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An idealized assessment of the economics of air capture of carbon dioxide in mitigation policy

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ABSTRACT

This paper discusses the technology of direct capture of carbon dioxide from the atmosphere called air capture. It develops a simple arithmetic description of the magnitude of the challenge of stabilizing atmospheric concentrations of carbon dioxide as a cumulative allocation over the 21st century. This approach, consistent with and based on the work of the Intergovernmental Panel on Climate Change (IPCC), sets the stage for an analysis of the average costs of air capture over the 21st century under the assumption that technologies available today are used to fully offset net human emissions of carbon dioxide. The simple assessment finds that even at a relatively high cost per ton of carbon, the costs of air capture are directly comparable to the costs of stabilization using other means as presented by recent reports of the IPCC and the Stern Review Report.

1. Introduction

In 2007, former U.S. Vice President Al Gore testified before the United States Congress that climate change represented ‘‘a planetary emergency—a crisis that threatens the survival of our civilization and the habitability of the Earth’’ (Gore, 2007). The primary international policy in response to the threat of climate change is the Framework Convention on Climate Change (FCCC), negotiated in 1992, and its 1997 Kyoto Protocol. The FCCC and the Kyoto Protocol focus on reducing the concentrations of anthropogenic greenhouse gases in the atmosphere, primarily carbon dioxide (CO_2). During 2007, countries have been actively engaged in negotiating future targets and timetables for limiting emissions of greenhouse gases, with little success (Anderson, 2007).

This paper focuses on one approach to dealing with accumulating atmospheric carbon dioxide called ‘‘air capture,’’ which refers to the direct removal of carbon dioxide from the ambient air. Air capture has received remarkably little attention in debates on policy responses to climate change, but this seems to be changing (e.g., Jones, 2008). By contrast, the capture and storage of carbon dioxide from power plants has received considerable attention (e.g., IPCC, 2005), with all major assessments of future mitigation assuming some amount of carbon capture from power plants and the subsequent sequestration of the captured carbon dioxide (e.g., IPCC, 2007a; IEA, 2008). In this paper I explore some of the economic considerations associated with air capture of carbon dioxide, and do not address issues of storage, which are explored in depth elsewhere, and represent one of numerous technical and social obstacles to deployment of air capture technologies. Thus, the current exercise should be viewed as exploratory and idealized.

In conducting any analysis of the economics of mitigation a wide range of assumptions must be introduced to the analysis. Examples include assumptions about the rate of future spontaneous decarbonization of the global economy absent climate policies, the future size of the global carbon sink (e.g., via oceanic absorption), the political and technical feasibility of technologies not yet in wide use (e.g., carbon dioxide sequestration), and so on. Each of these assumption can (and should be) challenged, but as they are about the future, such

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challenges are unlikely to be resolved absent the actual prototyping and implementation of air capture technologies, which is in fact proceeding (Jones, 2008). The approach used in this paper is to introduce assumptions consistent with, and where possible derived directly from, the reports of the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC). This is not so much a reflection of the expected accuracy of the IPCC's assumptions (which I and colleagues have challenged elsewhere, e.g., Pielke et al., 2008), but to place the present analysis on an apples-to-apples basis with the IPCC analyses. In situations where a direct replication of the IPCC's assumptions is not possible, the analysis here seeks to err on the side of conservatism, that is, over-estimating future costs of air capture. Relying on the assumptions of the IPCC will of course not eliminate challenges to the assumptions of the analysis, but it will mean that the approach here is found to be flawed, then the same criticism must also be applied to the work of the IPCC and mitigation policies more generally.

Under the assumptions used in the paper, surprisingly, the costs over the 21st century of deploying air capture to fully stabilize greenhouse gas emissions are comparable to, and under some assumptions more favorable than, the costs of stabilization presented by the Intergovernmental Panel on Climate Change (IPCC, 2007a) and the widely discussed Stern Review Report on the Economics of Climate Change (Stern, 2007). Three conclusions follow from the analysis: First, the greater the imperative to reduce carbon dioxide emissions, the greater the potential importance of air capture and thus the more attention to research, development, and deployment should be paid to the technology. Second, air capture deserves a far greater role in debates about policy responses to climate change (cf. Sarewitz and Nelson, 2008). Third, if nothing else, discussions of air capture can help to focus debates on climate change by clearly distinguishing the means and ends of climate policies.

2. What is air capture?

The IPCC, both in its 2005 report on capturing and sequestering carbon dioxide and its 2007 Fourth Assessment Report mentioned air capture only in passing (IPCC, 2005, 2007a).[1] However, in recent years the possibility of air capture in response to the build-up of anthropogenic carbon dioxide in the atmosphere has received increasing attention (e.g., Baciocchi et al., 2006; Yeboah et al., 2006; Broecker, 2007; Hansen et al., 2007; Hoffert et al., 2002; Keith et al., 2006; Lackner et al., 1999; Lackner, 2003a; LANL, 2002; Parson, 2006; Sachs, 2007; Zeman, 2007; AFP, 2008; Jones, 2008; Sarewitz and Nelson, 2008). The technology was studied as early as the 1940s and proposed in the 1970s as a source of energy (Zeman, 2007). In 2006, Al Gore and Richard Branson, owner of Virgin Group of companies, called more attention to air capture when they announced the Virgin Earth Challenge promising $25 million to the first "commercially viable design which results in the removal of anthropogenic, atmospheric greenhouse gases."[2] Unlike all other proposals to "geoengineer" the climate system by addressing the consequences of climate change, such as by seeking to offset average global temperature changes with particulates released into the stratosphere (Keith, 2000), air capture is fundamentally different in that it seeks to address one of the primary causes of climate change by directly reducing atmospheric levels of carbon dioxide (Parson, 2006). It differs from proposals to capture carbon dioxide from power plant emissions in that it focuses on removal of carbon dioxide from ambient air.

