Robert M.
La Follette School of Public Affairs
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Working Paper Series
La Follette School Working Paper No. 2011-015
http://www.lafollette.wisc.edu/publications/workingpapers

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August 2011

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Willingness to pay for a climate backstop: liquid fuel producers and direct CO2 air capture

Gregory F. Nemet* Adam R. Brandt†

Abstract

We conduct a sensitivity analysis to describe conditions under which liquid fuel producers would fund the development of a climate backstop. We estimate (1) the cost to develop competitively priced direct CO2 air capture technology, a possible climate backstop and (2) the effect of this technology on the value of liquid fuel reserves by country and fuel. Under most assumptions, development costs exceed individual benefits. A particularly robust result is that carbon prices generate large benefits for conventional oil producers—making a climate backstop unappealing for them. Unilateral investment does become more likely under: stringent carbon policy, social discount rates, improved technical outcomes, and high price elasticity of demand for liquid fuels. Early stage investment is inexpensive and could provide a hedge against such developments, particularly for fuels on the margin, such as tar sands and gas-to-liquids. Since only a few entities benefit, free riding is not an important disincentive to investment, although uncertainty about who benefits probably is.

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1 Introduction

The lack of progress to date in addressing climate change is driven in large part by pervasive collective action problems. Foremost, climate stability is a non-excludable public good, so countries have incentives to free-ride on the emissions reductions of others. The central role that energy plays in the climate problem makes achieving cooperative outcomes especially difficult because countries tend to be averse to relinquishing sovereignty over decisions about how they produce and use energy. Resolving the resulting impasse is even more challenging in that stabilizing the concentration of greenhouse gases (GHGs) in the atmosphere requires substantial investments in the development of low-carbon technologies. The investments required to accomplish this transformation of the energy system are large. The International Energy Agency (IEA) estimates that the investment required to address climate change will be \$11 trillion between 2010 and 2030; this amount is in addition to the \$26 trillion that will be needed to meet energy demand in the absence of concern about climate change (IEA, 2009). The magnitude of required investment is not however the main problem. Because nascent technologies, especially very novel ones, can be copied and reverse-engineered, knowledge generated by these investments is difficult to appropriate: it spills over from one firm to another, and similarly from one country to another. Knowledge spillovers reduce the incentives to invest in technologies, giving rise to a second public goods problem (Nordhaus, 1991, 2011; Jaffe et al., 2005): countries and firms have incentives to free-ride on the technology investments of others.

Because the technological transformation needed to stabilize GHG concentrations is so large—and the potential for rapid increase in climate-related damages so serious—there is interest in technologies that might address the climate problem more immediately (MacCracken, 2009; Victor et al., 2009; Azar et al., 2010; Boucher and Folberth, 2010). Some of these would increase the earth's albedo while others would remove CO2 from the atmosphere. Several possible methods for removal of CO2 exist, including biological capture via photosynthesis, hydrothermal carbonization of biomass, and chemical absorption, for example, by reacting air with lime and sodium hydroxide. Technologies to chemically remove CO2 directly, hereafter called direct 'air capture' (DAC)have shown some promise of feasibility in that on the order of several tons of CO2 have been captured from ambient air. Because this technology may be scalable with non-increasing marginal costs, it has properties of a backstop technology, i.e. its marginal costs could determine marginal abatement costs (Keith et al., 2006; Pielke, 2009; Barrett, 2010). The cost of air capture would thus put an upper limit on CO2 prices.

Obvious challenges abound in capturing and storing CO2 at a scale many orders of magnitude larger than laboratory tests. Indeed studies question whether air capture provides a complete backstop (Socolow et al., 2011), particularly raising concerns about storage of captured CO2, including: adequacy of capacity; safety and efficacy due to leakage; and whether marginal costs will remain non-increasing. On the other hand, the much higher locational flexibility of air capture compared to power plant capture would avoid increasing costs due to transport and saturation of individual reservoirs. Alternatives to physical storage could also increase capacity (Stephens and Keith, 2008). At present the extent to which storage limitations exist remains highly uncertain (IPCC, 2005; Socolow et al., 2011) and in this study we treat air capture as a possible backstop. Even so, the magnitude of potential benefits motivates calls for research investment (Lackner et al., 1999; Keith, 2009; Caldeira and Keith, 2010) as well as a bill introduced in the 111$^{\text{th}}$ U.S. Congress offering a prize for air capture (Barrasso et al., 2009).

1.1 Unilateral action on climate

As direct CO2 removal and planetary scale albedo modification have garnered more serious consideration, concerns have increased about efficacy, adverse effects, and associated governance issues (Caldeira and Wood, 2008; Levi, 2008; Kintisch, 2010). Much concern has focused on unintended environmental consequences (Robock, 2008; Wetter, 2009). This concern extends to ethical issues about whether to even proceed with research (Morrow et al., 2009), given the possibility of a 'moral hazard' that would discourage near-term abatement (Lemoine et al., 2010). Other discussions have focused on the governance issues that arise from climate solutions that may be inexpensive, risky, and potentially feasibly implemented by a very small number of actors (Parson, 2006; Victor, 2008; Shepherd et al., 2009; Virgoe, 2009). While air capture does not involve many of the concerns of other geo-engineering approaches, it does retain one important similarity; it is possible that a small group of actors could deploy the technology on a scale sufficient to affect the climate (Barrett, 2009; Chichilnisky and Eisenberger, 2009). It thus shares the governance concerns associated with a small group of actors determining climatic, and therefore social, outcomes. It is possible, in the face of debilitating collective action problems, that this potential for unilateral action might actually be an asset.

Might a small group of actors decide to fund the development of air capture technology such that it becomes effective, free of significant side-effects, and cost competitive relative to other abatement options? If such a group were to exist, who would comprise the group, and what would their motivations be? One plausible response to these questions is that direct air capture is especially appealing for producers of liquid fuels in that it is one of the few approaches to avoiding the damages of climate change that preserves the value of their reserves. Whereas biologically derived fuels and electrification of transportation provide alternatives to fossil-based vehicle fuels, air capture could make liquid fuels a low-carbon option, much as CCS would do for coal-fired power plants. Moreover, unconventional petroleum producers are more vulnerable to carbon prices than conventional producers (Johansson et al., 2009), and thus may derive particularly high benefits from a negative emissions technology such as air capture. Also, production of liquid fuels has tremendous economies of scale, leading to high industry concentration, widespread government ownership, and enormous profits on subsurface resources. Or, put differently, the number of distinct actors in the liquid fuel industry is small and they have ample funds (and motivation) to develop such technology. Groups of countries, such as OPEC, have shown a willingness to relinquish sovereignty to pursue a cooperative outcome (Smith, 2005).

1.2 Approach

This paper takes a benefit-cost approach to identify circumstances in which a small group of actors may be willing to invest in the development of air capture technology. We take a bottom-up approach to estimate the costs incurred in order to fund the development of air capture from a laboratory technology to a mass-produced commercial product with costs below the marginal cost of emissions abatement. We then use a model of liquid fuel supply to estimate the change in the value of reserves for fuel producers via the reduction in the price of CO2 due to air capture. Our initial hypothesis was that this reduction in the price of CO2 would generally provide benefits to producers; however, our results show that that some reserves lose value under lower CO2 prices and thus air capture does not benefit them. Uncertainty in this domain is pervasive: the outcomes of investment in air capture, the stringency of climate policy, as well as the characteristics of the supply and demand for liquid fuels all include important sources of uncertainty. Therefore this analysis focuses on characterizing the uncertainty resulting from varying input assumptions to the model. The results are intended to examine overall feasibility and, through extensive sensitivity analysis, to identify the most important sources of uncertainty. Section 2 describes a model that estimates the value to oil producers of developing air capture technology. The results under base case assumptions are included in section 3. A sensitivity analysis follows in section 4 to examine the robustness of the results and to identify the most influential sources of uncertainty. In the final section (5), we consider governance and other issues that arise from these results.

