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PUTTING COSTS OF DIRECT AIR CAPTURE IN CONTEXT

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Abstract

This working paper provides an overview of various estimates and claims on direct air capture (DAC) of carbon dioxide, and places them in a broader context of global climate policy. Unlike other techniques of climate engineering, DAC has received significant attention from startups since its main issue is deemed to be the direct implementation cost (not side effects or social concerns), which could be significantly reduced with successful innovation. Publicly available sources demonstrate that there is a huge range of cost estimates with three orders-of-magnitude differences, with the upper end on the order of 1000 USD/t-CO_2. Cost values reported by private companies tend to be lower than academic estimates, though there is no a priori reason to believe that either is inherently biased. In light of this huge uncertainty, the only way to resolve it may be to build an actual plant at scale, as a leading scholar put it. It is nevertheless important to monitor technological progress since climate policy analysis would increasingly require such cost parameters and because technology understanding would guide policy of research and development of this nascent technology. A periodic review of this nature would provide a basis to ascertain the progress of DAC technology development.

Introduction

Among many techniques of carbon dioxide removal (CDR) or negative emissions technologies (NETs), direct air capture (DAC) of carbon dioxide stands out as it attracts a conspicuous group of stakeholders: investors and entrepreneurs (Cressby 2015). DAC represents "an industrial process that captures CO_2 from ambient air, producing a pure CO_2 stream for use or disposal" (Keith 2009). The Center for Carbon Removal even hosted a webinar titled "Future Voices in Direct Air Capture" in August 2016, inviting startup companies developing DAC technology (including a spin-off from an established player).[1] Though the number of companies is relatively small, the group is growing, and increasingly receiving public funds as well (e.g., Climeworks). There are issues with large requirements of energy and water (Smith et al. 2016), but the main concern with DAC is the direct financial cost (Keith 2009), which successful innovation could potentially reduce. This is in sharp contrast with ocean iron fertilization, large-scale afforestation and bioenergy with carbon capture and storage (CCS) and the like, for which debate is dominated by concerns about substantial risks of various side effects.[2]

In this paper, we mean by the cost of DAC the direct financial cost of implementing this technology, excluding any externalities not covered by current policies and regulations.

The cost of DAC is important not just from the viewpoint of profits but also from the perspective of climate policy. The Paris Agreement recognizes the role of negative emissions technologies to balance emissions and carbon sinks in the latter half of the 21st century (Horton et

1 See http://www.centerforcarbonremoval.org/blog-posts/2016/8/17/event-recap-future-voices-in-direct-air-capture
2 Another important issue with CCS is potential leakage of captured CO_2.

al., 2016). But there is more to consider. DAC may turn out to be a backstop technology, capping the marginal cost of abatement of greenhouse gas emissions and acting an anchor for climate policy goals (Allen 2016). Better cost estimates would also enable integrated assessment models (IAMs), a very influential set of policy analysis tools, to incorporate DAC in their mitigation portfolio. Few exercises treated DAC explicitly so far (e.g., Chen and Tavoni, 2013; Fuss et al., 2013). As the negotiators decided to decarbonize the global economy and seek to contain global warming below 2 or 1.5 degrees Celsius under the Paris Agreement, exploring such a solution is of the utmost necessity.

Because of its importance, there have been some debates on the cost of DAC, even within expert circles. As Keith (2009) notes, DAC is not a magic technology. For applications like the International Space Station or submarines, this technology is already being regularly utilized. The real question is whether one can create a scalable technology, and particularly at low cost. Some touted the potential low cost of DAC (e.g., Holmes and Keith 2012) whereas an expert committee at the American Physical Society (APS 2011) and House et al (2011) cautioned on such optimistic estimates.[3]

This white paper tries to capture the snapshot of cost estimates and claims from various sources in order to provide a reality check and stimulate policy discussions. Because much of research and development activities happen within the private sector (with some public support)[4], our attempt is destined to be incomplete; a startup may rightfully conceal its technology and cost

3 The author of the paper (House et al. 2011) felt that even the APS report was optimistic. See IEAGHG (2012).
4 For example, Climeworks in three projects under the EU Horizon 2020 scheme (Climeworks 2016).

information to stave off competition. We nevertheless compiled a reasonable coverage of cost data from industrial and various sources. A periodic review of this nature would provide a basis to ascertain the progress of DAC technology development.

Unlike an academic report, we consider this working paper a living document. We made our best efforts to collect up-to-date information on various cost numbers. If one thinks that some numbers are misrepresented, we are happy to correct it.

