Mopping up carbon

Jun 6, 2013 13 comments

Technologies that capture carbon dioxide directly from the air would help us to manage climate change and make profitable by-products in the process. But the financial feasibility of such schemes is controversial, as **David Appell** reports

Mopping up carbon

The problem of climate change essentially boils down to this: can we find a way of keeping the number of carbon dioxide (CO_2) molecules in the atmosphere to four out of every 10,000 molecules of air – or will the figure rise to five or more? If only that extra molecule could be plucked from the air, the climate problem could be mostly solved without a drastic restructuring of the world's energy infrastructure. It may sound madly ambitious but that is just what a few scientists and engineers are planning to do, and hoping to make some money from it to boot.

Removing CO_2 from the air is not an especially new idea. In fact, it is relatively simple and done on spacecraft and submarines all the time. But achieving "negative emissions" economically, at large scales, is a much harder and more urgent problem. Unless the energy used for the removal is carbon free, or sufficiently small, the benefits will simply not cover the costs. And therein lies the challenge.

Existing efforts to remove CO_2 are based at power stations – which give off 40% of global CO_2 emissions – and involve capturing the gas as it leaves the plant. But these techniques do nothing to counteract the 60% of global emissions that come from cars, buildings, ships, planes and other "point sources". The search is therefore on for new techniques that directly capture CO_2 from the air. Facilities performing this "air capture" could be located anywhere, utilizing the atmosphere as a pipeline from billions of sources of CO_2, however minute or mobile.

Despite doubts arising from theoretical studies of the cost of carbon capture, those getting their hands dirty think that CO_2 could be removed directly from the air in massive quantities for perhaps as low as $100 per tonne. Once collected, the CO_2 could then be pumped underground into geologic storage areas – a technique known as sequestration – where it would be trapped for potentially millions of years, with little leakage, doing no harm to planet or people. The gas could also be sold to oil companies, which routinely inject carbon dioxide into oil reservoirs to reduce the oil's viscosity, enabling easier extraction. Other customers could include large-scale flower growers, who fill their greenhouses with CO_2 to keep plants warm.

The technology to do all of these things already exists, but in bits and pieces; the challenge is

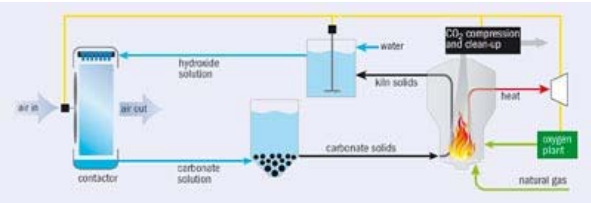
to put the various components together on a large scale, and to do so cheaply. One interesting initiative is the Virgin Earth Challenge, which was launched in 2007. Sponsored by Richard Branson, it offers $25m to whoever can demonstrate a sustainable and scalable design to permanently remove a billion tonnes of carbon from the air every year for 10 years. Some 2600 groups applied to the challenge and last November the finalists were picked – six from the US and one each from Denmark, Sweden, the Netherlands, Switzerland and Canada – who now have five years in which to win the prize.

One finalist is Carbon Engineering – a firm based in Calgary, Canada, that is financially backed by Bill Gates, the Canadian government and others. "We've made a huge amount of technical progress," says the company's chief executive David Keith, who is also a prominent climate scientist at Harvard University, "and we're understanding how we might make it work as a business."

According to climate expert James Hansen, there is certainly a need for such enterprises. As he wrote in 2007, the global surface warming that has already been (or is bound to be) created – coupled with the unceasing increase in carbon emissions, and the currently inadequate mitigation efforts (see "The carbon problem" below) – implies that "a feasible strategy for planetary rescue almost surely requires a means of extracting greenhouse gases from the air". If CO_2 could be captured from ambient air more quickly than nature does it, the world might even be able to overshoot whatever warming threshold is deemed "dangerous" and later stabilize the climate gradually via net negative carbon emissions.