2 A model of willingness to pay for a backstop technology

Our model contains two sub-modules: the first calculates the value of oil reserves and the second calculates the cost of air capture technology (Fig 1). The two models are linked in that the cost of air capture affects the global price for CO2 in the oil valuation model. The potential benefit to oil producers of having air capture available is that it may increase the value of their oil reserves relative to a situation in which the technology is not available. The cost of developing air capture is the sum of RD&D expenditures, including demonstration, and learning investments.[1]

2.1 Assumptions about carbon prices

In an effort to cover a wide range of plausible carbon prices, we consider three pathways. First, we use the prices that emerge from the 'optimal' climate policy calculated by Nordhaus (2008); about $10/tCO2 in 2010 escalating at 2%/year ('low policy' case). Second, as our 'high policy' case, we employ the prices assumed in a recent modeling project by Johansson et al. (2009), which assumes prices starting at $20/tCO2 in 2010 escalating at 5%/year. Our 'mid policy' case uses a combination of the two; $10/tCO2 in 2010 escalating at 5%/year. This 'mid policy' case is our base assumption for climate policy. A first important note is that these represent globally averaged prices and thus correspond to a current worldwide emissions-weighted price of $5/tCO2 (Nordhaus, 2010). Second, these prices reflect the interactions of the stringency of climate policy and the costs of emissions abatement. We do not explicitly project the future costs of other mitigation

[1]Further details about the approach and data used are included in a Supporting Information document: https://mywebspace.wisc.edu/nemet/web/si_wtpcb.html.

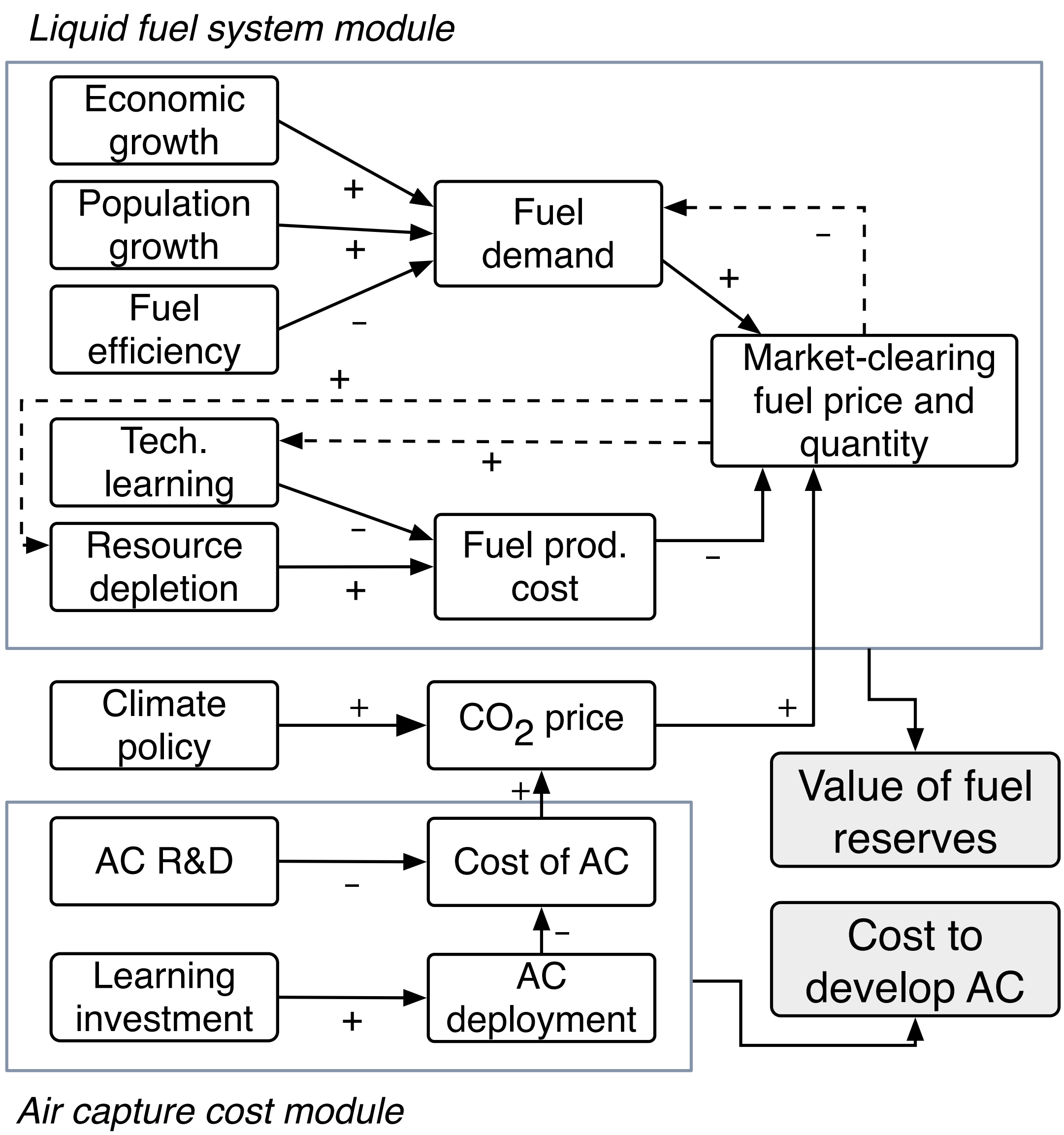


Figure 1: Modeling approach showing the two primary modules. Plus and minus signs refer to direction of effect.

technologies. We only assume that carbon prices (without air capture) reflect the price at which the marginal cost of emissions abatement is equal to the marginal cost of climate damages. This is a general assumption and is independent of the policy instruments used to price the climate-related damage externality. Carbon prices are highly uncertain and thus feature prominently in our sensitivity analysis below.

2.2 Value of oil reserves

In order to calculate the benefits of air capture deployment, an oil market model is used to calculate future revenue streams to liquid fuel producers (Brandt et al., 2010; Brandt and Farrell, 2008). The Regional Optimization Model for Environmental impacts from Oil substitutes (ROMEO) is used to calculate future production of fuels, carbon taxes paid, and revenues accruing to fuel producers. The NPV of these revenues is compared in cases with and without air capture technology in order to determine the economic viability of air capture development.

2.2.1 ROMEO overview

ROMEO models future production of liquid fuels in order to understand the climate impacts of the depletion of conventional oil and the transition to oil alternatives, such as non-conventional fossil-based fuels, biofuels, and electricity in battery electric vehicles (BEVs). ROMEO simulates the action of the global fuels market by calculating the economically-optimal time path of investment in production capacity, resource extraction, and fuel production. It accounts for resource depletion, resource endowments, and technological learning. By explicitly modeling the GHG consequences of a transition to oil substitutes, ROMEO supplements more informal analyses of the effects of liquid fuels production and depletion on the climate (Brandt and Farrell, 2007; Considine, 2007; Kharecha and Hansen, 2008).

ROMEO is a nonlinear optimization model, coded in the AMPL mathematical programming language (Fourer et al., 2003) and solved using the SNOPT solver (Gill et al., 2007). ROMEO includes 9 different liquid fuels: conventional oil, tar sands/extra-heavy oil, coal-to-liquids (CTL) synthetic fuels, gas-to-liquids (GTL) synthetic fuels, oil shale, grain ethanol, cellulosic ethanol, algae-based biodiesel, and electricity consumed in BEVs. ROMEO projects future fuel production over the 21st century for 7 model regions: USA, Canada, Russia, Brazil, OPEC, China, and the rest of the world (ROW). These regions include countries with large endowments in resources (e.g., Russia gas to GTL) or significant consumption centers (China). ROMEO does not optimize all 100 years of production simultaneously, but instead solves each year sequentially, without foresight about future demand or resource depletion. In comparison to other recent models of the transition to oil substitutes (such as the work of Greene et al. (Greene et al., 2003)), ROMEO includes more fuel types, and its year-by-year formulation captures some aspects of the volatility of the global oil market. Additional details about ROMEO are available in previous works (Brandt et al., 2010; Brandt and Farrell, 2008).

For this research, ROMEO has been improved from previous versions of the model (Brandt et al., 2010; Brandt and Farrell, 2008). Full documentation of the model structure used here, as well as the changes from previous versions of the model, is provided in ROMEO documentation (Brandt, 2011).

