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# CAPTURING THE IMAGINATION: PROSPECTS FOR DIRECT AIR CAPTURE AS A CLIMATE MEASURE (CASE STUDY)

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**Introduction**

To avoid more than 2°C of warming by this century's end, atmospheric carbon concentrations may well have to be limited to around 350 parts per million (ppm). This will be no mean feat- current carbon concentrations already stand at over 390 ppm. Closing the gap between 350 ppm and a plausible mid-range scenario in which concentrations rise to 500 ppm would require withdrawals of carbon dioxide ($CO_2$) from the atmosphere (or "negative emissions") of around 24 gigatonnes of $CO_2$ annually for 50 years[1].

Large scale negative emissions arguably rely on the cost-effective development of Direct Air Capture (DAC) technologies which could draw down $CO_2$ using chemicals which bind with it. The basic technology of DAC has been used for decades in submarines and, more recently, spacecraft. However, the viability of such systems changes when scaled up to the infrastructural levels necessary for large-scale negative emissions. Powering DAC could generate more carbon than it captures and will require effective linkages with the development of carbon storage. These issues are largely irrelevant for smaller and more contained activities underwater or in space, but are critical when applied to an intended climate measure.

The first proposals for climate DAC were published in 1999[2]; subsequently, it has come to be seriously considered as a supplement to climate mitigation. Interest has grown as the difficulties of accelerating carbon uptake by biological and oceanic capture options have become clearer[3], highlighted by the counter-productive effects of some biofuels policies[4]. This case study examines the development of DAC as a climate response and the obstacles remaining to its deployment at scale.

**How Would DAC Work?**

At its simplest, DAC works by absorbing $CO_2$ from the air onto a chemical receptor (or 'sorbent'), which has a strong attraction for the $CO_2$, in a similar way as a sponge absorbs water. The most commonly considered sorbents are alkaline compounds based on calcium or sodium which form carbonates when exposed to $CO_2$ and amine solutions (as used in many carbon capture and storage (CCS) demonstrations), although various other options are being explored[5]. Alkaline sorbents typically require more energy than amines, but the technologies involve lower capital costs.

Even with an effective chemical sorbent, this leaves a number of challenges. First, to capture $CO_2$, air must somehow be moved over the sorbent. When cleaning with a sponge, you take the sponge to the dirt, but in DAC, the $CO_2$ in air is typically brought to the collector. Many current proposals seek to use the natural power of the wind to do this, but some would rely on powered fans or exploit the air currents created by cooling towers. Second, once the sorbent is saturated it stops catching $CO_2$ and must be 'regenerated' in some way. You might wring out your sponge, set it somewhere warm to dry out, or rinse out the dirt with running water. All three methods are being tried to regenerate DAC sorbents: 'pressure swing' (squeezing out the $CO_2$), 'temperature swing' (warming up the sorbent to release the $CO_2$), and 'humidity swing' (washing out the $CO_2$). In all cases the $CO_2$ must be released from the sorbent in a controlled environment, so it can be compressed and stored away. Third, either at the capture stage or the regeneration stage, the $CO_2$ can get mixed with other chemicals or gases, and may require further purification as well as compression before it can be used or stored. Finally, all three steps require energy, which is the underlying limitation of large scale DAC.

## DAC as a Climate Response

DAC is not expected to be an alternative to conventional mitigation nor to point-source abatement through CCS. Rather, it is intended as a supplement to such responses[6], providing a means to reduce ambient atmospheric concentrations of $CO_2$ or to offset dispersed emissions that are difficult to mitigate directly, such as those from air travel. The big challenge is that $CO_2$ is very dilute in air, which makes its capture energetically and financially difficult. But a growing body of research suggests a range of technical options and business or policy models that might make DAC viable[7].

Given the slow progress achieved in the deployment of CCS as a climate response, it is important to understand why we might also seek to capture $CO_2$ from the air, rather than from the $CO_2$-rich flue gases emitted from power stations. Developers of DAC seek to optimise the efficiency of their processes at much lower capture rates than the 90% typically expected of CCS on a power station. This cuts energy use *per unit* of $CO_2$ captured, but increases capital costs, as a larger facility would be required to capture the same *total* $CO_2$. Thus, there is good reason to develop the two approaches in parallel.

It has also been suggested that rather than being tied to places where large amounts of $CO_2$ are emitted – as is the case with CCS – DAC could be cost-effectively co-located with $CO_2$ storage facilities or with low carbon energy resources which are 'stranded' far from energy markets (and thus commercially unexploited), or developed on more remote, cheaper, less controversial sites[8]. However, these apparent advantages are largely illusory. Specific site characteristics (such as low humidity) are likely more significant for DAC than co-location. And, in carbon terms, there is almost certainly more benefit in finding ways to directly replace fossil fuel use with heat that is currently wasted (in cooling towers for example) or solar power from remote deserts, rather than using such sources to power DAC. Moreover, remote locations can add to costs of construction and operation, while public concerns about $CO_2$ capture, transport and storage are not limited to issues of direct exposure[9].