Chemical capture

One of the most straightforward ways to remove CO_2 from air is with a solid or liquid chemical compound that soaks up the gas. Known as "carbon dioxide scrubbing", it is a tried and tested technique that has been used at power plants, and Carbon Engineering and other similar companies have made it their method of choice because the process is simple, proven and continuous. Ambient air is first drawn through a scrubber or "contactor" where an alkali solution (such as aqueous lye) absorbs CO_2 molecules and converts them into a carbonate salt. After the salt is heated in a kiln, the CO_2 is then released and captured, before the residue is reacted with water and other compounds to produce the same liquid alkali, which is then fed back into the contactor to be reused. The net yield is concentrated CO_2 gas (figure 1).



1 Chemical capture process

Carbon Engineering has successfully built air-capture prototypes powered by natural gas, the CO_2 from which is directly captured and combined with that extracted from air. Because atmospheric CO_2 is well mixed, such plants could be sited where energy costs are lowest, environmental conditions such as temperature or humidity are most favourable, or where CO_2 disposal is cheapest and most convenient. (In contrast, power plants are not necessarily located where CO_2 sequestration is possible or most practical, often requiring that the gas be piped elsewhere.)

Scrubbing CO_2 from the waste flues of power plants today costs $50–100 per tonne of CO_2, a value that air-capture proponents dream of someday reaching. Once the CO_2 is captured it is ready for sequestration or reuse, ideally at the same location. Pipelines and injection wells would have their own regulatory challenges, issues of public acceptance regarding impacts and leakage, and expense (see "Burying climate change for good"). The few sequestration projects that exist today, such as that at the Sleipner gas field in Norway, which has been

running since 1996, all involve capturing CO_2 from flue gases, but bury only about a million tonnes of CO_2 per year.

Artificial leaves

Ambitious carbon-capture schemes are all very well and good, but there already exist amazing machines capable of removing CO_2 from the air: plants and trees. Every year, land vegetation sucks up about 220 gigatonnes (220×10^9 tonnes) of CO_2 in photosynthesis, although it is, of course, returned to the atmosphere when the plants and algae die and decompose. Vegetation is therefore not a net sink of CO_2 – but there are clever ways to turn it into one.

Since carbon makes up about half the dry weight of a tree (depending on species), Ning Zeng, a climate scientist at the University of Maryland, suggested in 2008 how to temporarily solve part of mankind's carbon problem by using forests as "carbon scrubbers". This would involve actively managing them by collecting trees and woody debris, before anaerobically burying them deeper than five metres.

Zeng published another paper last year, which found that if wood was harvested from half the world's forested land and then buried underground, 2.8 gigatonnes of carbon would be trapped per year. (If this carbon was instead allowed to decompose it would release 10.3 gigatonnes of CO_2 into the atmosphere.)

Likewise, in a world stressed for agriculturally productive land, planting (or recovering) enough forest land looks out of the question, which is why some scientists are looking at making artificial leaves and artificial trees. These structures not only take CO_2 out of the air as does conventional photosynthesis, but some also produce carbon-neutral liquid fuels in the process.

In photosynthesis, plants convert the energy of sunlight into stored energy in the form of carbohydrates, removing CO_2 and producing oxygen and water in the process. Scientists are trying to do much the same thing, but with "leaves" made of silicon or polymers. Some implementations are sources of carbon-free energy, collecting sunlight that generates oxygen and hydrogen gas for fuel cells. But for Klaus Lackner, a physicist at Columbia University, the focus is to absorb CO_2. His carousels of plastic filters are laced with a CO_2-absorbing material; as they become saturated with CO_2, they are rinsed with water in a vacuum chamber and the dissolved CO_2 separates for collection.

Lackner's leaves are about 1000 times more efficient at absorbing CO_2 than real leaves, per unit surface area, and need not be exposed to sunlight, so they can be closely spaced. However, they do not come cheap: a single tree, which can remove one tonne of CO_2 a day, currently costs about $20,000. Kilimanjaro Energy, Lackner's company, plans to develop and commercialize this and other carbon-capture technologies, and is one of the Virgin Earth Challenge finalists.