ROMEO models future transportation fuel demand with a log-linear partial adjustment model for petroleum demand (Cooper, 2003; Gately, 2002). Demand grows with population growth and per-capita economic growth, and declines as the price of fuels increases due to depletion. Fossil fuel inputs to liquid fuels production deplete using a logistic depletion cost function (Greene et al., 2003). Biofuels capital, feedstock and operating costs are derived from various literature sources (Brandt, 2011). Importantly, the cellulosic ethanol resource base is a function of total terrestrial net primary productivity (NPP) (Haberl et al., 2007) and is reduced by exogenous NPP consumption for other biomass needs (Imhoff et al., 2004).

Regional area-specific NPP values (gC/m^2/yr) are assigned to each country from the work of Haberl et al. (2007), which are then multiplied by the area of each country to arrive at an estimate of terrestrial NPP.[2] This NPP is the biomass resource that is apportioned between fuel uses (e.g., three biofuels modeled in ROMEO) and other exogenous biomass uses such as fiber or pulp and paper (Imhoff et al., 2004). Constraints serve to limit the fraction of NPP allowed to be consumed in biofuels and bio-products markets. This biomass availability module implicitly includes waste biomass resources because it includes all NPP resources (although waste biomass is not explicitly partitioned from non-waste biomass in model resource accounting). Grain-based biomass fuels have indirect land use change GHG emissions included in their emissions profile (Searchinger et al., 2008).

Electric transport is included in ROMEO as battery-only EVs (PHEVs are not modeled for simplicity).

[2]This method arrives at an aggregate value within 3% of the calculated global value of Haberl et al., implying stable behavior during disaggregation to country-level data.

BEVs costs, efficiencies, and capacities are modeled per unit of oil displacing capacity (Brandt, 2011). For example, since the fuel unit tracked in ROMEO (and balanced in the oil market module) is EJ of liquid fuel produced, BEV capital costs are therefore the incremental capital costs associated with *displacing* a unit of liquid fuels per year. This depends on assumptions about incremental investment costs for BEVs, amount of liquid-fuel based driving displaced by BEVs, and BEV capital lifetime (Brandt, 2011). Low range BEV costs are for current BEV technology, based on comparing Nissan Leaf technology to hybrid and conventional IC engine technology, while high range costs are from academic studies of BEV technology costs (Plotkin et al., 2009) (low range costs are used here by default).

2.2.2 Base case methodology

The base oil model case includes moderate assumptions regarding the future transition to liquid fuels. It is assumed that alternative resources are abundant, and that their costs are at the low end of current estimated ranges. These settings represent a future world with continued technological improvement, as seen in the 20th century. More specifically, the baseline parameter settings include: medium oil supply, high alternative fuel supplies, low alternative fuel costs, moderate growth constraints, moderate demand elasticity, moderate learning rates, and moderate population growth and GDP growth rates. See Brandt et al. (2010) for more numerical values associated with these settings.

2.3 Cost to develop air capture technology

We use published figures to estimate the cost of removing CO2 over time and the cost to develop the technology. Given the early stage of the technology, these values are of course highly uncertain. We only aim to arrive at a reasonable set of estimates and the conclusions that result from them are all conditional on this assumed price path. We conduct extensive sensitivity tests in section 4. As in other work we calculate future costs as a function of both R&D and learning-by-doing (Nemet and Baker, 2009; Barker and Scrieciu, 2010). We separately estimate RD&D and learning investments required to develop the technology.

2.3.1 Deployment of air capture technology

Using studies of the deployment of previous energy technologies (Grubler et al., 1999; Knapp, 1999), we assume that deployment of air capture proceeds gradually over the course of the 21st century according to a logistic function. Because we are interested in assessing air capture's role as a potential backstop technology, we assume what is likely an upper bound on air capture deployment. Based on the results of Pielke (2009) we assume 750 GT of carbon is removed over the century, enough to offset a substantial portion of human emissions and in the range of "likely" economic storage capacity available (IPCC, 2005). Following Rogers (1958) we model adoption using the logistic function:

$$Q_t = \frac{Q_{max}}{1 + e^{-(a+c(t-t_0))}} + r \tag{1}$$

where, Q_t is the annual quantity of CO2 removed at time, t; a is the constant of integration used to position the curve horizontally on the time scale; c is the rate of growth coefficient; k is the amount of capacity installed at time, $t_o = 0$; and Q_{max} is the difference between the saturation level and r. See Table 2 for values of coefficients used and further detail is provided in the Supporting Information.

2.3.2 Initial cost of air capture technology

We surveyed ten studies on the initial costs of air capture (Fig. 2).[3] The median upper bound across the studies was \$150/tCO2, the median lower bound was \$54/tCO2, and the median central estimate was \$106/tCO2. Five studies estimated a long term "floor" for the cost of air capture technology, which ranged from \$19–70/tCO2 with a median of \$33. We also take a bottom-up approach by separately estimating capital cost, operations and maintenance (O&M), and the cost of the energy input required to run the plant (see details in Appendix). This approach generates an initial cost of cost of air capture in 2020 of \$102/tCO2r (Table 1). The initial value lies near the median of the range of estimates provided in Fig. 2. Costs thereafter are dynamic; they are affected both by investments in RD&D and by production-related effects, such as economies of scale and learning by doing.

[3] All values in constant 2010 dollars.

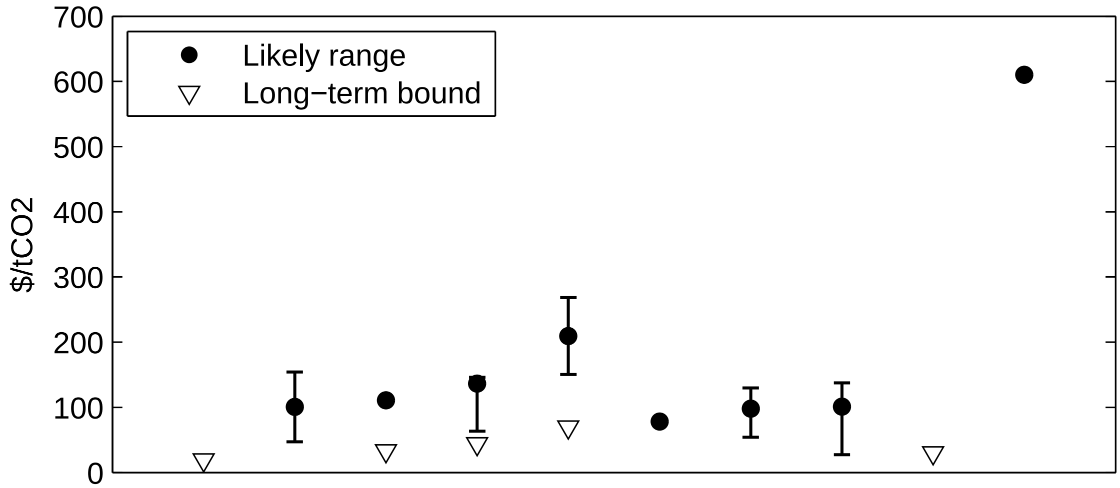


Figure 2: Survey of estimates of the cost of air capture technology. Studies are displayed from left to right by date of publication. Studies are shown in Appendix Table 5.

Table 1: Bottom-up cost estimates

	Initial costs		Future costs	
Cost component	Value	$/tCO2r	b_j	E_j
Capital	$211m/plant	31	-0.15	Plants
Energy	$35m/yr	69	-0.21	tCO2r
Op. & Maint.	$1m/yr	3	-0.21	tCO2r
Total	$51m/yr	102		

2.3.3 Effect of RD&D investment

Research, development and demonstration (RD&D) includes research on the basic technology, developing functioning system, and then demonstrating the technology at commercial scale. We describe two possible RD&D programs: our base case, or *low* program, requiring a discounted investment of \$9 billion and a *high* program, which costs \$19b.[4]. We assume RD&D affects air capture technology in two ways: (1) RD&D is needed to make the technology feasible on a commercial scale in 2020 and (2) RD&D can produce breakthroughs that allow the production-related cost reductions to persist longer than without RD&D. Both outcomes are uncertain. Our base case assumption is that the program succeeds in making air capture feasible but fails to produce breakthroughs that push it beyond a floor on costs. Using the survey of long-term costs, we use \$60/tCO2r as the cost 'floor.' Sensitivity analysis includes consideration of alternative outcomes.