Various proposals have been advanced for air capture, several have been operationally tested, and at least several are being commercialized (Jones, 2008; GRT, 2007; Stolaroff, 2006; Zeman, 2007). The most straightforward means of air capture is simply through photosynthesis. Hansen et al. (2007) propose that carbon dioxide emissions from power plants fuelled with biomass might be captured at the source and then sequestered in the deep sea (cf. IPCC, 2005). Keith et al. (2006) have developed a prototype system that uses sodium hydroxide and lime to remove carbon dioxide from the air (cf. Stolaroff, 2006). Lackner (2003a,b; and subsequently GRT, 2007) propose an alternative absorption technology that does not use sodium hydroxide, but which is not described in detail due to its proprietary nature.[3] Lackner, of Columbia University, is actively working to commercialize the technology with a company called Global Research Technologies Inc. located in Tucson, AZ (GRT, 2007). Once captured, a pure stream of carbon dioxide could then be sequestered in the same manner as carbon dioxide captured from power plants (for an overview see IPCC, 2005). One proposal suggests using peridotite carbonation, a natural geologic process involving rock that reacts with carbon dioxide, to capture and sequester carbon dioxide (Kelemen and Matter, 2008). There are a range of technologies being explored for air capture, making some form of the technology likely to be developed in coming years (Jones, 2008). Thus, it is not premature to begin considering the economics of the technology.

The long-term storage of carbon dioxide is not trivial and, like the storage of nuclear waste, raises important questions about long-term sustainability and public acceptance (see, e.g., Spreng et al., 2007). The analysis presented in paper proceeds with the assumption, following IPCC (2007b) and IEA (2008), that some considerable storage of carbon dioxide, e.g., in geologic formations or in the deep ocean, will be found feasible. To be absolutely clear, this assumption is not a prediction or evaluation of the ability to overcome future challenges of sequestration. If sequestration provides problematic for technical or political reasons, then not only will air capture be fundamentally limited, but so too will be carbon capture and storage, which is now a fundamental part of the climate policies of the EU, G8, United States, and present in virtually all mitigation scenarios of the IPCC, IEA, and other major assessments of mitigation policy. A comprehensive treatment of issues associated with sequestration can be found in IPCC (2005), and a review of sequestration issues goes

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[1] IPCC (2005) acknowledges the technology (p. 108), but excluded its discussion. The 2007 report also acknowledges air capture (WG III, Chapter 4, p. 286) but does not discuss it in any depth.

[2] http://www.virginearth.com/.

[3] Other proposals are discussed by Zeman (2007) and Baciocchi et al. (2006).

well beyond the scope of the present analysis. Suffice it to say, sequestration is not a trivial obstacle to overcome.

3. Carbon dioxide arithmetic[4]

Understanding the challenge of stabilizing carbon dioxide levels in the atmosphere at a constant amount requires understanding the dynamics of stocks and flows (Sterman and Booth Sweeney, 2002). Here is how the challenge looked in 2007, using the analogy of a bathtub filling with water. Imagine that it is in fact a giant bathtub, 450 cm deep, filled to a depth of 380 cm. The spigot is adding water at a rate of 8 L/min, prompting some concern about the tub overflowing. There is also a drain at the bottom of the tub that is allowing water out at the rate of about 4 L/min.[5] For every 2 L added to (removed from) the bathtub the water level increases (decreases) by 1 cm. To add to concerns about overflowing the tub the filling rate from the spigot will increase over the next half hour to more than 12 L/min.

The challenge that you face is to keep the bathtub from overflowing. Based on the filling rate, its rate of increase, and the open drain, the tub will overflow in about 24 min. If you can somehow stop the increase in the filling rate, limiting it to 8 L/min (or a net of 4 L/min = 2 cm/min increase in water level in the tub), you will gain an additional 9 min before the tub overflows. Maybe you can use that extra time to prepare for the overflow, but it will not change the end result. The only way that you can prevent an overflow is by reducing the net rate at which water is filling the tub to zero—in other words, for the water level in the tub to become stabilized at a fixed level, the water filling the tub must be less than or equal to the amount of water being removed, in this case the 4 L/min going down the drain.

A simple bathtub model approximates the dynamics associated with the challenge of stabilizing carbon dioxide concentrations in the atmosphere. Parallel to the bathtub model, the following sections describe anthropogenic emissions (which can be thought of as the water filling the tub from the spigot) and natural sinks (equivalent to the water being removed from the tub via the drain), and how they might be combined in a very simple fashion to enable a calculation of the economic costs of air capture.