Working on it

Cost controversy

Accompanying these emerging air-capture technologies is the ultimate hope that they might

be useful to help stop climate change, and perhaps even reverse its effects by returning the atmosphere and oceans to something like their pre-industrial state. A 2011 report by the American Physical Society (APS) entitled *Direct Air Capture of CO_2 with Chemicals*, however, cast doubt on such ambitions. The APS report set out to explain the basic principles, technology and economics of air capture with chemicals to non-experts, and to encourage discussions among a broad audience of scientists and policy-makers.

One key figure in the report is that a typical sorbent would capture, per square metre over which air flows, only about 20 tonnes of CO_2 per year. Since a 1000 MW coal-fired power plant emits about 6 megatonnes of CO_2 annually, a 10 m high capture material would need to be 30 km long to adsorb the plant's entire emissions. The report also estimated that a direct air-capture system, built today, would cost at least $600 per tonne of CO_2. Direct air capture, it concluded, "is not currently an economically viable approach to mitigating climate change".

Critics hit back, suggesting that these pessimistic predictions were premature at best, and even potentially misleading. Indeed, the report and its backlash from some respected scientists garnered a good deal of media attention, including a lengthy write-up in the *New York Times*. Mark Workman, a researcher at the Grantham Institute for Climate Change at Imperial College London, who recently co-authored an assessment of negative-emissions technologies, calls the report "controversial" and says "estimates of the cost of negative-emissions sequestration are often used to either negate or endorse the role of negative-emissions technologies in addressing climate change, and therefore often subject to political bias". The high cost estimates are motivated, he says, by "a desire to keep the focus solely on preventing climate change via mitigation".

The report does indeed state that it provides "no support for arguments in favour of procrastination in dealing with climate change that are based on the imminent availability of direct air capture as a compensating strategy". But Workman feels "the mitigation narrative isn't working" and sees negative-emissions technologies as an essential bridge. "We need to develop this line of research in order to buy time to introduce the low-carbon economy at rates at which energy-system technologies take to diffuse, which is up to 100 years, rather than being compressed into the next 30–40 years," he says.

Carbon Engineering research scientist Geoffrey Holmes, on the other hand, thinks that air-capture plants in reality will be more efficient than the model used as the basis for the report's predictions. "One crucial point," says Holmes, "and one opportunity that the APS authors missed in their system, is that our heat and power generation are integrated on-site, so when we use energy to capture CO_2 from the air, we also generate all the electricity demand for our own plant, and we capture the CO_2 created by the gas combustion to produce that energy." This avoids emitting new CO_2 that would partially counteract the CO_2 just captured.

Another way Carbon Engineering has lowered its costs is by designing its contactor structures around cooling tower technology – which is optimized to cheaply and efficiently ingest bulk quantities of air – rather than traditional gas scrubber technology. While the details are proprietary, their structure costs less than half of a similarly sized contactor considered in the APS report.

The company has now started work on a pilot plant near Alberta that aims to capture 500 tonnes of CO_2 per year and test equipment and designs ready for a commercial-scale plant that is planned to capture 100,000 tonnes of CO_2 annually. While Carbon Engineering's carbon-capture rate is slightly higher than the APS report's prediction, to achieve it they will need to use many stacked vents and contactors.

Carbon Engineering chief Keith sees the removal of CO_2 as just one prong in the attack on climate change and, along with other entrepreneurs, is far more interested in the business opportunities. Keith sees the big prize as being direct fuel synthesis. Captured CO_2 could be fed to algae to produce biofuels, or reacted with hydrogen molecules (obtained by splitting water using renewable energy) to produce high-energy-density carbon-neutral hydrocarbon fuels that could power cars, trains and planes that emit no net carbon pollution. Keith

believes the price of such carbon-neutral liquid fuels might someday slash prices at the pump.

There are certainly many other ideas for how CO_2 might be removed from air faster than natural processes. For example, iron fertilization of ocean regions would create algal blooms that, when they die, take the carbon with them to the ocean floor. Another options is "accelerated weathering", which could fix a concentrated stream of CO_2 as carbonate by reacting it with natural silicates, speeding up a process that in nature takes millennia. Reforested land, meanwhile, would remove about 50 kg of CO_2 per square metre.

Green ideas

Race against nature

Should a climate emergency appear – perhaps a sharp acceleration in the melting of the Greenland or Antarctic ice sheets, or a steep rise in radiative forcings as rapidly thawing permafrost releases methane – the world may be willing to pay whatever it takes to remove CO_2 from the air.

