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Carbon Capture and Sequestration

mechanical compression to provide the work of separation and will not provide competitive energy consumption. In addition to separating oxygen for the production of CO₂, stoichiometric oxygen (about 20%) must be provided for hydrogen contained in the coal and for the excess required for adequate combustion (about 15%). Consequently, the estimated work for oxycombustion starts at 0.22 MWh. This estimate does not include the irreversibility of the exchangers and distillation columns in the air separation unit, nor does it include the irreversibilities of compressing the excess and leakage air along with the CO₂.

Amine scrubbing will be applied first on large coal-fired boilers with 12% CO₂. It would also be useful with boilers fired by biomass at 14% CO₂, cement plants at 25% CO₂, and steel works with 25% CO₂. It will be less attractive with gas-fired combined cycles at 4% CO₂ or gas- or oil-fired boilers or heaters at 7% CO₂. Amine scrubbing, in use for nearly 80 years, is a robust technique that is ready to be tested and used on a scale

appropriate for CO₂ capture from coal-fired power plants. Process and solvent improvements should reduce the energy use to 0.2 MWh/ton CO₂. Other advanced technologies will not provide solutions as energy-efficient or as timely to decrease CO₂ emissions from conventional coal-fired power plants.

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PERSPECTIVE

Why Capture CO₂ from the Atmosphere?

David W. Keith

Air capture is an industrial process for capturing CO₂ from ambient air; it is one of an emerging set of technologies for CO₂ removal that includes geological storage of biotic carbon and the acceleration of geochemical weathering. Although air capture will cost more than capture from power plants when both are operated under the same economic conditions, air capture allows one to apply industrial economies of scale to small and mobile emission sources and enables a partial decoupling of carbon capture from the energy infrastructure, advantages that may compensate for the intrinsic difficulty of capturing carbon from the air.

Even if we could halt human carbon emissions today, the climate risks they pose would persist for millennia—assuming that we must rely only on natural processes to dissipate our carbon cycle perturbation and the resulting climate changes (1). The impact of carbon emissions persists longer than that of nuclear waste (2), the archetypical long-lived waste product. An immediate emissions halt is essentially impossible, however, and simple extrapolations of emission trends suggest that even with strenuous efforts to limit emissions, CO₂ concentrations in the atmosphere will rise beyond 450 parts per million before mid-century, passing the level commonly invoked as a ceiling above which the risk of dangerous climate change becomes unacceptably high. Moreover, the climatic response to elevated CO₂ concentration is uncertain, so a small risk of catastrophic impacts exists even at today's concentration, and that risk grows

monotonically as emissions continue to drive up the atmospheric CO₂ burden.

Technologies for decarbonizing the energy system, from solar power to the capture of CO₂ from the flue gases of coal-fired power plants, can cut emissions but they cannot reduce the climate risk posed by the carbon we have already added to the air. It may be possible to increase Earth's reflectivity, engineering a cooling that counteracts the CO₂-driven warming (3, 4). Although climate engineering may be important for managing climate risk, it cannot eliminate the long-term climate and geochemical risks posed by elevated CO₂. It is therefore in our interest to have a means to reduce atmospheric CO₂ concentrations in order to manage the long-run risks of climate change. Unless we can remove CO₂ from the air faster than nature does, we will consign Earth to a warmer future for millennia or commit ourselves to a sustained program of climate engineering.

Air capture is an industrial process that captures CO₂ from ambient air, producing a pure CO₂ stream for use or disposal (5, 6). It is one of an emerging set of technologies for remov-



ing CO₂ from the atmosphere that includes biomass energy with CO₂ capture, along with various means of accelerating geochemical weathering (7, 8).

Over the long run, the ability to remove CO₂ from the air should be viewed as an essential tool in our kit for managing carbon-climate risks. We therefore need, at the minimum, a serious long-term exploratory research effort to develop air capture along with other direct methods for removing CO₂ from the atmosphere.

In the near term, efforts to limit climate risk should focus on reducing emissions. Capturing CO₂ from the air, where its concentration is 0.04%, might well seem premature, given that there is still no power plant in which CO₂ is captured from the full exhaust stream. One might well conclude that there is little reason to develop and deploy air capture in the coming decades, before we can reduce emissions to the near-zero level where the ability to drive global emissions negative becomes relevant. The global energy system is marvelously diverse, however, and in

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that diversity there are important niches where air capture might play a role in reducing emissions in the near term, long before we are able to bring emissions near zero.

Near-term development of air capture only makes sense if it can be realized at a sufficiently low cost. Two factors make capture from air more difficult than from exhaust streams: first, the higher thermodynamic barrier due to the lower concentration of CO₂ in air; and second, the energy and materials cost of moving great quantities of air through an absorbing structure. These factors present a smaller barrier than one might expect from the 300:1 difference in partial pressure between CO₂ in power plant exhaust and in the ambient air. The energy required to separate gases scales as the log of partial pressure, and if one includes the energy needed for compression to pipeline pressures, the thermodynamic minimum energy required for air capture is only about 50% larger than for a post-combustion process (5).