3.1. *Anthropogenic emissions and atmospheric concentrations of carbon dioxide*

Carbon dioxide accumulates in the atmosphere due to anthropogenic (i.e., human) activities, including the burning of fossil fuels and land use practices (IPCC, 2007b). Several hundred years ago atmosphere concentrations of carbon dioxide were about 280 parts per million (ppm) rising to about 380 ppm in 2007 (IPCC, 2007b). Concentrations have increased because carbon dioxide accumulates in the atmosphere faster than it is removed. Emissions are conventionally described in units of billions of tons, or gigatons (Gt). The addition to the atmosphere of approximately 7.8 $GtCO_2$ (equivalent to 2.13 Gt carbon, or GtC)[6] leads to an increase in CO_2 concentration of 1 ppm (see, e.g., Enting et al., 1994; Socolow and Lam, 2006).[7] Wigley (2007) observes that the relationship of emissions and concentrations varies over time. This complexity is ignored in the analysis below.[8] For the remainder of the paper I express emissions in terms of GtC.

In 2007 the U.S. Energy Information Agency estimated total global emissions of carbon dioxide to be about 8 GtC and projected them to rise to more than 12 GtC by 2030 (Energy Information Administration, 2007a).[9] IPCC (2007a) reports a median scenario for global emissions in 2100 to be 60 GtC, with its baseline scenarios ranging from 10 GtC to 250 GtC, reflecting enormous uncertainties about the future (IPCC, 2007c, cf. Pielke et al., 2008). Using the IPCC median value for global emissions for 2100 and interpolating to that value from the EIA estimate from 2030 provides a midrange estimate of global carbon dioxide emissions for the 21st century.[10]

3.2. *Natural sinks of carbon dioxide*

Some of the carbon dioxide emitted through human activity is absorbed by the oceans and by various processes of the land surface (IPCC, 2007b). In 2007, the IPCC estimated for the period 2000–2005 that the oceanic uptake of carbon dioxide to be 2.2 GtC per year with a standard deviation of 0.5 GtC (cf. Sabine et al., 2004). Land surface processes resulted in a net uptake of 0.9 GtC with a standard deviation of 0.6 GtC.[11] The IPCC estimates the total annual natural sink of carbon dioxide for 2000–2005 to be 3.1 ± 1.5 GtC. Because the uptake of carbon dioxide is related to processes that change in complex ways due to growing carbon dioxide concentrations, projections of sink values for the future are necessarily highly uncertain (IPCC, 2007b).

In projections of future concentrations of atmospheric carbon dioxide concentrations Pacala and Socolow (2004) assume an annual average land sink of 0.5 GtC until 2054, and

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[4] I borrow the title of this section from Broecker (2007). For a more sophisticated approach see Socolow and Lam (2006).

[5] Were this example to be made even more realistic, the outflow rate would be variable, and related to the inflow rate.

[6] Based on the molecular weights of carbon and carbon dioxide, the mass of a CO_2 molecule is 3.664 times more than a C molecule. So to convert from a mass expressed in terms of carbon dioxide to that expressed in terms of carbon requires dividing by 3.664. See ORNL (1996).

[7] Broecker (2007) uses 4 GtC/ppm and Parson (2006) uses 2.16 GtC/ppm. The U.S. Department of Energy CDIAC uses 2.13 GtC which is the value that I use here. See ORNL (1996).

[8] I can find no studies that explore the relationship between large, instantaneous changes in net emissions, such as would occur via large-scale air capture, and the carbon cycle. Such studies would be necessary for studies of the costs of air capture that have the complexity of analyses of the IPCC on the cost of other forms of mitigation.

[9] The values used here refer to the ''reference'' or mid-range estimates.

[10] The EIA projects that the annual growth in global emissions will decrease from 2.2% from 2008 to 2009 to 1.3% from 2029 to 2030. Continuing from 2030 a rate of annual increases that decreases by 3.5% per year (i.e., the rate of increase in emissions from 2040 to 2041 is 96.5% of the rate of increase from 2039 to 2040, and so on) leads to emissions of approximately 60 GtC in 2100, which is the IPCC median scenario.

[11] These values are presented in Table 7.1 on p. 516.

Table 1 – Cumulative twenty-first century maximum emissions (columns 2–4) for associated stabilization levels (column 5), from IPCC (2007a).

IPCC stabilization category	Total CO_2 emissions 2000–2100 (Gt)	Equivalent total C emissions 2000–2100 (Gt)	Equivalent total C emissions 2008–2100 (Gt)	Associated stabilization level
A1	1100	300	240	<440 ppm
C	3000	820	760	480–570 ppm
E	5020	1370	1310	>855 ppm

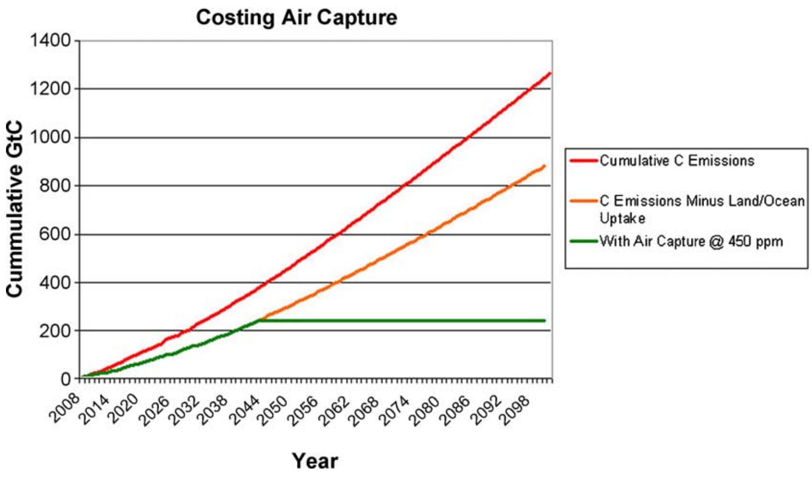

Fig. 1 – The cumulative cost of air capture can be calculated as the difference between the orange and green curves at a point in time multiplied by the cost per ton of carbon of air capture. The green curve reflects full offsetting of net human emissions of carbon dioxide beginning in 2043. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