The rest of this white paper is organized as follows. Section 2 briefly gives a technology overview. Section 3 summarizes commercial R&D activities and cost estimates. Section 4 provides a possible way forward.

Description of DAC technologies

We now briefly review DAC technologies. The intent here is not to be comprehensive but to provide a launch point for the summary table in the following section. For a comprehensive review on the academic literature of DAC technologies, including those on the cost estimates, see Micah Broehm et al. (2015) and Sanz-Pérez et al.(2016).

We can classify DAC technologies by how CO_2 is absorbed or adsorbed. Here we consider (1) liquid sorbents and (2) solid adsorbents.

(1) Liquid Sorbents

Liquid sorbents used in a typical DAC system are alkaline solution such as NaOH and KOH. Figure 1 shows a schematic flow of DAC using liquid sorbents. When the ambient air is passed through a base (NaOH alkaline solution in this case), acidic gases such as CO_2 are captured. The alkaline solution that contains CO_2 is mixed with $Ca(OH)_2$ solution to precipitate in the form of $CaCO_3$. Precipitated $CaCO_3$ is pressed to remove water. Precipitation is heated at around 800C to separate gaseous CO_2 and solid CaO. Separated CaO can be used as $Ca(OH)_2$ by hydration.

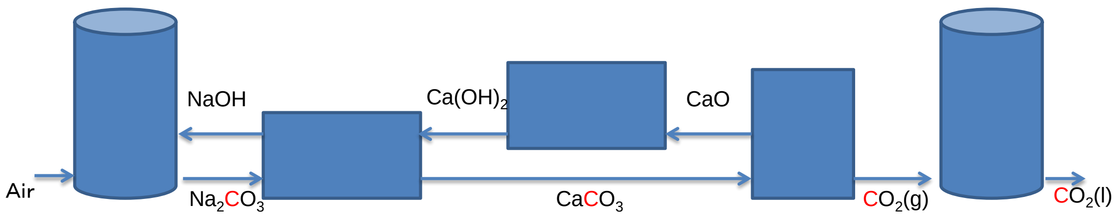

Figure 1: Schematic flow of DAC using liquid adsorbent (Keith, 2006). Captured carbon is highlighted in red.

(2) Solid adsorbents

Ambient CO_2 is captured in a strong-base ion exchange resin. The filter of the DAC technologies using solid adsorbents is made of the ion-exchange resin. There is a variety of filter shapes because of the flexibility of the resin. Air flow into the filter is produced by a fan or blower. Natural air flow could also be used. Saturated filters are regenerated by putting it in moisture circumstance or heating it to release captured CO_2. Figure 2 shows a schematic flow of DAC using a solid adsorbent.

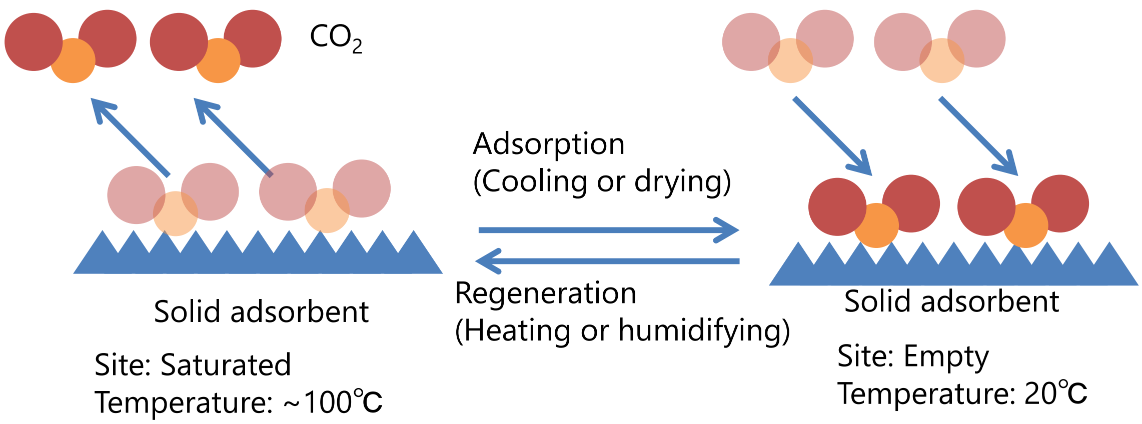

Figure 2: Schematic flow of DAC using solid adsorbent

In the following, we put our emphasis on the cost, but one should remember that the DAC requires a huge amount of energy and water. For instance, Smith et al. (2016) suggest an energy requirement of ~150EJ/y for an annual removal rate of 12.1GtCO2 in 2100. This can be contrasted with the 2014 global final energy consumption of 395EJ/y (IEA 2016).