Our best guess is that the CO_2 from the roughly 40% of emissions coming from power plants could be captured for about $50 per tonne. If air-capture technology drew down the remaining 60% from smaller sources for, say, $100 a tonne, the total cost would be more than $2 trillion to negate one year's emissions at current rates of about 30 gigatonnes of CO_2 per year. This is equivalent to a hefty 4% of the world's total GDP.

While that figure is about twice as expensive as the (revised) estimate of the Stern Review – a report compiled for the British government in 2006 to assess the costs associated with mitigating climate change – air capture would have several advantages over currently envisioned mitigation schemes. Primarily, it would not require unilateral action across the entire planet or rebuilding an infrastructure the world has spent the last 150 years perfecting. Like carbon offsets, carbon could be captured by whomever can do it easiest and wherever they can do it cheapest. And it would eliminate the morality play that now accompanies the climate debate, where ends and means are often reversed as different factions use climate change as a cudgel in the fight for their individual causes.

As Keith wrote in *Science* in 2009, "Unless we can remove CO_2 from the air faster than nature does, we will consign Earth to a warmer future for millennia, or commit ourselves to a sustained programme of climate engineering."

And those are options nobody wants.

The carbon problem

Despite all warnings, emissions of greenhouse gases are increasing exponentially – a

predicament the seriousness of which many still do not appreciate. The CO_2 emitted by the average Briton over just 80 minutes – about 1.3 kg – will ultimately trap a Hiroshima bomb's worth of heat: 63 terajoules. That heat will alter the Earth's climate and oceans for millennia – the CO_2 content of the Earth's atmosphere will be about 10% higher 100,000 years from now than it would be without today's emissions.

But solving the problem by replacing our energy system is daunting indeed. With colleagues, Ken Caldeira of the Carnegie Institution for Science has calculated that the world needs to install roughly one large (900 MW) carbon-emissions-free power plant every day for the next 50 years to stabilize overall global surface warming at 2 °C. And if, as seems likely, the target is relaxed to something like 4 °C, the required number is still about one power plant every two days.

To date, mankind has emitted about 1400 gigatonnes of CO_2 from burning fossil fuels, and another 600 gigatonnes from land-use changes such as deforestation. But there are still enormous amounts of economically viable fossil fuels left to extract and burn, of which 70% is in the form of coal; if we used it all it would unleash a further 3200 gigatonnes of CO_2. In fact, burning all the fossil fuels on the planet would create at least 37,000 gigatonnes of CO_2, and for every 1000 gigatonnes emitted, the climate response is about 0.4 °C of surface warming, plus or minus a third. Humans could easily create an inverse ice age if we wanted to – a mean global surface warming of 6–7 °C, or more.

About the author

David Appell is a science writer living in Salem, Oregon, US

13 comments

Add your comments on this article

1 **adrianvance**
Jun 6, 2013 10:33 PM

What utter nonsense.

CO2 is a “trace gas” in air, insignificant by definition. It absorbs 1/7th as much IR, heat energy, from sunlight as water vapor which has 80 times as many molecules capturing 560 times as much heat making 99.8% of all "global warming." CO2 does only 0.2% of it. For this we should destroy our economy?

Carbon combustion generates 80% of our energy. Control and taxing of carbon would give the elected ruling class more power and money than anything since the Magna Carta of 1215 AD.

See The Two Minute Conservative via Google or: adrianvance.blogspot… and when you speak ladies will swoon and liberal gentlemen will weep.

2 **continuous**
Jun 7, 2013 12:59 AM
Moorabbin, Australia

Frozen planet

I can just see the future unfold;
-CO2 industry emerges and becomes profitable
-oil/coal reserves get exhausted by an out of control oil industry
-Atmospheric CO2 is depleted by an out of control industry
-Earth cools too much
-fusion research is still 20 years away
-oops!!!
WoMan kind just has to learn stop pooping in the pooch!

Edited by continuous on Jun 7, 2013 1:01 AM.