an ocean sink of about 2.8 GtC in 2004 increasing to about 3.9 GtC in 2054, or a cumulative uptake due to oceans of 180 GtC over 50 years, or an average over these 50 years of 3.6 GtC/year.[12] The analysis below follows Pacala and Socolow (2004) and uses a value of 4.1 GtC to represent the annual average size of natural carbon dioxide sink to 2100.[13] Other assumptions about the magnitude of the size of the natural sink could certainly be used. For instance, should the reader wish to assume that the natural sink is zero, then this would add about an additional 380 GtC to the mid-range emissions trajectory to 2100.

3.3. *IPCC stabilization scenarios*

The assumptions presented in the previous two sections allow for projection of emissions and corresponding atmospheric concentrations of carbon dioxide to 2100. The 2100 value of 794 ppm is above the median of the reference scenarios used by the IPCC (2007b). The cumulative C emissions 2008–2100 can be thought of as an ‘‘allocation’’ that could be ‘‘spent’’ at any time during that period and still meet the concentration target (cf. Broecker, 2007; Pacala and Socolow, 2004; Socolow and Lam, 2006). In its Fourth Assessment Report, IPCC (2007a) provides an estimate of the cumulative emissions in the 21st century associated with various levels of stabilization of the atmospheric concentration of carbon dioxide.[14] The median values are shown in Table 1.

Table 1 shows the IPCC median value for a 21st century carbon allocation leading to <440 ppm carbon dioxide to be 240 GtC. Under middle range estimates for emissions and the size of the natural sink, for a stabilization level of <440 ppm under the scenario described here based on IPCC midrange values the 21st century carbon allocation will have been completely spent by 2043.[15] Under the same assumptions, total anthropogenic emissions are about 1260 GtC for the remainder of the 21st century (i.e., 1260 GtC are the cumulative emissions from 2008 to 2100). Thus, 240 GtC represents about 20% of this value, which is consistent with the often-cited need to reduce 21st century emissions by 80%. Fig. 1 shows the cumulative emissions of carbon, the net cumulative amount after adjusting for natural sinks, and the effects of air capture of all emissions upon reaching a threshold of 240 GtC. For a stabilization level of less than 570 ppm, roughly twice pre-

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[12] Pacala and Socolow (2004) suggest that their estimate of a total natural sink of 180 GtC from 2004 to 2054 has an uncertainty range of −25 GtC to 125 GtC, for a total natural sink over the time period of 155–305 GtC, or an annual average of about 3–6 GtC.

[13] Broecker (2007), by contrast, does not discuss natural sinks, but his calculations imply a natural sink of 4 GtC in 2007 increasing to 8 GtC by 2050 (Broecker, per. corres.). Compare Wigley (2007).

[14] See IPCC (2007a), Table 3.5 and Fig. 3.18.

[15] Consistent with the analysis here, UNDP (2007) suggests that a 450 ppm threshold will be reached between 2032 and 2042 depending on the scenario.