Cost estimates by DAC companies

We have collected academic publications and various industrial sources (mostly company websites) to compile cost estimates of DAC systems and place them in context (Table 1; Figure 3). We also asked companies and the Center for Negative Carbon Emissions for technical and economic information. The assumptions for cost estimates are not available in many cases, especially for the cost the company claims. We use the figure they claim as is in this working paper.

The following is a brief description of the technology of each company. Note that Carbon Engineering, Global Thermostat, Climeworks, Carbon Sink, and Coaway are nominated as finalists of Virgin Earth Challenge.[5]

Cost estimates by technology developers

Carbon Engineering (CE) led by David Keith is developing a technology using a combination of KOH and $Ca(OH)_2$ solutions. A prototype became operational in 2011. The 1 t-CO_2/day demonstration plant has been in operation since October 2015. CE envisages that their DAC technology is applicable to large scale CO_2 demand such as enhanced oil recovery. Keith (2006) estimated the CO_2 capture cost to be 136USD/t-CO_2 under the condition of 4USD/GJ of heat and carbon free electricity of 0.07 cent/kWh. A reason for its low capture cost is that the technology is similar to mature paper manufacturing technologies.

The Center for Negative Emission of Arizona State University (led by Klaus Lackner) is developing a DAC technology based on ion exchange resin. It is assumed that the whole equipment is stored in a shipping container. Lackner (2009) estimated the capture cost to be 30~200 USD/t-CO_2. Further cost reduction is expected by mass production in the journal paper. When the filters are regenerated, water to desorb CO_2 and electricity for moving parts is necessary (humidity swing). The required energy for regeneration is 50 MJ/mol.

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5 See http://www.virginearth.com/finalists/

Global Thermostat is developing “amine based chemical sorbents bonded to porous honeycomb ceramic monoliths.”[6] The demonstration plant has been operated at SRI International. The capture cost at the scale of 1 million tons per year is estimated to be 10 to 35 USD/t-CO_2. Energy required to capture is 160 kWh/t-CO_2, 4.4 GJ/t-CO_2 (95 C steam).

Climeworks, located in Switzerland, is developing a CO_2 filter that is a kind of solid adsorbent. They sold the first commercial plant of 900t-CO_2/year for greenhouses in October 2015. It was reported that Climeworks and Danish engineering company Union Engineering started to develop a plant that supplies beverage-grade CO_2 funded by the Eurostar program. Heat of 1800 – 2500kWh/t-CO_2 (100 C) and electricity of 350 – 450 kWh/t-CO_2 are required for regeneration.

Carbon Sink focuses on technology to supply CO_2 for greenhouses. The capture technology is based on amine-based ion exchange resin. They said that the capture cost is less expensive than CO_2 supplied by cylinders or by fossil fuel combustion. The regeneration method is humidity swing that is similar to that of the Center for Negative Emission of Arizona State University.

The system Coaway is developing is based on alkaline solution to capture atmospheric CO_2. It is assumed that the solution is regenerated by waste heat from adjacent power plants or oil refineries. The quantity of heat is not available. They mentioned the capture cost of CO_2 is less than 20 USD/t-CO_2 in the case of waste heat utilization from a power plant.

Skytree is a spin-out company from ESA (European Space Agency) and develops their CO_2 capture technology. CO_2 is captured on an electrostatic site distributed in porous plastic beads. The

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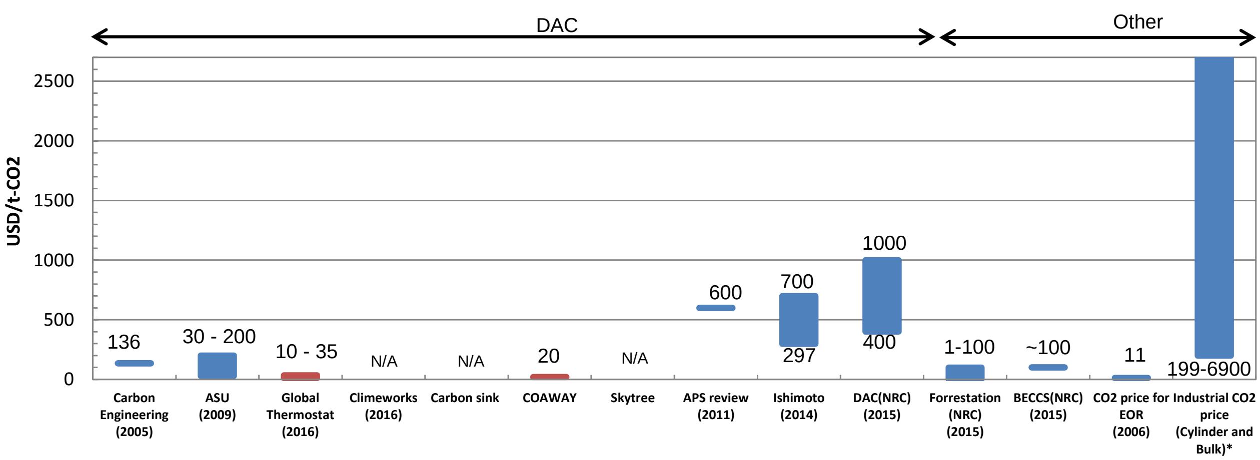
6 See http://globalthermostat.com/a-unique-capture-process/