2.3.4 Effects of scale and learning by doing

After commercialization, the costs of air capture decline as a result of economies of scale and learning by doing. We use learning rates from the previous work on carbon capture at power plants, the closest analogy for air capture (Rubin et al., 2007; van den Broek et al., 2009). We calculate the cost of air capture technology (C_t) as the sum of the three cost components—levelized capital cost, energy cost, O&M cost—denoted by $j = 1, 2, 3$. Each of the three cost components m_j has a learning parameter b_j and a corresponding measure of experience E_j. Measures for E and values for b are shown in Table 1. Based on previous work on costs for nascent technologies (Nemet and Baker, 2009), we use the power function:

$$C_t = \sum_{j=1}^{3} \left(\frac{E_{t,j}}{E_{t=o,j}} \right)^{b_j} \cdot m_{t=0,j} \tag{2}$$

Table 2 summarizes the values used in the base case for this analysis.

2.3.5 Learning investment

Learning investment is the extra deployment investment required to 'buy-down' the price of a technology until it is equal to a competing technology. Here, the competing technology is the marginal cost of climate

[4]Supporting Information provides details of activities and timing.

Table 2: Air capture cost model: variables used and base case values

Symbol	Description	Base	Units
General			
δ	Interest Rate	0.02	
P_t	CO2 prices under climate policy		$/tCO2
Deployment curve			
a	Constant of integration	-7.50	
c	Growth rate	0.17	
Q_{max}	Upper asymptote	16.4	
r	Amount removed at $t = 0$	0	
Plant characteristics			
d	Capacity: MT CO2 Captured/plant/yr	0.50	10^6tCO2
K_t	Capital Cost of a Plant ($B/plant)	0.211	$10^9$$
E_t	Energy Cost of CO2 ($/tCO2)	69.03	$/tCO2
M_t	O&M Cost of CO2 ($/tCO2)	2.53	$/tCO2
h	Plant Lifetime (years)	50	years
Technological change			
L_1	Learning rate - Capital Cost	0.101	
L_2	Learning rate - Energy Cost	0.135	
L_3	Learning rate - O&M Cost	0.135	
C_f	Floor Price ($/tCO2)	60.00	$/tCO2

change mitigation, assuming no air capture, P_t (see section 2.1). We denote t_α as the year at which the two are equal. The price for CO2 emissions permits when air capture is available is:

$$P'_t = \min(C_t, P_t) \tag{3}$$

The present value of learning investments, or subsidies, S is based on this cost difference and the amount deployed (Q):

$$S = \sum_{t=0}^{t_\alpha} Q_t(C_t - P_t)(1 + \delta)^{t_o - t} \tag{4}$$

where δ is the assumed discount rate. The total cost to make air capture technology competitive with other forms of climate change mitigation is the sum of learning investment and research, development and demonstration investment, $R + S$.

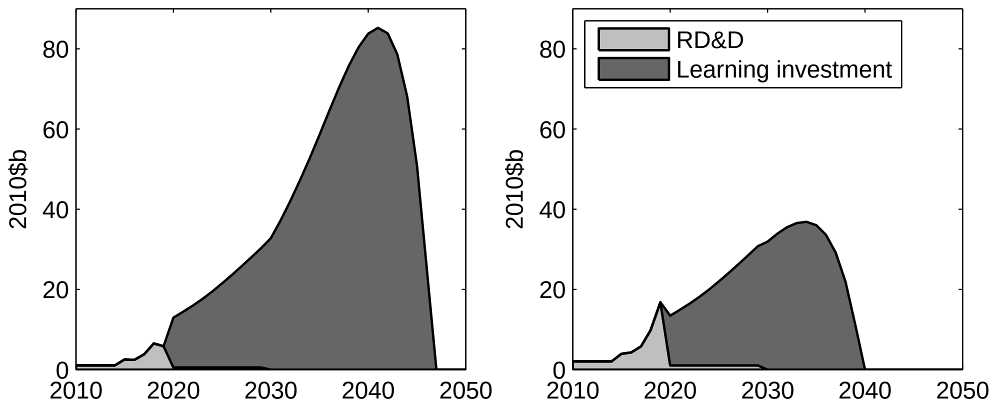


Figure 3: Costs to develop air capture technology: research, development, demonstration, and learning investment ($R+S$, undiscounted, \$b/year). Left panel shows base case *low* R&D program and right panel shows *high* R&D program.

3 Cost benefit results under base assumptions

This section compares costs and benefits using our base case assumptions.

3.1 Costs: RD&D and learning investment

The cost to develop air capture technology is sensitive to a variety of assumptions, which we evaluate in section 4. Under the base assumptions of: 5% cost of capital, medium CO2 costs, and the middle technical outcome, in which there is a binding price floor, the present value of the sum of research, development, demonstration, and learning investment is \$405b. It is \$769b at 2% discount rate and \$185b at 10%. As shown in Fig.3, nearly 90% of the development cost is for learning investments; these are lower when higher R&D reduces the initial cost.

An important determinant of the size of learning investments is the difference in the cost of air capture and the economy-wide marginal cost of CO2 abatement. Under our base case assumptions, air capture reaches its cost floor (\$60/tCO2) in 2029. Fig. 4 shows the path of CO2 prices (P) in the absence of air capture, and the cost of air capture (C). In a sensitivity analysis we assess a highly optimistic technical outcome, in which the floor is removed, the cost of air capture technology falls to \$31/tCO2 in 2050 and

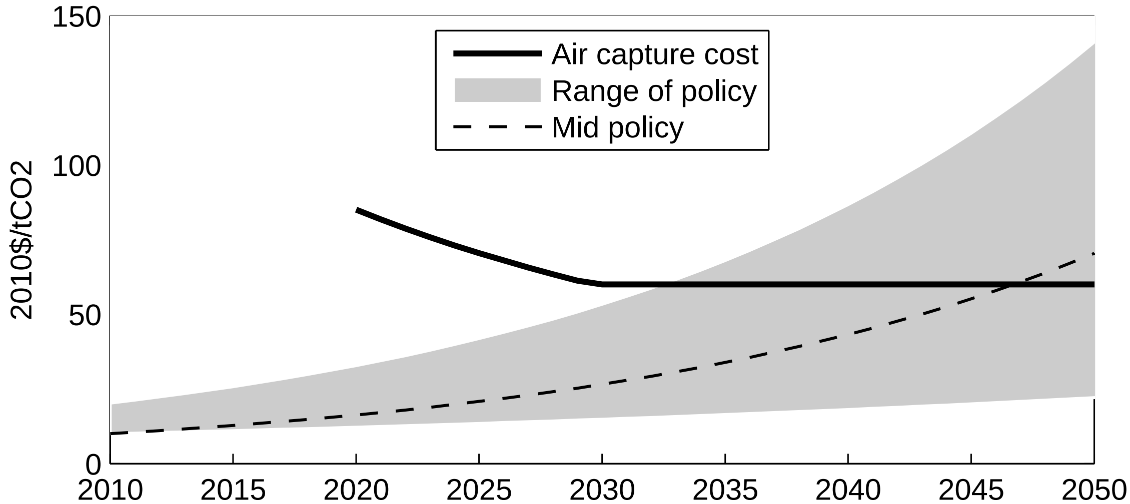


Figure 4: Assumed price of CO2 emissions permits under range of policy assumptions (gray) and base case policy assumption (dashed line). Solid line shows cost of air capture under base case outcome—feasible but with a floor on cost.

$19/tCO2 in 2100.[5] In this most favorable case, which we assess in section 4, the cost of air capture first sets the global price for CO2 mitigation in 2039.

3.2 Benefits: change in value of oil reserves

In aggregate, and under base case assumptions, the availability of air capture reduces the value of reserves for fuel producers. But some entities do benefit; tar sands and grain biofuels become much more valuable with air capture available. It is also important to note that the imposition of a carbon price itself creates winners and losers. In particular, conventional oil and battery vehicles benefit; conversely these two fuels lose about half of that benefit when air capture is available. The results we discuss in the rest of this section are all calculated under base case assumptions. We discuss the results in three steps (1) with no carbon price, (2) with the imposition of a carbon price but no air capture, and (2) with both a carbon price and air capture.