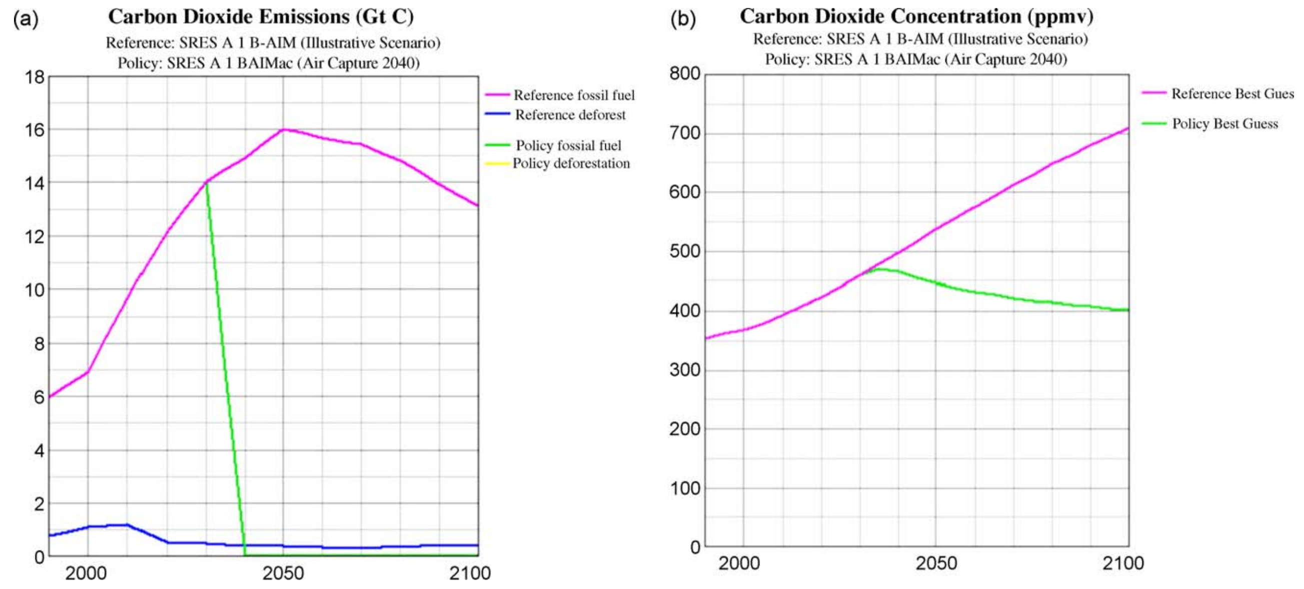

Fig. 2 – (a) Global annual carbon dioxide emissions and (b) carbon dioxide concentrations, with air capture implemented to offset all emissions by 2040. Reference scenario is SRES A1B-AIM.

industrial concentrations, under the scenario described here, the 21st century carbon allocation will have been completely spent by 2074.[16] The 21st century carbon allocation related to stabilization at >855 ppm will not be exceeded by 2100 under the assumptions presented here.

3.4. *The dismal prospects for stabilization at 450 ppm CO_2*

Climate change and the challenge of reducing carbon dioxide emissions have been on the agenda of policy makers for at least two decades, with considerable attention having been devoted to the issue in the past 10 years since the initial agreement on the Kyoto Protocol in 1997. Since that time global emissions growth has shown no sign of abatement, and instead have increased by about 30% (see Canadell et al., 2007; Raupach et al., 2007).

Successful stabilization at 450 ppm carbon dioxide, often equated with a target for global average temperature change of 2 °C adopted by the European Union, would require completely transforming the global energy system over the next 30–50 years, a challenge that faces enormous technological, social, institutional, and political obstacles (Hoffert et al., 2002; Rayner and Malone, 1998). To understand the magnitude of the challenge, consider the following observation of Caldeira et al. (2003):

> To achieve stabilization at a 2 °C warming, we would need to install ~900 ± 500 MW [mega-watts] of carbon emissions-free power generating capacity each day over the next 50 years. This is roughly the equivalent of a large carbon emissions-free power plant becoming functional somewhere in the world every day. In many scenarios, this pace accelerates after mid-century… even stabilization at a 4 °C warming would require installation of 410 MW of carbon emissions-free energy capacity each day.

Given the languid pace of political negotiations on climate change and the inexorable growth in emissions, it is not surprising that calls for the advancement of air capture technologies have become more common. Of course, there is no guarantee that the installation of air capture facilities would be any les controversial than new nuclear plants or coal facilities with CCS. Even so, Hansen et al. (2007) suggest that the fate of the planet depends upon successfully deploying air capture technologies, "a feasible strategy for planetary rescue almost surely requires a means of extracting [greenhouse gases] from the air."

3.5. *Stabilization via air capture in a simple climate model*

The effects of air capture on the atmospheric concentrations of carbon dioxide can be illustrated with a simple climate model called MAGICC which has been used by the IPCC to project future temperature change and sea level rise (Wigley, 2003). Fig. 2a and b shows an example scenario that assumes air capture is used to fully compensate for all human emissions of greenhouse gases by 2040. Fig. 3a and b shows the same analysis for 2070. Both examples begin with one of the IPCC SRES scenarios (A1B-AIM) with rapid emissions growth.

The stabilization levels in each case are consistent with the conclusions presented in the far more simplistic examples

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[16] For comparison, the very simple analysis in Table 1 suggests that 570 ppm will be exceeded at cumulative emissions of 620 GtC, which is less than the IPCC "allocation" by 140 GtC (presumably due primarily to my overly simplistic treatment of carbon cycle feedbacks, cf. Wigley, 2007). To the extent that the simple analysis presented here serves to underestimate (overestimate) the size of the 21st century carbon allocation, it will lead to overstating (understating) the costs of air capture.

