Direct Air Capture: A Model Based Assessment

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Abstract

This paper provides an innovative assessment of the role of direct air capture of CO_2 from ambient air (DAC) on the feasibility of achieving stringent climate stabilization. We use the WITCH energy-economy-climate model to investigate the long term prospects of DAC, implementing a rather comprehensive technological specification based on novel estimates by the American Physical Society (APS, 2011). Assuming global cooperation on a stringent climate policy we find that: (1) DAC is deployed only very late in century, long after other low carbon options, though at a massive scale; (2) DAC has a significant impact on the marginal and total abatement costs (reducing them) and on the timing of mitigation (postponing it). DAC also allows for a prolonged use of oil, with a positive welfare impact for the energy exporting countries. Finally, we assess the role of DAC in a less than ideal climate policy by exploring its potential for engaging energy exporting countries in climate mitigation activities by means of a "clean oil" market in which oil exporters can sell oil decarbonized via DAC.

Keyword: Direct Air Capture Oil Exporters Climate Change Mitigation

1 Introduction and Background

The little progress made in global GHG mitigation over the last 20 years is increasingly in conflict with the recommendation of many climate scientists regarding stringent climate mitigation targets. With equilibrium temperature increase being in first order approximation linearly related to cumulative CO_2 emissions (Salomon et al., 2010), it immediately appears that the chances of keeping temperature from exceeding threshold such as the 2C signpost are strictly intertwined with our ability to achieve net negative emissions at some point in the future, as a way to partly undo the carbon budget that originates from past and future emissions. When accounting for the additional trade-off between climate safety and fairness, carbon removal programs of massive scale (e.g. 1000 $GtCO_2$) have been proposed (Tavoni et al., 2012). Already, century scale integrated assessment models (IAMs) foresee a significant role of negative emissions (Azar et al., 2010), as these would allow to reach otherwise infeasible targets (Clarke et al.,

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2009), and to implement more modest emission reductions in the short and medium term (van Vuuren and Riahi, 2010). Several IAMs have implemented carbon removal technologies in the past few years, and have mostly concentrated on the ones of biological nature (such as reforestation and biomass with CCS), as these are the ones with more favourable short term prospects. However, at the magnitudes foreseen, potential conflict over the use of land and of its products might be substantial (Wise et al., 2009).

Additional carbon removal options have thus been considered in the literature (Royal Society, 2009), among which Direct Air Capture of CO_2. DAC is a technology for removing CO_2 directly from ambient air through chemicals (e.g. sodium hydroxide) in cooling-tower-like structures (Bickel and Lane, 2010). Theoretically DAC could compensate for all carbon dioxide emissions in the atmosphere (Lackner 2009), as it does not have an obvious upper constraint (Royal Society, 2009). Moreover, unlike other CCS technologies, DAC is not necessarily coupled with the existing energy infrastructures, and allows achieving mitigation irrespective of where and how the emissions occur. For example, right now half of the emissions come from the very distributed or mobile sources (e.g. homes and cars), which is difficult to be captured at the source (Keith et al., 2005). The flexibility that DAC provides, out of its decoupling from energy infrastructures, could enable to capture this part of carbon (Keith, 2009). However, because it tackles sources with low CO_2 concentrations rather than concentrated streams, the costs of DAC are expected to be considerably higher than the currently discussed alternatives. Depending on how the experiments are designed and the different assumptions on technological improvement, engineers have generated a wide range of cost assessments, from around \$136/tCO_2 (Keith et al., 2005) to \$550/tCO_2 (APS, 2011). Some of the experiments also differentiate the costs of carbon captured and of carbon avoided (APS, 2011), considering that to power DAC plants additional emissions would occur even if the plants are fuelled in the least carbon-intensive way.