Fig. 5 shows fuels production by type in the case with no carbon tax applied. One can see that overall demand grows by 65% by mid-century and by 120% by 2100. Conventional oil production declines steadily

[5] Of that cost 75% is due to energy input costs, 22% due to amortized capital costs, and 3% due to O&M costs. The relative importance of energy inputs is a result of more substantial learning based reductions in capital costs and a low base case interest rate that makes capital investments relatively inexpensive.

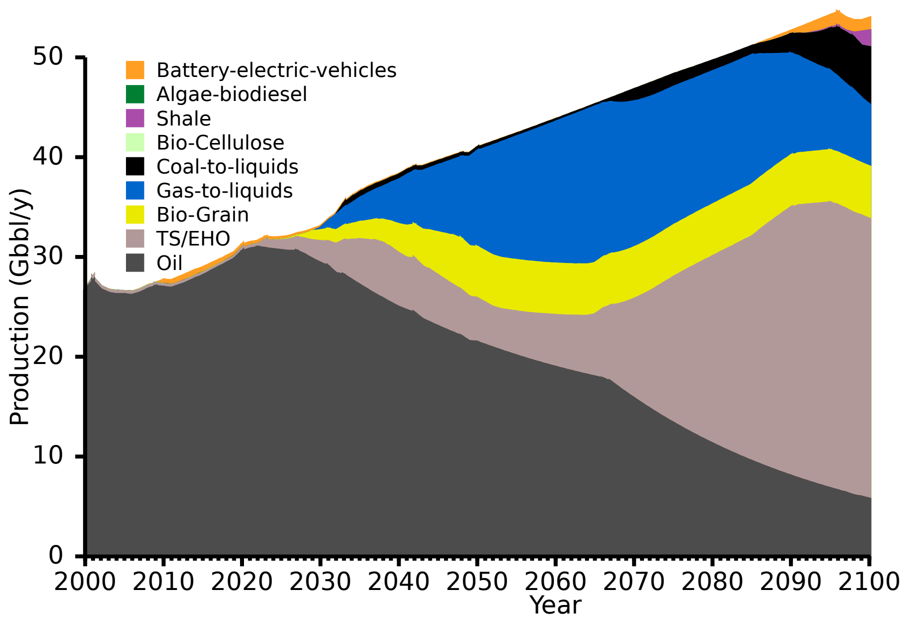


Figure 5: Fuel production with base assumptions and no carbon price. TS/EHO refers to tar sands and extra-heavy oil.

beginning in 2020 and is primarily replaced by tar sands, gas-to-liquids, and grain ethanol. Other fuels meet demand at the very end of the century.

When a price on CO2 is applied, new types of fuels are produced (Fig. 6). Demand itself is lower, but due to relatively low long-run price elasticity of demand, only moderately—by 7% in mid-century, and by 19% by 2100. The relative carbon intensities of other fuels affect their total costs. As a result, production of grain ethanol is much lower; tar sands production decreases; and GTL remains large. Battery-electric vehicles become important in the last quarter of the century. Consumer prices for fuels become much higher in the second half of the century.

Note that in any scenario with a carbon tax, there is divergence ("wedge") between the market-clearing liquid fuel price and the revenue received by fuel producers. This is one of two mechanisms by which liquid fuel producers can gain or loose revenues due to a carbon tax. The second mechanism is lost sales resulting from a tax-induced reduction in the amount of a fuel type sold. While above it was noted that overall

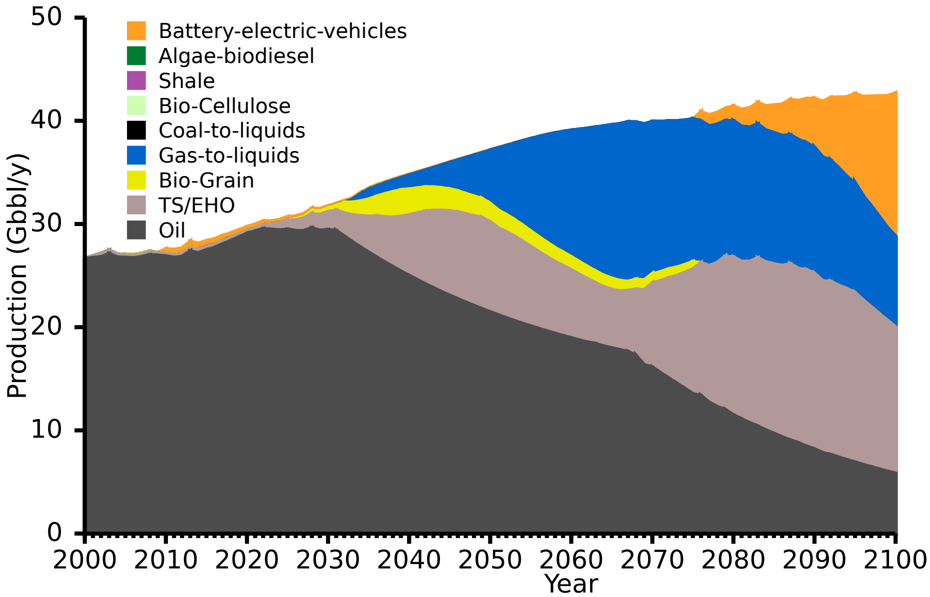


Figure 6: Fuel production with base assumptions and carbon price in effect (no air capture).

demand does not drop significantly due to a carbon tax, price-induced demand reductions affect different fuel producers very unevenly. This is because demand reductions affect the marginal, most expensive fuel, not the entire production mix. For example, because conventional oil production declines during model runs due to geological production constraints, while remaining generally less expensive to produce than the marginal fuel (such as CTL or cellulosic ethanol), conventional oil producers in most cases do not face reductions in sales volume due to a carbon tax. The carbon tax also affects the relative profitability of each fuel type, given the differently sized carbon tax wedges for each fuel.

These shifts in production and prices affect the reserves value of each fuel (Fig. 7). Conventional oil benefits tremendously from a moderate carbon tax with gains in the tens of trillions. The reason is that fuel prices become much higher under carbon prices so oil enjoys higher prices without any affect on its own production levels; conventional oil not only has relatively lower costs of production, but also has a lower carbon intensity compared to alternatives like GTLs and tar sands (Farrell et al., 2006). Johansson et al. (2009) found a similar result. Electric vehicles are the other major beneficiary of a carbon price. Fuels

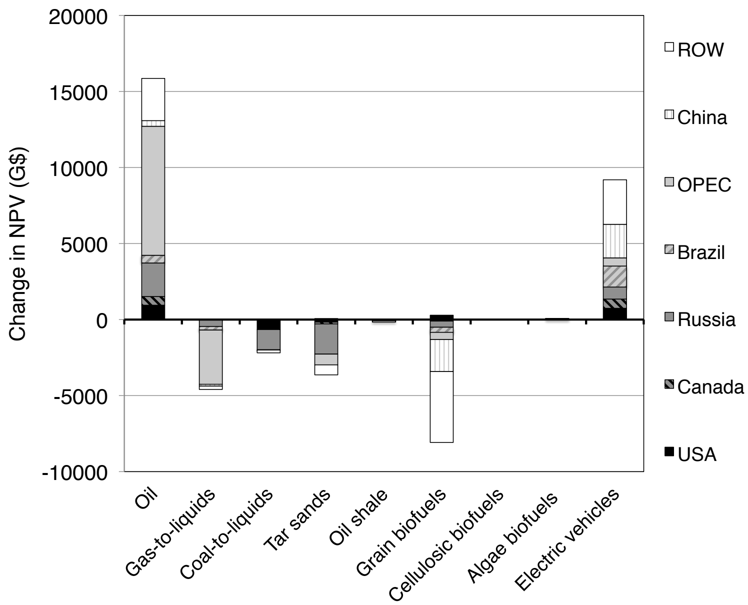


Figure 7: Change in NPV due to the imposition of a CO2 price for fuels (stacked by region, assuming air capture not available).

with higher carbon intensities— GTL, CTL, tar sands, and grain biofuels—have large losses due to a carbon price. Regionally, most entities have both winning and losing fuels so net effects for each region are smaller than the fuel-specific effects.