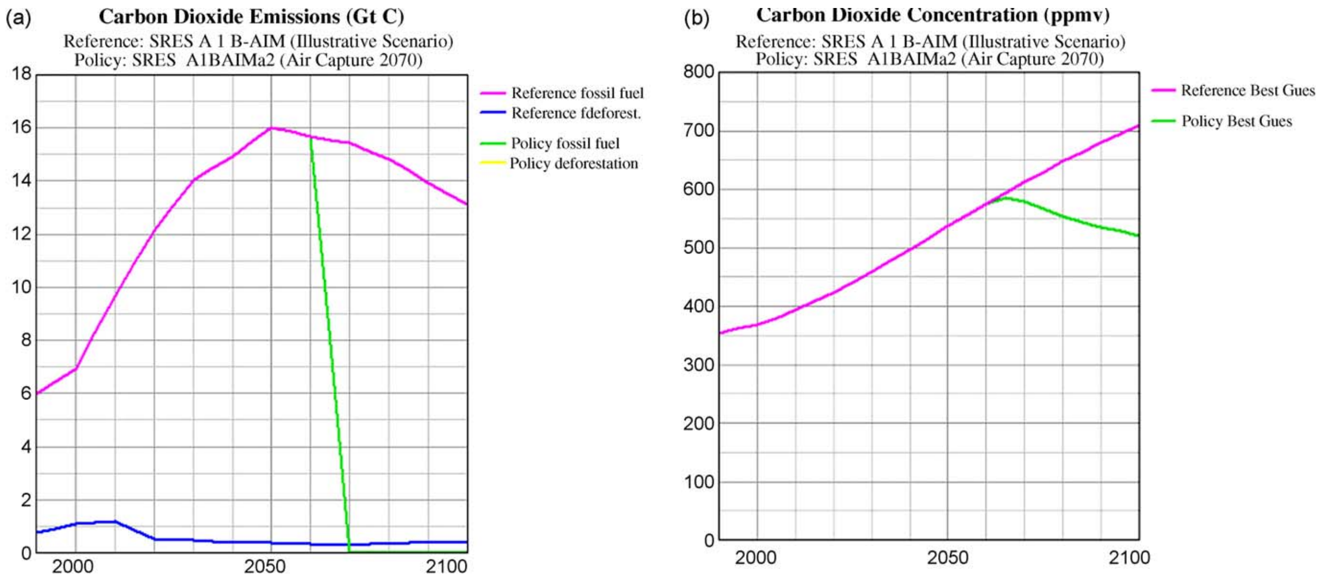

Fig. 3 – (a) Global annual carbon dioxide emissions and (b) carbon dioxide concentrations, with air capture implemented to offset all emissions by 2070. Reference scenario is SRES A1B-AIM.

developed above with a few minor exceptions.[17] One conclusion from this simple exercise is that air capture is compatible with stabilization of atmospheric concentrations at very low levels. There is no reason in principle why air capture could not be used to reduce atmospheric concentrations by an amount greater than annual emissions, thus making any concentration target reachable. The examples shown here are also consistent with the assessment of costs developed in the next section.

4. The surprising economics of air capture[18]

Estimates vary for the cost of capturing carbon dioxide directly from the atmosphere. Keith et al. (2006) suggest that using existing technology the costs could be as much as $500 per ton of carbon, and perhaps eventually under $200 per ton. In 2007 Keith suggested that the cost of air capture could drop below $360 per ton (Graham-Rowe, 2007). Columbia University's Klaus Lackner has suggested that the costs today are less than $360 per ton of carbon, and may eventually fall beneath approximately $100 per ton.[19] IPCC (2007a) discusses air capture only in passing:

> Studies claim costs less than 75 US$/t$CO_2$ [$275/tC] and energy requirements of a minimum of 30% using a recovery cycle with $Ca(OH)_2$ as a sorbent. However, no experimental data on the complete process are yet available to demonstrate the concept, its energy use and engineering costs.[20]

In the simple exercises below I use three values for the costs of air capture: (a) the highest value from Keith et al. (2006) of $500 per ton of carbon, (b) the estimates of Lackner and Keith in 2006 and 2007 of $360 per ton, and the lowest estimate provided by Lackner in 2006 of $100 per ton. The IPCC (2007a) estimate falls near the middle of this range.

4.1. *The costs of global stabilization via air capture*

At 2.13 GtC equivalent to 1 ppm carbon, this means that the current (idealized) costs of air capture are about $1 trillion per reduced ppm of atmospheric carbon dioxide at a cost of air capture equal to $500/tC. $1 trillion represented about 2.5% of global GDP in 2007. At $500/tC complete mitigation of net 2008 human emissions would cost about $4 trillion, or about 10% of global GDP. At $100 per ton the 2007 cost would be about 2.0% of global GDP.

If the goal of air capture is to limit the total carbon dioxide emissions during the remainder of the 21st century to less than the 240 GtC allocation suggested by the IPCC, then there are many different temporal paths over which air capture might be implemented. That is, it is the cumulative emissions over the

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[17] For example, in the MAGICC examples human emissions are reduced to zero whereas in the simple example above they are reduce to the size of the natural carbon sink.

[18] Geoengineering strategies in general appear to have ''incredible'' (i.e., small) costs, see Barrett (2008).

[19] Here is Prof. Lackner on PBS Newshour, 8 June 2006: ''With off-the-shelf items we have right now, I can drive the cost of CO_2 capture from air below $100 per ton of CO_2 [$360 tC]. And I feel that, if you pursue this longer, the ultimate end game will be below $30 per ton of CO_2 [$100 tC].'' (Online NewsHour, 2006). Zeman (pers. corres.) suggests that $100/tC may not be attainable before 2050. In an unpublished analysis Herzog (2003) suggested the cost to be $480 per ton.

[20] Working Group III, Chapter 4, p. 286. The IPCC provides no reference or justification for its cost estimate. The IPCC's dismissal of air capture in this manner is surprising, because much of the IPCC's analysis of the prospects for and costs of greenhouse gas mitigation depend upon policies and technologies whose implementation has not been proven successful in practice.

Table 2a – Cost of air capture as a percentage of global GDP, assuming 2.9% global GDP growth to 2100 after IPCC (2000).