3 **continuous**
Jun 7, 2013 1:08 AM
Moorabbin, Australia
What utter nonsense indeed: Quote:

> *Originally posted by* ***adrianvance*** ▸
> CO2 is a “trace gas” in air, insignificant by definition. It absorbs 1/7th as much IR, heat energy, from sunlight as water vapor which has 80 times as many molecules capturing 560 times as much heat making 99.8% of all "global warming." CO2 does only 0.2% of it. For this we should destroy our economy?

Simplistic arguments like this are misleading:- Read the article before belching such nonsense please!

" ... for every 1000 gigatonnes emitted, the climate response is about 0.4 °C of surface warming, plus or minus a third. ..."

Edited by continuous on Jun 7, 2013 1:19 AM.

4 **adrianvance**
Jun 7, 2013 4:59 PM

Quote:

> *Originally posted by* ***continuous*** ▸
> What utter nonsense indeed: Quote:
>
> > *Originally posted by* ***adrianvance*** ▸
> > CO2 is a “trace gas” in air, insignificant by definition. It absorbs 1/7th as much IR, heat energy, from sunlight as water vapor which has 80 times as many molecules capturing 560 times as much heat making 99.8% of all "global warming." CO2 does only 0.2% of it. For this we should destroy our economy?
>
> Simplistic arguments like this are misleading:- Read the article before belching such nonsense please!
>
> " ... for every 1000 gigatonnes emitted, the climate response is about 0.4 °C of surface warming, plus or minus a third. ..."

Do the physics, if you can, as have I and you will see that I am correct. Blaming CO2 for "global warming" is ridiculous. There is not enough of it to do anything. It is a poor absorber of IR compared to water vapor. The word "trace" in physics means insignificant.

5 **appell**
Jun 8, 2013 1:49 AM
Portland, United States

Water vapor is a feedback, not a forcing

Adrian: Except the amount of water vapor in the atmosphere doesn't change (except in the very short-term), except in response to temperature. That is to say, it is a feedback, not a forcing like CO2.

6 **appell**
Jun 8, 2013 4:47 AM
Portland, United States

CO2: Principal control knob

adrianvance wrote:
CO2 is a “trace gas” in air, insignificant by definition. It absorbs 1/7th as much IR, heat energy, from sunlight as water vapor which has 80 times as many molecules capturing 560 times as much heat making 99.8% of all "global warming."

Not really. While water vapor is indeed a powerful greenhouse gas, it alone can't raise Earth's surface temperature above freezing. It's only the additional presence of CO2 that does that -- without the CO2 most of the water vapor would freeze out of the atmosphere and the Earth would be an icehouse.

A useful paper is:
Lacis, A.A, G.A. Schmidt, D. Rind, and R.A. Ruedy, 2010: Atmospheric CO2: Principal control knob governing Earth's temperature. Science, 330, 356-359, doi:10.1126/science.1190653.
pubs.giss.nasa.gov…2010_Lacis_etal.pdf

7 **M. Asghar**
Jun 8, 2013 6:45 PM

Beyond water

The Earth has always had the same amount of water and it always absorbs the same amount of IR. Keeping everything unchanged, there should not be any quick "global warming" just due due to this fact. If there is some global warming, there has to be another agent such as the change in the amount of glasshouse gases such as Co2 and Methane.

CO2 is a “trace gas” in air, insignificant by definition. It absorbs 1/7th as much IR, heat energy, from sunlight as water vapor which has 80 times as many molecules capturing 560 times as much heat making 99.8% of all

"global warming." CO2 does only 0.2% of it. For this we should destroy our economy?

8 **CairnsM**
Jun 10, 2013 10:49 PM

2 trillion is not a impediment

Implementing the Tobin Tax could easily recoup the "carbon tax". Currency speculators trade 1.8 trillion a day (Fact Sheet on Tobin Taxes). Economists would have to find a way to tax that optimally but the Tobin Tax could bring in 2 trillion a year. This is honestly all a matter of priorities. There is no reason why we can not implement this technology tomorrow other than political reasons. Economics is just an extension of politics and political theory.