When air capture is available, under the same climate policy as above, the fuel mix shifts and demand rebounds (Fig. 8). Almost all of these affects occur in the second half of the century. Demand in 2050 is approximately the same as under climate policy, but by the end of the century, it has returned to approximately the same level as without any climate policy. With air capture available, tar sands production becomes much larger, ultimately meeting half of demand by 2100. Grain biofuels also increase production substantially. Battery electric vehicles no longer play a major role in meeting demand. Air capture availability dampens fuel prices considerably—not only by reducing the marginal abatement cost, but by obviating the need for more expensive oil substitutes, such as BEVs.

The two largest beneficiaries of air capture are tar sands and grain biofuels, primarily because their production increases, but also because they pay a lower CO2 penalty Fig. 9. Two fuels have large negative

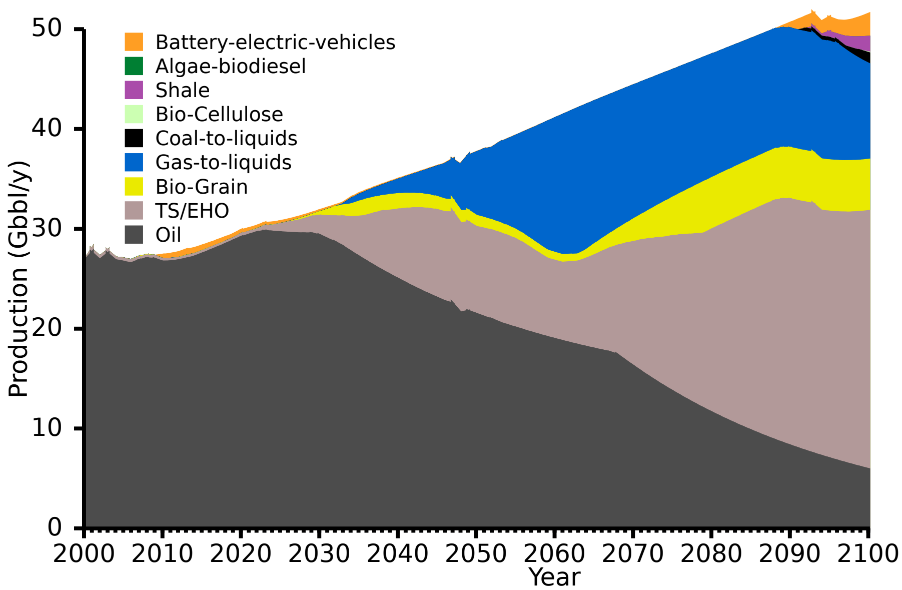


Figure 8: Fuel production with base assumptions and carbon price in effect *with air capture available*.

benefits under air capture, but for different reasons. Conventional oil has no change in production, but loses revenue because prices are so much lower under air capture. Battery electric vehicles lose because they are no longer competitive when CO2 prices are low due to air capture. Regionally, Canada, due to its tar sands, is the only region with net benefits from air capture. All other regions have net losses due to impacts on their oil reserves and battery vehicles.

3.3 Summary benefits and costs in base case

As shown in Fig. 9, only a few fuels, regions, and fuel-region pairs benefit from having air capture available; many entities incur large losses in value and most have very small effects. When one compares these benefits to the costs to develop air capture, as calculated in section 3.1, the number of entities with benefits greater than costs is an even smaller number than those who benefit. Indeed, our analysis identifies only 5 entities (e.g., regional-industries, such as Canadian oil sands producers) that would enjoy benefits that are larger than the costs to develop air capture if they made the entire investment themselves. Given the 63 total regional-industries included in the supply model, it is clear air capture only has benefits under relatively unique circumstances (e.g., Canadian oil sands deposits being large, low cost, and of moderate carbon intensity). The following section assesses the robustness of these findings.

4 Sensitivity Analysis

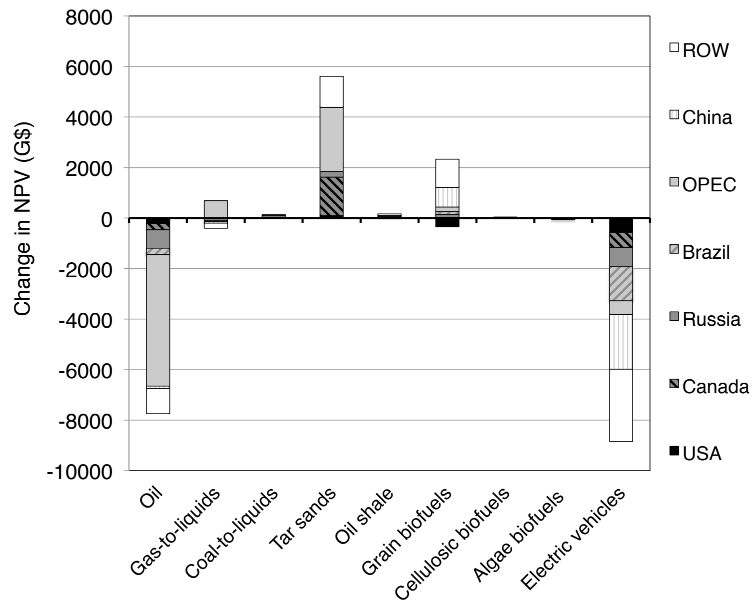
We examined the sensitivity of results to parameters affecting both air capture and the liquid fuels industry.

4.1 Assumptions assessed

Sensitivity variations affecting the general environment include:

Stringency of climate policy: The base case climate policy ($10/tCO2+5%/yr) is changed to a weak policy ($10/tCO2+2%/yr) and a strong one ($20/tCO2+5%/yr) as discussed in section 2.1.

Discount rate: The discount rate is changed from a social discount rate (2%) to a commercial discount rate (10%). This reduces the value of long-term reductions in the carbon tax, while simultaneously



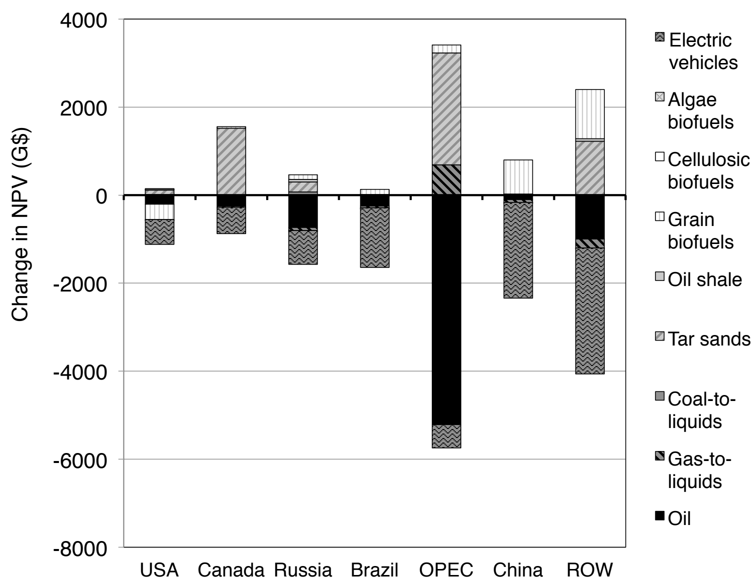


Figure 9: Change in NPV due to the development of air capture, with a CO2 price in place; for fuels (upper) and regions (lower).

reducing the NPV of costs of air capture deployment.

Price elasticity of demand for fuels: The long-run elasticity of demand is increased. The short-run elasticity remains equal to that of Cooper (2003), but the long-run elasticity is increased to 1.5 times the default value. Because the elasticity of demand for a product is partially dependent on the number of substitutes for it, this case represents a future in which more substitutes for liquid fuels exist.

In addition, sensitivity analysis is performed on air-capture specific parameters:

Initial cost: The initial cost of air capture is twice that of base case at \$170/t CO2 captured.

Longer-term cost floor: The air capture technology becomes advanced so that the floor constraint of \$60 /t is removed.