	$500/tC	$360/tC	$100/tC
450 ppm cost to 2050	2.7%	1.9%	0.5%
550 ppm cost to 2050	0.0%	0.0%	0.0%
450 ppm cost to 2100	2.1%	1.5%	0.4%
550 ppm cost to 2100	1.5%	1.1%	0.3%

Table 2b – Cost of air capture as a percentage of global GDP, assuming 2.5% global GDP growth to 2100 after Stern (2007).

	$500/tC	$360/tC	$100/tC
450 ppm cost to 2050	3.0%	2.2%	0.6%
550 ppm cost to 2050	0.0%	0.0%	0.0%
450 ppm cost to 2100	2.7%	2.0%	0.5%
550 ppm cost to 2100	2.0%	1.4%	0.4%

21st century that matter, not the specific emissions trajectory. For purposes of discussion, the analysis that follows assumes that air capture of all net human emissions is implemented immediately upon reaching the 240 GtC limit and thereafter. This is practically unrealistic; however, other more realistic implementation ‘‘paths’’ for deployment air capture could of course be envisioned, however would not alter the calculations of average costs presented here. The analysis errs on the side of understating costs as there are no assumptions made about the economies of scale associated with a widespread deployment and likely reductions in costs of the technology (e.g., McKinsey, 2008).[21] The calculation of cost involves simply multiplying the expected capture cost per ton of carbon by the integral of the difference between projected emissions and emissions under air capture. If the goal is to limit the total emissions to a fixed cumulative amount, such as the 240 GtC discussed above, then the choice of specific air capture deployment path is irrelevant to the cost calculation.

Under these assumptions, Tables 2a and 2b show the cumulative costs of air capture over the periods 2008–2050 and 2008–2100 for different stabilization levels and different costs per ton of carbon. Table 2a assumes an annual global GDP growth rate of 2.9% following IPCC (2000),[22] and Table 2b assumes after Stern (2007) an annual global GDP growth rate of 2.5%. Stern (2007) uses a global GDP of $35 trillion in 2005. No effort has been made here to account for the time value of money or different approaches to calculating economic growth across countries, which have been discussed elsewhere in great depth in the context of climate change, and all dollars are expressed in constant-year terms.

All of the values presented in Tables 2a and 2b for the costs of stabilization at 450 ppm via air capture fall within the range of those presented in the Stern (2007) which suggested that stabilization at 450 ppm carbon dioxide would cost about 1% of global GDP to 2100 (with a range of ±3%).[23] Stern (2007) explained how one might think about this value:

> ... if mitigation costs 1% of world GDP by 2100, relative to the hypothetical ‘no climate change’ baseline, this is equivalent to the growth rate of annual GDP over the period dropping from 2.5% to 2.49%. GDP in 2100 would still be approximately 940% higher than today, as opposed to 950% higher if there were no climate-change to tackle.

If air capture technology could be implemented at $100 per ton, then the cost to stabilize emissions over the 21st century would be less than the Stern median estimate. For stabilization at 550 ppm or about twice pre-industrial, air capture costs nothing prior to 2050.

Similarly, the ranges of costs for air capture are comparable to those presented in IPCC (2007a) which estimated the costs of mitigation for 2050 at a level of 535–590 ppm carbon dioxide equivalent (comparable to Stern’s 450 ppm carbon dioxide) to fall within the IPCC range of −1% to 5.5% of global GDP in 2050. The IPCC median value of 1.3% is less than the costs air capture at $360 cost per ton of carbon, but almost three times the cost at $100 per ton.

Making global cost estimates for any complex set of interrelated systems far into the future is a dubious enterprise. However, the analysis here shows that using very similar assumptions to the IPCC (2007a,c) and Stern (2007), air capture compares favorably with the cost estimates for mitigation provided in those reports. The main reason for this surprising result, given that air capture has a relatively high cost per ton of carbon, is the long period for which no costs are incurred until the stabilization target is reached. Further, a factor not considered here (nor, apparently, in Stern or IPCC) is that the economy would likely grow at a higher rate than with early, aggressive mitigation, meaning that the costs of air capture would be a smaller fraction of future GDP than comparable costs per ton of C requiring large costs early in the century. The cost of air capture under the assumptions examined here is also less that the projected costs of unmitigated climate change over the 21st century, which Stern (2007) estimated to be from 5% to 20% of GDP annually and IPCC (2007d) estimate to be 5% of global GDP by 2050.

There are additional several factors, beyond those already discussed, which serve to overstate the cost estimates of air capture found in Tables 2a and 2b. Carbon dioxide emissions from power plants, representing perhaps as much as half total emissions over the 21st century could be captured

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[21] McKinsey (2008) observes that a wide range of energy and energy-related technologies for purposes of mitigation see substantial effects of economies of scale.

[22] This growth rate is consistent with the emissions profile, and higher than in other IPCC scenarios which have lower rates of increasing emissions.

[23] Stern (2007) equated a 450 ppm carbon dioxide level with a 550 ppm carbon dioxide equivalent concentration, which includes other gases.

at the source for a cost considerably less than direct air capture.[24] The technical, environmental, and societal aspects of carbon sequestration are identical for capture of carbon dioxide from both power plants and ambient air. To the extent that improvements in efficiency and overall emissions intensity occur, these developments would further reduce total emissions and thus the need to rely on air capture.[25] The assumptions here assume simplistically a fixed average cost of air capture over time, whereas experience with technological innovation suggests declining marginal costs over time (e.g., McKinsey, 2008).