energy requirement of regeneration is not available. One of the initial markets they are targeting is algae growth enhancement in aquariums.

Other studies

Ishimoto et al. (2014) implemented sensitivity analysis of DAC cost. Investment costs used in the sensitivity analysis were mainly based on the aforementioned APS study (2011). The National Research Council (2015) also provides cost ranges of DAC, afforestation and bioenergy with carbon capture and storage (BECCS).

Figure 3 combines and compares cost estimates from various sources.



*The price supplied by a cylinder is in 2016 and the price of bulksupply is the average of 2004-2014.

Figure 3: Capture cost of DAC, other technologies and industrial CO_2 gas prices. Blue bars are from various publications. Red bars are from the webpages of the companies. The assumptions for cost estimates are not available in many case especially for the cost company claims. We use the figure they claim as is in this white paper. The CO_2 Price for EOR (Enhanced Oil Recovery) is from Steeneveldt (2006).

Comparing different cost estimates

As is clear from Figure 3, although the cost uncertainty in the academic literature is vast, the costs claimed by startup companies are often lower than values in the academic literature (we discuss this point further below). In particular, an authoritative panel of the American Physical Society suggested a cost of 600USD/t-CO_2, which is much higher than what businesses suggest is possible.

There could be a multitude of reasons for such a discrepancy, but one that is avoidable is a possibility that the companies and academics are examining different system designs, as pointed by Holmes and Keith (2012). The next round of such a study should at least make cost estimates as much consistent with company designs as possible, by involving (or seeking inputs from) the industry and startups.

Another important point is to look at not only the total cost but also component-level costing, a point also raised by Holmes and Keith (2012). Though we may not be able to agree on the overall cost of a DAC system, some subsystems might be more amenable to consensus. For example, Holmes and Keith (2012) suggest that the contactor cost would be on the order of 60 USD/t-CO_2. This would further illuminate the area where uncertainty is highest and more research is needed.

Last but not least, the cost is not the only factor to consider. The effect of DAC should be evaluated on a comprehensive, life-cycle basis. Smith et al. (2016) have shown that DAC more energy-intensive than most other types of NET/CDR and on par with enhanced weathering. It would be helpful to substantially reduce energy intensity of DAC, and power it with zero-carbon energy to the extent feasible.

Niche market for DAC

As recently summarized by Nemet (2016) in the context of NET/CDR, specialized, niche markets are of critical importance for a new innovation. New technologies need a space where they can be tested and improved while they are supported by an actual market, not by a huge state subsidy. Such a niche market does not have to be supported by climate policy. Rather it can be CO_2 for food and beverages or CO_2 for enhanced oil recovery since some technological features of DAC might provide competitive advantages over existing CO_2 sources.

Our analysis shows that DAC does have a niche, initial market. The present CO_2 market is approximately 80 million ton per year. The current or potential demands include enhanced oil recovery (30-300 Mt/y), urea yield boosting (5-30Mt/y), food processing, preservation and packaging (~8.5Mt/y), and beverage carbonation (~8Mt/y) (Parsons Brinckerhoff 2011). The price of CO_2 in a cylinder or in bulk is higher than the cost numbers from various sources. Also, such a market is not the only one available. The price of carbon dioxide used for enhanced oil recovery (EOR) is ~11USD/t-CO_2. EOR might not contribute to the overall goal of climate change risk management over the long-term, but still it may contribute to innovation in the technology to capture CO_2 from the air. Regardless of the actual choice of niches, the DAC technology will have some initial markets. Whether these niche markets are sufficient in size and price remains to be seen.