In the US, the carbon scrubbing infrastructure could be paid for with a progressive tax scheme for capital gains and earned income. The OP may not realize it but even Reagen recognized that earnings in the stock market should be taxed the same as earned income. I would go further and include more tax brackets to tax individuals taking 250k-500k-1m-5-10-25-50-100 etc million out of the stock market each year. Of course someone would have to figure out the optimal tax for each bracket but there is no need to tax individuals taking less than 250K out of the market.

If anyone reads this and is interested in tax reform check out Michael Hudson from the University of Missouri.

Edited by CairnsM on Jun 10, 2013 10:50 PM.

9 **CairnsM**
Jun 10, 2013 11:08 PM

I just want to add that the world's total GDP in 2012 was 83.12 trillion. 4% of that is 3.3 trillion not 2 trillion which the article states. The 2 trillion required to implement these programs is 2.4% of total world GDP. That is a substantial difference. If the author meant nominal world GDP then that is 71.38 trillion in 2012 and the 2 trillion represents 2.7% of nominal world GDP.

I'd like to know what he used to get 4%. I did not look at the G20 GDP for 2012 but that could be the GDP used in this article.

10 **appell**
Jun 11, 2013 2:07 AM
Portland, United States

GDP

CairnsM:

GDP is complicated. Do you mean nomimal-GDP or PPP-GDP?

In any case, the costs simply aren't known well enough that the difference matters.

Look at the big picture, not the small.

11 **appell**
Jun 11, 2013 2:18 AM
Portland, United States

about GDP

CairnsM:

I used a PPP-GDP of $69,244.4 B$ in 2000 dollars, from EIA - CO2 Highlights 2011.

But it is important not to get lost in the details. These numbers have large uncertainties, and costs are probably not known to better than 25%.

Nor is the future GDP known that well.

Put that all together, and future costs may be 3% of GDP, or 5%.

Either is terrifying.

12 **CairnsM**
Jun 11, 2013 9:35 PM

I am looking at the CIA World Fact Book for 2012 which is in 2012 dollars not 2000. I don't know what numbers the paper knocking these carbon techs used in their analysis (not all that important). The result is still like you said anywhere from say 2.5-5% of world GDP.

If the numbers are 2 trillion then that is not a true impediment because we well really they are able to allocate

resources and tax the system in ways to make this plausible. The FED has demonstrated that it can print money and no one (the elites at the power levers) will really complain as long as the big players are getting their cut. Of course it'll all catch up with us with time.

If instead the FED printed 2 trillion a year to fund construction of these technologies especially the carbon leaf (I somewhat buy into their talking points) while hopefully keeping waste and fraud at a minimum then its possible to create this infrastructure. Sequestering CO2 is not my favorite solution. They need to find ways to utilize CO2 that limits its ability to off gas and re-enter the atmosphere. The algal industry is still very young and algal fuels run into the same problem as every bio-fuel. Other options are available even if it means creating algal fertilizer or simply burying the algae to keep the carbon out of the atmosphere. (I know that none of this is likely or really possible but its to just illustrate that not using these technologies is a choice. We are not dealing with laws like gravity when dealing with economic choices.)

Is there a way to produce pure carbon from the extracted CO2 to produce raw materials for a the emerging nano-tech sectors?

And green dry cleaners should become more popular which in the long run will reduce the incidence of cancer (not exactly 2 trillion reduction in long term costs but its a start).

Things are so much easier when you just need to convert measurements in science then deal with GDP and all of the other economic indices.

Thanks for the response and article.

Quote:

> *Originally posted by* ***appell*** ▸
> CairnsM:
>
> I used a PPP-GDP of $69,244.4 B$ in 2000 dollars, from EIA - CO2 Highlights 2011.
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> But it is important not to get lost in the details. These numbers have large uncertainties, and costs are probably not known to better than 25%.
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> Nor is the future GDP known that well.
>
> Put that all together, and future costs may be 3% of GDP, or 5%.
>
> Either is terrifying.

13 **Climate chemist**
Jun 20, 2013 10:15 PM

Well written article but you did not mention that very large issue with the process that David Keith is working on. Heating solid materials to 850 degrees in a highly efficient manner without excessive heat losses is a significant challenge. Scaling up to multiple ton throughput per hour and keeping the heat losses low is going to be very challenging. I