Consideration of these factors could reduce the values presented in Tables 2a and 2b by a significant amount perhaps by as much as half. Uncertainties in rates of increasing emissions, economic growth, and concentrations mean that the values presented here could be more or less than under different assumptions. Because the analysis relies on the mid-range values of the IPCC for these various factors, it is unlikely that a more comprehensive treatment of uncertainties would lead to qualitatively different conclusions if one begins with assumptions underpinning and implications following from the IPCC.

To summarize, the idealized exercise conducted here finds that air capture using 2008 technology is of about the same costs as the costs estimates for stabilization at 450 ppm or 550 ppm carbon dioxide presented by IPCC (2007a) and Stern (2007). If the costs of air capture decrease to $100 per ton of carbon, then over the 21st century air capture would in fact cost much less than the costs estimates for stabilization presented by IPCC (2007d) and Stern (2007). This surprising result suggests, at a minimum, that air capture should receive the same detailed analysis as other approaches to mitigation.

4.2. *Case study: full mitigation of U.S. auto emissions with air capture*

One can also engage in a much more focused analysis of the costs of air capture in climate mitigation. In 2005 United States auto emissions were responsible for about 6% of total global emissions (Energy Information Administration, 2005). Six percent of 2007 carbon emissions are about 0.48 GtC (Energy Information Administration, 2005). All United States automobile emissions of carbon dioxide could be offset through air capture for a cost of $48 billion at $100/tC, $173 billion at $360/tC, or $240 billion at $500/tC. For comparison, were the U.S. to have signed on to the Kyoto Protocol requiring a 7% reduction in 1990 levels of emissions, the annual cost of meeting this target via air capture (using 2006 emissions values) would be about $125 billion at $360/tC or about $173 billion at $500/tC (Energy Information Administration, 2007b). In 2008 in Europe the cost of a 2008 certified emissions reduction credit under the Kyoto Protocol was about $100/tC, so air capture is 3.6–5 times more expensive than the penalties likely to be paid by signatories to Kyoto who are expected to miss their targets.

The values for offsetting U.S. carbon dioxide emissions from gasoline in automobiles may be easier to understand in terms of the cost of a gallon of gasoline. In 2005 the United States used approximately 140 billion gallons of gasoline (Energy Information Administration, 2007c). Assuming 150 billion gallons for 2007 equates to a gas tax of $1.15 (at 360 per ton) or $1.60 per gallon (at $500 per ton). These levels of taxation are smaller than gas taxes in many European countries. In principle, all of the emissions of carbon dioxide from automobiles in the United States could be removed via air capture using today's technology at marginal costs that are of the same magnitude as the inter-annual variability of gasoline prices, and U.S. consumers would still have among the lowest gasoline prices in the world.

5. Conclusion

One way to think of air capture is as reflecting an unambiguous cost estimate of addressing the growing concentrations of greenhouse gases in the atmosphere. These costs are unambiguous because the processes are straightforward, involving costs that can be accurately quantified. Understanding the costs of air capture requires no complex economic models laden with layer upon layer of assumptions about the effects of government polices, social institutions, and human behavior. It is therefore quite straightforward to evaluate the costs of air capture. From this perspective air capture provides a fixed target against which to evaluate other approaches to mitigation, to the extent that they can demonstrate effectiveness (i.e., reducing concentrations in practice, not just in theory) at a cost less than air capture, they might be preferred. As much attention should of course be paid to practical effectiveness as to cost.

If nothing else, discussions of the merits of air capture may serve to help to better identify the distinction between the climate change justifications for pursuing mitigation, which air capture addresses elegantly, and the non-climate change benefits of mitigation, to which air capture offers very little (cf. Sarewitz and Nelson, 2008). Arguably, many advocates of greenhouse mitigation support aggressive action not simply because of the direct climate benefits, but also because of the ancillary benefits, including ''limiting the aggregate scale of human population and economic activity'' (Parson, 2006). To succeed in winning support, any significant policy proposal will require a coalition of supporters whose reasons for lending their support will be varied, and even contradictory with each other. However, if the differences between formal goals and actual reasons for support become too large, it may threaten the possibility for any action to occur. Air capture makes it more difficult for supporters of mitigation to import into the debate their

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[24] For a review of the costs of carbon capture and storage (CCS), see IPCC (2005). Zeman (2007) observes that IPCC (2005) ''describes various technologies focused on emitters producing at least 0.1 Mt per year of CO_2 [~0.27 MtC]. All totalled, these sources produce 13.6 Gt of CO_2 [~3.7 GtC] annually while global emissions are estimated at 25.7 Gt of CO_2 [7.0 GtC]. The nominal 90% capture rate of most CCS technologies suggests that more than 50% of global emissions would remain unabated even if these were fully deployed.''

[25] In addition, if the allowable ''carbon allocation'' is understated (overstated) by the simple methodology here, then there would be less (more) need for air capture and corresponding less (more) costs, see footnote 19.

underlying agendas unrelated to stabilizing carbon dioxide concentrations.

Air capture may or may not contribute to efforts to stabilize greenhouse gas concentrations. But so long as scientists and policy makers frame climate policy as in terms of stabilizing concentrations of atmospheric carbon dioxide, then given current indications of its potential effectiveness and cost, air capture deserves to be among the options receiving attention in the international climate policy debate.

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