Prospects for DAC in the near term

The fact that the DAC space is dominated by startups reflects that the business of building a DAC system is a high-risk, high-return undertaking. We will not know which companies (if any) will succeed, nor whether an industry will grow in the future.

Because of the inherent risk in technology development, it is rather difficult to monitor the progress of this nascent technology. If the field is showing some progress and needs some push from the government, discussions about technology itself are a prerequisite. In light of the crucial role backstop technologies are expected to play in the decarbonization objective enshrined in the Paris Agreement, policymakers and the public need information on the DAC technology development and its cost trend. Businesses do not need to disclose everything, but their claims on technology and costs should be subject to scrutiny.

Although our analysis showed that the costs suggested by companies are lower than the academic literature would imply, we cannot immediately jump to the conclusion that the startups are underestimating the cost. It is possible that academic studies are overestimating the cost. As Keith (2016) notes, a study by Curtright et al. (2008) produced the cost projection of solar photovoltaics, which turned out to be overly conservative. The study was an elicitation exercise involving many experts. The group of experts as a whole could not capture the sudden drop in the cost that actually occurred.

The lesson here is not that either academics or companies are more prone to cost biases. Rather, the exercise of cost projection inherently suffers from a deep uncertainty. As a leading proponent put it (Keith 2009), probably the only way to resolve the ongoing cost debate is to build an actual plant (on a large scale).

This working paper attempted to summarize the claims on DAC costs. We hope that this will stimulate debates and discussions.

Acknowledgement

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Appendix 1. Summary of DAC Company Technologies

Company name (CEO or Key person), Location	Technology description and its R&D status	Capture cost and assumptions	Other
Carbon Engineering (Adrian Corless David Keith), Calgary, Canada	• Alkaline solution （KOH/Ca(OH)$_2$ • One of potential application is EOR. • The carbon intensity （35 g -CO_2/MJ) is lower than that of the present EOR （95 g -CO_2/MJ） • Demonstration plant (1t-CO_2/day)	136$/t-$CO_2$ Natural gas: $4/GJ Carbon free electricity $0.07/kWh（Kieth 2005）	
Center for Negative Carbon Emissions, Arizona State University (Klaus Lachker), Arizona, USA	• Ion exchange resin (Strong based amine) • Bench scale plant • In the future, automated capture module packaged into a standard cargo shipping container. Cost reduction by mass production is assumed.	Prototype: 220$/t-$CO_2$ Target: 30$/t-$CO_2$ (Lackner 2009)	Established in 2004

Global Thermostat (Dr. Graciela Chichilnisky), New York and New Jersey , USA	• Honeycomb spongy ceramic board with amine capture sites. • Regenerated with steam of 85-100 C. Applicable to air and flue gas in power plant. • Pilot and Commercial Demonstration plants operating since 2010 at SRI International. • In the future, 100,000t-CO_2/year/commercial module in the future. Foot print is 20-500 t-CO_2/yr/m2	10~35$/t-$CO_2$ for 1 million t/yr 160 kWh/ t -CO_2, 4.4 GJ/t-CO_2（95 ℃）	Established in 2010
Climeworks (Dr. Christoph Gebald Dr. Jan Wurzbacher), Switzerland	• Solid sorbents • Regenerated with 100 C heat. CO_2 for greenhouses, beverage company. • The first commercial plant of 900t/year delivered.	Heat：1800-2500kWh/ t - CO_2（100℃） Electricity：350-450kWh/t-CO_2	Established in 2009
Carbon Sink	• Ion exchange resin (Strong based amine) specialized for CO_2 supply in green houses. • Regeneration by humid swing • No information for R&D status is available at present.	The cost is lower than CO_2 supplied by small tanks and/or fuel combustion.	Established in 2014 by Infinitree LLC
COAWAY (Robert B. Polak), New York, USA	• Alkaline solution. • Soluble sorbents precipitate after reactions with CO_2 in flue gas. Precipitates are decomposed by waste heat of power plat (95 C）. • Capture facility is located on the capture tower.	< $20/t （assumed to utilize waste heat for regeneration）	

	• No information for R&D status is available at present.		
SKYTREE (Max Beaumont), Amsterdam, Netherlands	• Electrostatic absorption on a porous plastic bead. CO_2 is captured by electrostatic properties on a porous plastic bead. • Regeneration by humid swing. Goal is CO_2 supply for biofuel. Specialized for Products for aquarium and water treatment at the moment. They have projects of aquariums, water treatment, and air conditioning with partners respectively. • Products for aquarium market are being prepared.	Heat：80~90 ℃ for regeneration	A spinout company from ESA