It is nevertheless clear that air capture will always cost more than post-combustion capture from power plants if both facilities are designed and operated under the same economic conditions. Economics tells us, however, that there is surprising value in the freedom to build a capture plant where the costs of construction and operations are cheap. Moreover, air capture allows one to apply industrial economies of scale to a myriad small and hard-to-control CO₂ emitters such as aircraft and home furnaces. Finally, air capture enables the partial decoupling of carbon capture from the energy infrastructure, easing the constraints that arise when new energy technologies must be integrated into the existing infrastructures and making it easier to build a capture plant near the best sequestration sites (5, 6, 9).

In combination with the carbon market, air capture might allow carbon to be physically removed in the most cost-effective circumstances, eliminating the necessity for controlling the most expensive sources (such as aircraft) even if it is necessary to reduce net carbon emissions to zero. Air capture thus enables a physical carbon arbitrage distinct from the arbitrage achievable by carbon markets. The near-term value of air capture is thus rooted in its ability to exploit niches opened by the technological and economic diversity of our energy systems.

The benefits of air capture are moot, however, if the costs are unacceptably high. The cost of air capture is uncertain and hotly disputed. Some have argued that the costs would be prohibitively high (10), or that investing funds in research on air capture is a mistake because it diverts attention from more important areas (11). In sharp contrast, others have argued that air capture might be comparatively inexpensive and that it could play a central role in managing CO₂ emissions (6, 12).

Air capture is neither a silver bullet nor a hopeless dream: It is simply another chemical engineering technology. Disputes about cost can

only be resolved by developing a few air capture technologies to the point where they can be independently evaluated. Costs cannot be understood until specific processes are developed to a far greater technical depth than has been achieved to date. As with other energy technologies, it is not possible to determine the cost through small-scale university research alone. Instead, costs will only become evident with pilot-scale process development and when costing can be performed by contract engineering firms with relevant expertise.

Current research on air capture technology is centered on a handful of academic groups or small start-up companies. At least two groups are using a solid sorbent system that is regenerated in situ: One method uses ion exchange membranes with humidity-swing regeneration (6, 13), whereas the other uses solid amines on a mesoporous silica substrate similar to those that are being developed for CO₂ capture from power plants (14). Most of the other methods start with the absorption of CO₂ by an alkaline aqueous solution, which typically makes the capture step cheaper but raises the cost of regeneration. The method pursued by my group, for example, captures CO₂ with alkali hydroxide solutions, which are strongly absorbing, contamination-insensitive, and can have minimal water loss, factors that lower the cost and technical risk of the absorption step. The tradeoff is the large energy demands of the regeneration step, which is a variant of the caustic recovery processes used in the pulp and paper industry, chosen to maximize scalability and minimize technical risk (15, 16). Our baseline system uses natural gas as an energy source, but others are developing solar kiln technology for air capture (17). Finally, at least two other groups are using electrochemical cells to regenerate the spent caustic solution (18), and another aims to reduce the cost of regeneration by using a much weaker hydroxide solution to lower the regeneration energy, in combination with catalysts to overcome inherently slower CO₂ uptake of the weaker absorbent (19).

There are no government funding programs that specifically target the development of air capture, and I estimate that the total annual expenditure for these efforts is currently less than \$3 million per year, of which more than half is private. A more substantial investment of government R&D funding is warranted for at least three reasons. First, early estimates suggest that air capture will be competitive with technologies that are getting large R&D investments. For example, the cost of cutting CO₂ emissions by displacing carbon-intensive electricity production with roof-mounted solar photovoltaic panels can easily exceed \$500 per ton of CO₂. Yet even skeptics (10) suggest that a straightforward combination of existing process technologies could probably achieve air capture at lower cost. And the fact that several groups have raised private money for commercialization suggests that there

are investors who believe that it is possible to develop technologies to capture CO₂ from air at costs closer to \$100 than \$500 per ton of CO₂.

Second, air capture offers one route to make carbon-neutral hydrocarbon fuels (CNHCs) for vehicles by using captured CO₂ to make synthetic fuels. Deep reductions in emissions from the transportation sector will require a change in vehicle fuel. Each of the three leading alternative fuel options—electricity, biofuels, and hydrogen—faces technical and economic hurdles that preclude major near-term reductions in transportation emissions. CNHCs represent a fourth, fundamentally different alternative: a method for converting primary energy from carbon-free sources such as solar or nuclear power into high-energy-density vehicle fuels compatible with the current vehicle fleet. It is unclear whether CNHCs will be competitive with the three leading alternatives, but they are promising enough to warrant R&D support on a par with efforts aimed at advancing the alternatives (20).

Finally, air capture allows negative global CO₂ emissions. Although this is a distant prospect, it is important because it represents one of the few ways to remediate human impact on the carbon cycle, an impact that is otherwise all but irreversible (1, 5).

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