Although DAC is more flexible, capture and storage of carbon from concentrated sources has received greater attention in major assessments like IPCC (2005, 2007) and IEA (2008) over the past years. Few analysis has been carried out so far on the potential role of DAC, and even fewer have formulated it in a way that allows capturing the full impacts of DAC on the mitigation options, carbon trading and the energy services. Keith et al. (2005) find that DAC lowers the cost of a worst-case climate scenario, since it decreases the need for near-term mitigation; but long-run mitigation is increased because the marginal cost of abatement decreases in the long term. The cost of DAC, according to their estimation, will be comparable to the general abatement cost as well as the cost of other CCS options. Pielke (2009) also finds a substantial role of DAC in climate stabilization; this follows quite straight from the assumptions about the cost of technology (assumed to range between 27 and 137 \$/tCO_2). On the other hand, Nemet and Brandt (2012) find that DAC would not pass a cost-benefit analysis, unless either its cost can be substantially decreased, or a very stringent climate policy is confronted, or the demand elasticity of liquid fuels is higher than what historically observed.

Given the strong and often polarizing debate surrounding DAC, additional analysis is warranted. This paper is meant to do so, by advancing the understanding of DAC along several dimensions. First, we use the most recent and most detailed techno-economic assessment of DAC carried out by the American

Physical Society (APS, 2011), which assessed the requirements of DAC in terms of physical capital, operation and maintenance, electricity and heat. Second, we incorporate DAC in a fully fledged integrated assessment model, which allows us describing the technology in sufficient detail and to compare and contrast it with a full suite of alternative mitigation options. Finally, we assess the regional incentives in deploying DAC under different assumptions about international climate policy.

The paper is organized in the following way: Section 2 describes how DAC has been implemented into an integrated assessment model; Section 3 elaborates the series of results regarding a wide range of effects of DAC, under the assumption of global cooperation on climate change. Section 4 focuses on a fragmented climate policy case and introduces a "clean oil" market via DAC as a way to provide incentives to oil exporting countries; Section 5 concludes.

2 Methodology

Throughout the paper we employ the World Induced Technical Change Hybrid (WITCH) model as our main tool of analysis (Bosetti et. al 2006)[1]. The model has been designed to study the social-economic aspects of the climate change issue. It is a hybrid model, disaggregated into 13 regions, and composed by a top-down economic growth model and the bottom-up module that describes the energy sector. This is quite parsimonious and accounts for about 15 main mitigation technologies for fossil fuel CO_2, non-CO_2 Kyoto gases and land use CO_2. Relevant for this analysis, CO_2 can be captured by three fossil fuel sources in addition to DAC (coal, gas and biomass) and then be stored underground, with costs being endogenously related to the cumulative quantity of CO_2 stored in each macro-region via supply cost functions calibrated by Hendriks et. al (2004).

We specify and calibrate the techno-economic parameters of DAC following the APS (2011) report. The report provides estimates for the physical capital, the maintenance cost and the energy requirement to operate a DAC plant able to capture 1 $MtCO_2$ per year. Table 1 lists the main parameters. For physical investments and operation and maintenance costs, we use as reference the cost estimates directly provided by APS in their 'realistic' scenario. APS also provides estimates for an 'optimistic' case with lower costs, which we also explore as a sensitivity analysis regarding the deployment of DAC. In addition, we model the energy inputs to DAC both in terms of power and heat. DAC is a very energy intensive technology and neglecting the energy demand associated with its deployment – as done so far in the integrated assessment analysis of DAC– could result in a significant underestimation of the total energy supply, if the deployment is vast. For electricity, we assume that for each DAC plant it can be generated from any low-carbon source which can be either (or a combination of) nuclear, renewables (wind and solar) or fossil fuel (coal, biomass and gas) with CCS. This is left to the model as an optimization problem. Regarding heat, we assume that it is generated using natural gas (similarly to what discussed in APS) but we make the additional assumption that the CO_2 associated with its burning is also captured, at the cost shown in Table 1. As discussed above, the cost of transporting and injecting CO_2

[1] A full description of the model is beyond the scope of the paper and would exceed the page limitations for this article. The interested reader can access all information at the model website www.witchmodel.org and the references therein contained.

underground is a function of the regional capacity of the reservoirs: as a result, the different CCS options (coal and gas for power, gas for DAC heat, and DAC itself) will compete against each other as the cost of CO_2 storage will increase as best sites are progressively used. Table A1 (in Appendix) provides the regional supply cost curves used in the model.