## DAC Options and Obstacles to Development

The credibility of the sector received a major boost in 2007 with the launch of the Virgin Earth Challenge (VEC)[13] which offers a $25 million prize for a scalable, sustainable and commercially viable form of atmospheric $CO_2$ removal.[14] The front-runners for the VEC are the technical leaders in DAC development: David Keith, Klaus Lackner and Peter Eisenberger (see table 1).[15]

**Table 1: Leading proposals for Direct Air Capture**

| **Lead Scientist** | **David Keith** | **Klaus Lackner** | **Peter Eisenberger** |
|---|---|---|---|
| **Company** | *Carbon Engineering* | *Kilimanjaro Energy*, formerly *GRT* | *Global Thermostat* |
| **Funding** | Private investors including Bill Gates | Venture-capital | Private investors |
| **Technology** | Alkaline sorbent scrubbing; temperature swing regeneration, low capital cost components but energy intensive – relying on stranded energy and waste heat | Humidity swing amine sorbent; high capital, low energy cost | Temperature swing amine; sorbent releases its $CO_2$ at a lower temperature than CCS amines; capital intensive, but mainly using waste heat (at around 95$^{o}$C[10], from refineries, cement production or aluminium smelters) |
| **Outputs** | High purity $CO_2$ | $CO_2$-enriched air | High purity $CO_2$ |
| **Development stage** | Prototype demonstrated in 2012; full-scale pilot plant planned by 2015 | Lab-scale demonstration | Small scale module capturing about two tons of $CO_2$ a day operating since 2013 |
| **Possible or published strategies for commercial development** | Integrating air capture into low-carbon liquid fuels markets (via EOR[11]); using $CO_2$ to fertilise algae for biofuel production; or direct production of synthetic fuel | Algal fertilisation; or with addition of purification and compression, chemical or food and drink uses of $CO_2$ might be initial customers | Algal fertilisation; or sale of $CO_2$ for incorporation into cement or plastic or for carbon tax credits. |
| **Estimated costs** | Long-term below \$100/tonne-$CO_2$, with estimates of the pilot plant costs understood to be around \$135/tonne | Theoretical estimates of \$25 – \$40/tonne[12]. But business plans imply \$200 -\$300 per tonne for compressed purified $CO_2$ | Unclear. Eisenberger *et al*modelled potential uptake based on a cost per tonne $CO_2$ of just \$25 |

While these and other VEC entrants are racing to pilot scale demonstration, research into other methods and materials for carbon capture continues apace. Some promising possibilities such as metal oxide frameworks (MOFs) may prove suitable for air-capture as well as flue-gas capture[16]. Some MOFs appear to offer better absorbency without an equivalent increase in the energy costs of subsequent release. However, the behaviour of MOFs in real ambient conditions is as yet unknown.

Moreover, major obstacles remain in scaling up. To deliver significant negative emissions would require an industry as large in physical scale as the current oil and gas sector[17]. The obstacles to such large-scale commercialisation include energy requirements and storage availability as well as social acceptability, cost and funding mechanisms.

At scale, even relatively efficient forms of DAC would require very substantial amounts of energy. McLaren (2012a) compares the estimated energy requirements for capturing 24 gigatonnes of $CO_2$ a year with current world global energy consumption. Alkaline scrubbing methods would require the equivalent of an extra 60% of total energy use, and even amine based methods around 10% – in addition to the massive efforts already foreseen to transform and extend existing energy systems. A breakthrough in nuclear fusion might make this plausible, but otherwise, deployment of DAC will likely compete for scarcer and more expensive energy.

DAC developers often assume that carbon storage will be developed for CCS, and can be treated as a simple ‘bolt-on’ to DAC. However, basic questions about storage location and availability, and regarding purification and compression before transmission and storage, have not been fully considered. While official upper estimates of global carbon storage[18] would be more than adequate for DAC to achieve safe atmospheric levels of $CO_2$; at the more conservative end of the range, estimates of affordable storage capacity are below the likely aggregate requirements for negative emissions. Regional scarcity might also be significant. In some regions, concerns about safe and publically acceptable storage availability have already begun to influence CCS policy[19].

The social acceptability of DAC is far from assured. Public opposition to carbon storage has hampered CCS development in several countries[20], while place-based concerns about energy infrastructure (such as windfarms) could be replicated in the context of proposals for large-scale deployment of air capture devices[21].

The cost estimates of promoters appear optimistic, and cannot be verified without much greater transparency. Keith‘s costs estimates contrast remarkably well with the figure of $600/tonne or more suggested by the American Physical Society for a similar, but generic, system, in one of the few independent assessments of the likely costs of air capture[22]. Keith has suggested ways in which the APS could have over-estimated[23] but these seem unlikely to account for the whole discrepancy. Lackner’s and Eisenberger’s published cost estimates are also lower than figures estimated in recent theoretical assessments ($240/tonne[24] and $1,000/ tonne[25]). In reality it seems costs are likely to lie somewhere between the theoretical estimates and those of the promoters.