Finally, sensitivity analysis is performed on aspects of the market for transportation fuels through making changes to ROMEO, including:

Oil availability: Moderate conventional oil endowment is replaced with the USGS 5% likely scenario (low probability, high oil availability). This shifts total pre-industrial oil endowment from $\approx$ 3000 Gbbl to $\approx$ 4000 Gbbl.[6]

Low-cost cellulosic ethanol: A breakthrough in cellulosic ethanol technology (apart from conventional learning-by-doing) reduces the starting cellulosic ethanol price reduced to 2/3 of the base case value.

Low-cost battery-electric vehicles: Breakthroughs in battery technology reduce the starting BEV costs. We assess costs at 2/3 and 1/3 of the base case value.

Technological learning rates: The learning rate for liquid fuels is increased from 7.5% to 15%, which is closer to the median for an analysis of over 100 energy technologies (Nemet, 2009).

These parameters are varied one at a time in 11 individual sensitivity analysis cases. Also, three important parameters—discount rate, carbon tax, and demand elasticity—are varied systematically in 12 combination sensitivity analyses. This combination sensitivity analysis allows an understanding of the interaction of more than one simultaneous change to input assumptions.

[6] See previous ROMEO articles for discussion of oil endowment as assessed by the USGS (Brandt et al., 2010).

Table 3: Sensitivity analysis on individual variables. Base case shows number of entities with net benefits from developing air capture.

				fuels	regions	pairs
Base case				2	0	5
		value		△ benefitting entities		
Sensitivity cases:		base	new	vs. base case		
1	Carbon price	mid	low	-2	0	-5
2	Carbon price	mid	high	2	1	10
3	Discount rate	2%	10%	-1	1	-4
4	Demand elasticity	—	×1.5	0	1	-2
5	A.C. cost_o	$85	×2	0	0	-2
6	A.C. floor	$60	$0	2	0	3
7	Oil availability	—	×1.3	0	2	1
8	Ethanol cost_o	—	×0.66	0	1	1
9	B.E.V. cost_o	—	×0.66	-1	0	-4
10	B.E.V. cost_o	—	×0.33	0	0	-1
11	Fuel learning	7.5%	15%	0	2	0

4.2 Sensitivity analysis results

Our benefit-cost outcomes are most sensitive to assumptions about: the stringency of carbon policy, discount rates, improved technical outcomes for air capture, and price elasticity of demand for liquid fuels.

Results from the sensitivity analysis are summarized in Table 3 for the 11 individual sensitivity cases and in Table 4 for the 12 combination sensitivity cases. For these results, the net benefit of developing air capture is computed 3 different ways: for each region across fuels, for each fuel industry across regions, and for each industry within each region (regional-industry). For each of these regional or industry entities, the NPV of benefits of air capture are compared to the NPV of the costs of air capture deployment. If benefits exceed costs, the region or industry is assumed to have motivation to fund air capture deployment and is included in the counts in these tables.

Stringency of climate policy is an important determinant of both costs and benefits. The effect of a high carbon price on the value of air capture can be seen in Case 2 in Table 3. GTL and tar sands have large benefits from air capture under this scenario of high carbon prices. Many regions produce these fuels, which leads to the finding of this case being the one with the most winning region-fuel pairs, 15. But to be sure, this does not mean there are no losing regions. In fact, benefits in aggregate are negative. Most of this is driven by the huge losses sustained by regions producing cellulosic biofuels, which only payoff at high carbon prices. By limiting these high prices, air capture creates large losses for these entities relative to the

Table 4: Sensitivity analysis on combinations of variables. Table shows change in the number of entities with net benefits from developing air capture.

	Sensitivity cases			△ benefitting entities vs. base case		
	Carbon price	Demand elasticity	Discount rate	Fuels	Regions	Pairs
1	low	base	2%	-2	0	-5
2	—	—	10%	-2	0	-5
3	—	high	2%	-2	0	-5
4	—	—	10%	-2	0	-5
5	mid	base	2%	-1	0	-4
6	—	—	10%	0	0	-1
7	—	high	2%	0	3	-1
8	—	—	10%	-2	1	-4
9	high	base	2%	2	1	10
10	—	—	10%	-2	0	-5
11	—	high	2%	1	0	8
12	—	—	10%	-2	1	-3

case with no air capture (i.e., by lowering the carbon tax, air capture enables wealth to accrue to fossil fuel producers rather than cellulosic biofuel producers). High carbon prices also affect the number of entities with net benefits by reducing the cost to develop the technology; under high carbon prices the technology becomes competitive without learning investments much sooner.

The costs of alternative low-carbon technologies have limited effect on the value of air capture to producing regions and industries. For example, individual sensitivity runs 9 and 10 examine the effect of BEV initial cost (before learning-by-doing) on the value of air capture. We see that as very low BEV costs are applied, the value of air capture is only modestly affected—fewer pairs benefit but some still do. This holds even when in the most optimistic cost assumption (case 10) BEVs supplant ≈60% of liquid fuels by the end of the time period. Note also that the finding that conventional oil producers benefit from the carbon price still holds, even with extremely inexpensive electric vehicles. This benefit is now smaller than in the base case and substantially smaller than the benefits accruing to BEV producers.

Unsurprisingly, given the long time frames, discount rates are crucial. It is difficult to arrive at a combination of assumptions that would make air capture NPV positive when using higher discount rates. We use 10% in this analysis but find even weaker incentives for investment at 15%, more typical of a corporate discount rate. High discount rates do reduce costs by reducing the present value of learning investments, but the effect in reducing benefits is generally much larger. In general, air capture investment will only take place using social discount rates.

We assumed that the cost of air capture has a practical lower limit. We see more entities with net benefits when we relax that assumption and allow costs to continue declining via the learning curve. Results are less sensitive to the initial cost of air capture. If that cost is higher than in the base case, learning improvements reduce the cost such that benefits are roughly the same; the costs of the learning investments are however substantially higher.

The price elasticity of demand for liquid fuels also matters, but in a more nuanced way. In the individual sensitivities, it slightly reduced the number of benefitting entities. The combination sensitivities show that high demand elasticity occasionally produces large global net fuel producer benefits from air capture. In fact, the only cases in which global benefits are positive (cases 3 and 7 in Table 4) occur when price elasticity is high. The intuition is that high price elasticity reduces the large benefits that accrue to oil producers due to the imposition of carbon prices. Since air capture reverses some of these benefits, this demand response makes air capture more valuably globally, although it does not affect the number of winners substantially.

The other factors we examine have effects but are less consequential. The sensitivity analysis provides a list of factors that deserve more examination for future work related to the incentives to invest in climate backstops.

5 Conclusion

Under base case assumptions, we found that the costs to develop air capture technology are greater than the benefits that accrue to the liquid fuels industry globally. This is primarily because the largest producers, conventional oil, obtain much larger revenues when an escalating carbon price is in place—a result also found by Johansson et al. (2009). This result on oil is robust to a wide range of alternative assumptions, even including inexpensive electric vehicles. For these producers, a possible backstop technology that reduces carbon prices reduces the value of their reserves. We also found that costs of air capture generally exceed benefits across a variety of changes to assumptions on input values. However, we did see exceptions; there are entities that benefit, both in the base case and under alternative assumptions. Unilateral investment in technology development remains a possibility.

Air capture does become attractive to several producers when one or more of the following occurs: carbon prices become very high; investment decisions are made using social discount rates; technical outcomes for air capture improve; and consumers reveal a higher price elasticity of demand for liquid fuels. We do not expect these outcomes, but neither are they easily dismissed. Climate sensitivity and expected climate damages could turn out to be so high that societies are willing to tolerate very high CO2 prices in order to avoid future damages. The extent of public sector involvement in both technology development and ownership of liquid fuel reserves is sufficient that the use of social discount rates may be appropriate. Studies have described mass-produced air capture units with very low capital costs and low energy input costs (see Fig. 2). Further, new types of vehicle owners from rapidly developing countries could have much more elastic demand than has been the case over the past few decades.

