a concentrated CO_2 product for profitable industrial use, such as in greenhouses, enclosed algal bioreactors, or for enhanced oil recovery. Thus, CO_2 capture from ambient air, or “air capture,” is an emerging technology that, if deployed on a large scale alongside traditional post-combustion capture, could play a critical role in stabilizing or even reducing global atmospheric CO_2 levels. However, its development currently lies entirely in the

hands of private enterprise, meaning initial deployments will focus on profit-generating applications, with technological developments perhaps leading to implementation of air capture as a climate change mitigation strategy in the future.

Disclosure

The author collaborates with and has a financial interest in Global Thermostat, LLC, a company actively engaged in commercializing technology for CO_2 capture from ultra-dilute gases.

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