Thus, reaching commercial viability may require strategies that undermine the effectiveness of DAC as a climate measure. These might include algal fuels and enhanced oil recovery (EOR) through $CO_2$ injection into oilfields. \$50/tonne is often cited as a level at which sale of captured $CO_2$ for EOR could be commercially viable. But the combustion of the additional oil produced through EOR releases more carbon dioxide than is captured in the EOR process. Overall system emissions are only reduced if less oil is produced elsewhere as a result of EOR or algal biofuel production, but this is at best uncertain in a market that is currently supply constrained. Treating DAC-EOR oil as 'lower-carbon oil'[26] might facilitate partial abatement, but at the risk of increasing the lock-in of existing fossil vehicle technologies. Moreover, the business models under development suggest that even the \$50 level remains elusive, as they typically rely on potentially higher value regulated or voluntary carbon offset markets.

For most DAC proponents a functioning carbon market with high carbon prices is seen as ideal. Yet financing DAC through carbon markets – whether official or voluntary – is problematic for climate policy. DAC is at a stage at which it is not competitive at existing carbon prices. To incentivise development will likely require direct support or specific regulatory drivers. Yet if it becomes competitive, unless the overall market caps are reduced, DAC would then drive out, rather than supplement, other mitigation approaches – acting purely as an offset. This is particularly problematic if storage availability proves to be limited[27].

**Prognosis and Conclusions**

Large scale DAC remains a 'technological imaginary'. It is no silver bullet for the climate problem, despite being almost certainly essential to long-term reductions of atmospheric $CO_2$. Even with technological and process breakthroughs it is likely to be expensive and slow to roll out. Yet from an optimistic perspective, technical developments in DAC might feed back into more efficient CCS processes, unblocking wider deployment of that technology. On the other hand, this could be just another example – alongside business models predicated on EOR – of how DAC might further lock-in societal dependence on fossil fuels.

Given such risks, the case for DAC research being guided by the principles of responsible innovation[28] is strong. However, most research is being conducted in the USA, funded primarily by private venture capital. This makes for high levels of commercial confidentiality and tight control over intellectual property, while risking promoter bias. Obtaining investment demands financial projections in which profitability appears credible, encouraging promoters to use optimistic technical assumptions. It also requires positive publicity and confidence in the prospects of the technology and its possible market, so a bubble of inflated expectations can easily result[29].

Yet belief in the future availability of relatively cheap DAC could fuel reluctance to take timely action on mitigation. Many modelling studies suggest the presence of negative emissions technologies leads to an allegedly 'economically efficient' delay in mitigation[30]. If DAC captures imaginations too well, it could increase the climate risks we face from possible tipping points in the system.

Policy makers must take care: with the right imagination and sound incentives DAC could accelerate mitigation and widen future options – done badly, policy for DAC could exacerbate lock in and undermine progress.

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[1]McLaren, 2012a

[2]Lackner et al, 1999

[3] McLaren, 2012a

[4] See for example Fargione et al 2008

[5] Jones, 2011

[6]Jones, 2011

[7] Keith, 2009

[8] Lackner et al, 2012; Keith 2009

[9]Mclaren, 2012b

[10] Eisenberger et al, 2009

[11]Pumping captured $CO_2$ into oilfields to enhance oil recovery, and formally ‘offsetting’ it against the $CO_2$ produced when the oil is burnt, so as to market the resulting fuel as ‘low-carbon’.

[12]Lackner, 2009; Lackner et al 2012

[13] *Virgin Earth Challenge*. Accessed Feb 2014 at: http://www.virginearth.com/

[14]Cynics might suggest that VEC’s sponsor, Sir Richard Branson, is protecting his aviation interests, but the prize and involvement of high profile judges such as Al Gore and James Hansen has inevitably raised the profile of serious contenders.

[15]The VEC and its candidates provide high-profile examples of the most commercially advanced technologies and options that are on the table; and concrete illustrations of funding sources, cost, technology, and claims made by developers.

[16]Jones, 2011; D’Alessandro et al, 2010

[17] McGlashan et al, 2012

[18]IPCC, 2005

[19]McLaren, 2012a

[20] McLaren,2012b

[21] See, for example, IPSOS Mori, 2010

[22]Socolow et al, 2011

[23] See Carbon Engineering 2011. *Comments on the APS report on Direct Air Capture*. Accessed Nov 2013 at:http://static.squarespace.com/static/51957744e4b088893b86e2f3/t/51b22658e4b0c62198bcd0a5/1370629720562/CE_APS_DAC_Comments.pdf

[24]McGlashan et al, 2010

[25]House et al, 2011

[26] *Carbon Engineering*, Accessed Nov 2013 at:http://static.squarespace.com/static/51957744e4b088893b86e2f3/t/51b22bb4e4b0df9f07656a15/1370631092291/CE-DAC-CCS-Comparison.pdf

[27]McLaren, 2012a

[28] Stilgoe et al, 2013

[29]Hansson, 2012; McLaren, 2012a

[30] For example, see Keith et al, 2006

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