5.1 Could investment occur?

Still, even if possible, is it realistic to expect that unilateral investment in developing air capture could occur? This involves three important issues: uncertainty in benefits, option value, and free-riding. First, there is inherent uncertainty in which entities will benefit from air capture because the beneficiaries tend to be marginal fuels. High cost fuels—such as coal-to-liquids, algae, and cellulosic ethanol—only play a role near the end of the century, so air capture makes little difference for them. On the other hand, conventional oil is relatively cheap to produce and has a modest carbon intensity, so it is used at full production in every case.[7] This is why conventional oil receives such massive benefits from a carbon price; prices increase as carbon-intensive unconventional fuels set the global price and demand for conventional oil does not change. Neither high cost fuels nor conventional oil benefit from a climate backstop that reduces the carbon price. In fact, conventional oil sees very large losses due to lower prices. In contrast, the intermediate fuels—those with mid-range costs and carbon intensities—are the ones affected by a climate backstop technology. In our modeling, those fuels are tar-sands, gas-to-liquids, and grain-based biofuels. These fuels are on the margin in the second half of the century when the costs of air capture begin to reduce the carbon price. Our base case results show large benefits to tar sands and grain biofuels. Alternative assumptions on relative levels of production costs and carbon intensities would add gas-to-liquids producers to the list of beneficiaries. Spec-

[7] The only reason for its diminishing share of overall production is depletion, which occurs steadily after 2020.

ifying who benefits involves uncertainty because the very fuels that might benefit are those that are on the margin. As a result, identifying beneficiaries is sensitive to assumptions about future costs. That uncertainty is likely to persist and will reduce the incentives for investment. In operational terms, the uncertainty about future demand for their fuels in any case renders these marginal producers less likely to invest in mitigation technologies. Uncertainty about CO2 storage constraints, and the possibility that air capture provides only a partial backstop, further reduce incentives.

Second, the decision to invest in air capture has option value. As shown in Fig. 3, the vast majority of the costs to develop air capture occur as learning investments. Presumably, after a 10 year research program, the technical feasibility of air capture will be more certain than at the beginning. Similarly, at that point one expects we would have better knowledge about climate sensitivity, social valuation of climate damages, marginal abatement costs, fuel extraction costs, demand for transportation fuels, and CO2 storage capacity. The decision to pursue the expensive investment in subsidizing early deployment of the technology need not be made immediately, but could be deferred to a later date when uncertainty about outcomes would be lower. Valuing the smaller, early stage research investments as an option would tend to encourage investment.

Third, even if an entity expects benefits to exceed development costs, it may choose to not invest if they believe that other beneficiaries will make the development investment. There may be strong incentives to free-ride. Our results suggest that this problem is not severe because so few entities benefit from air capture. In our base case results, there were only 5 region/fuel pairs with net benefits. Three of those we dismiss because the regions consist of groups of many countries (OPEC, rest of the world). Benefits are concentrated in the Canadian tar sands industry, and only Canada has net benefits aggregated across all its fuels. Free-riding is a negligible problem in our base case because there is only one entity with a clear incentive to invest. In the alternative cases, with more beneficiaries, free-riding might become a disincentive.

5.2 Issues beyond investment

This paper's focus on private benefits is not intended to diminish several concerns about air capture technology. In addition to the aforementioned possibility that air capture will prove technically infeasible or prohibitively expensive, other issues exist. To reduce climate damages, air capture depends on adequate storage and a sustained commitment to capture (Cao and Caldeira, 2010). Seepage of underground CO2, as well as leakage back to the atmosphere are also crucial issues (Wilson et al., 2007; Gerard and Wilson, 2009; Sharp et al., 2009). Unlike other mitigation options, air capture will not address non-climate issues related to petroleum import dependence and local air pollution (Nemet et al., 2010). Others have raised the issue of moral hazard—the possible availability of a negative emissions technology may discourage near-term abatement (Parson, 2006; Robock, 2008; Lemoine et al., 2010). The extent of this effect depends on the expected severity of the issues above, as well as societal risk-aversion to climate damages. Finally, like other geo-engineering methods, air capture raises the issue of legitimacy. Is it acceptable for a small group of countries—or even a single country or a single non-governmental actor—to make decisions that determine outcomes for the rest of the world?

Many issues raised in this paper are generalizable to other backstop technologies in which a new technology has the potential to set an upper limit on marginal abatement costs. Not all geo-engineering schemes would affect mitigation costs this way. Also, for several possible backstops, efficacy and adverse environmental consequences are much more serious. But other backstops may also be much less expensive to develop and deploy than air capture, making decisions around them more immediately relevant. Even though uncertainties around outcomes are deep, they need not preclude analysis. Expert elicitation has been used to assess difficult to predict outcomes, such as the returns to research (NRC, 2007; Baker et al., 2009). While the universe of people with expertise sufficient to provide reliable estimates in this domain is probably in the single digits, one could still use analysis to estimate implied probabilities of success required to go forward with investments; or alternatively, of adverse environmental consequences. Or, in an approach similar to that taken in this paper, wide sensitivity analysis can be performed in order to understand what conditions would positively or negatively affect the viability of a backstop technology.

A particularly important alternative approach would be to assess investment decisions not in the face of steadily increasing carbon prices, but rather in the face of rapid jumps in the urgency of emissions reductions, and consequently in abatement costs. An assessment including dynamic or unsteady behavior could also be applied to sudden step changes in model inputs, such as fossil fuel availability and renewable technology progress. Such analyses are needed, both for consideration of social outcomes, as well as the possibility of private incentives, which has been our focus here.

Acknowledgments

Thanks to Damon Bresenham, Diana Husmann, and Corey Singletary for research assistance on this project. This paper has benefitted from comments and suggestions during presentations at the International Energy Workshop, the Potsdam Institute for Climate Impact Research, and the University of Wisconsin. We are grateful for support from the Center for World Affairs and the Global Economy at University of Wisconsin, Madison. Much of this work was performed while Nemet was a Visiting Scholar at the Harvard Kennedy School. This research was partially supported by the National Science Foundation program on the Science of Science Policy, Award No. 0962100.

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Appendix

Air capture costs

Table 5 shows our survey of estimates of the costs of air capture. The same data are shown in Fig. 2. This survey includes a mean estimate for the lower bound cost of air capture using currently envisioned technology of $68/tCO2 with a median of $54/tCO2. This mean is close to the more detailed lower bound estimate provided by Stolaroff (2006) of $70/tCO2r. Given these values, we use $60/tCO2 as the 'floor' cost and allow costs to drop below that level if RD&D is successful in developing advanced air capture technology, such that it could approach the more optimistic long-term cost estimates suggested in several studies shown in Table 5.

We also produce our own bottom-up estimate of air capture costs using the following assumptions:

- *Capital*: We assume that air capture plants are of uniform scale and can remove 0.5MT of CO2/year. This amount is about twice as large as the plant described in Keith et al. (2006) and about 1/6 of the CO2 that a typical 500MW coal power plant emits annually. We assume these plants last 50 years. We use estimates of the capital cost of air capture plants provided in Stolaroff (2006). Using an average of basic and improved plants designs in that study, we calculate a capacity cost of $422/tCO2r/year.[8] Applying this capacity cost to our 0.5MT removal plant, we calculate a plant cost of $211 million. The levelized capital cost per unit of CO2 removed, at 7% cost of capital, is $31/tCO2r. Note that in our model runs we vary assumptions for discount rates.

- *Energy*: Energy input costs in Stolaroff (2006) were $69 in the improved case and $125/tCO2r in the base case.[9] Because we are assuming a large RD&D program, we use the former value as our estimate for energy costs.

- *O&M*: Following Stolaroff (2006) we assume that annual O&M costs are 4% of the levelized annual cost of capital of the air capture plant.

[8] We use the designation 'CO2r' to represent the amount of CO2 *removed*.

[9] This estimate includes an energy penalty based on combustion of natural gas to power the capture device.

Table 5: Studies estimating the Initial and future costs of DAC technology ($/tCO2).

	Authors	High	Mid	Low	Long term bound
1	Lackner et al. (1999)				19
2	Herzog (2003)	154	101	47	
3	Lackner and Sachs (2005)		111		33
4	Keith et al. (2006)	146	136	63	44
5	Stolaroff (2006)	268	209	150	70
6	IPCC (2007)		78		
7	Stolaroff et al. (2008)	130	98	54	
8	Pielke (2009)	138	101	27	
9	Lackner (2010)	200			30
10	Socolow et al. (2011)		610		
	mean	173	181	68	39
	median	150	106	54	33