Table 1 Costs and Energy Consumption of a 1MtCO_2 / yr. DAC plant

	'Realistic' case	**'Optimistic' case**
Physical Capital	\$350/tCO_2 captured	\$260/tCO_2 captured
Operation and Maintenance (Maintenance, Labour and Consumables)	\$120/tCO_2 captured	\$90/tCO_2 captured
Electricity consumption	490 GWH	490 GWH
Heat consumption	8.1 PJ	8.1 PJ
Additional Cost of Gas CCS	\$96/tCO_2 captured	\$96/tCO_2 captured
CO_2 transport and storage cost	Based on regional storage capacity, see Fig. A1 for supply cost curves	Based on regional storage capacity, see Fig. A1 for supply cost curves

Data Sources: APS (2011), Rubin (2011)[2]

To provide a reasonable deployment we make the additional assumption herefore, we assume that although as carbon price goes higher DAC might come online as a substitute for other CCS and the uptake will follow a more gradual path: the take-up rate of DAC is no more than 50% of the total captured carbon by other CCS technologies.

3. The role of DAC in an ideal stringent climate policy

Scenario Set Up

We start focusing our attention on the case of a stringent climate policy, with a global target on GHG concentrations set at 490 ppm-eq by the end of the century. This is a rather ambitious objective which falls only slightly short of maintaining global temperature increase below 2C above the pre-industrial levels. We assume an idealized policy setting in which global cooperation is in place starting from 2015 onwards, mitigation is allocated efficiently across countries by means of a frictionless global carbon permits trading scheme[3], and emissions can be borrowed and banked freely thus ensuring perfect temporal flexibility. In Section 4 we depart from this assumption and look into a more fragmented policy architecture. We compare a *base case* in which DAC is assumed to be not available, to a *DAC* one in which it is modelled as described in Section 2.

The global role of DAC

[2] For the additional cost of gas CCS, we adopt the average of the five cost estimation surveyed by Rubin (2011).

[3] Permits are allocated to regions based on the Contraction and Convergence scheme.

We begin by assessing the potential deployment of DAC for the stringent climate stabilization target considered. The global amount of DAC is shown in Fig. 1 for both the "realistic" case and "optimistic" case. In both cases, Fig.1 indicates that DAC is not a viable strategy until the second half of the century. DAC is deployed between 2065 and 2070 but quickly develops into a massive carbon sequestration programme, capturing more than 40 $GtCO_2$/year at its end of century. The optimistic cost estimation implies an earlier as well as higher level deployment, although the difference is not massive as Fig. 1 shows. From now on, we are going to stick to the realistic case for the further analysis. We have also tested with more lenient climate objectives, and found that for climate stabilization target equal or larger than 550 ppm-eq DAC is not deployed. These results thus indicate that DAC is a mitigation strategy only in the case of ambitious climate policies, and only late in the century, after all the other main mitigation options have been put in place.

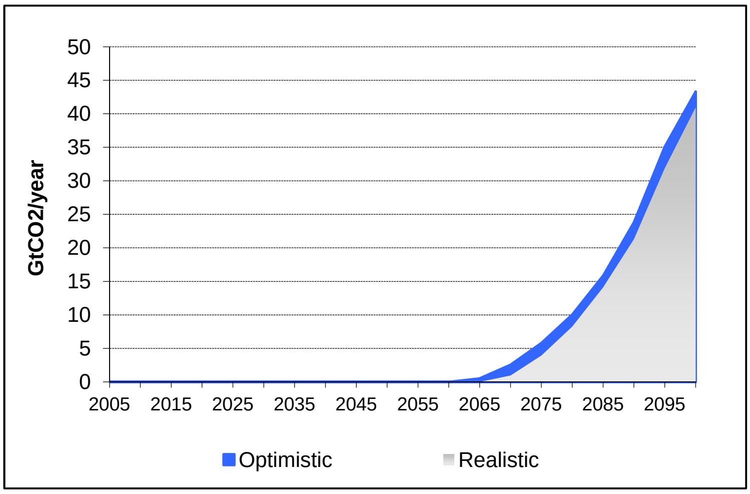


Figure 1 Global DAC: Amount and Timing

The scale of deployment, also as a consequence of the assumed temporal flexibility, is remarkable, with about 607 $GtCO_2$ cumulatively captured via DAC over the century. As a result, DAC has a significant impact on the climate mitigation strategy. The possibility of achieving large negative emission targets substantially affects the optimal mitigation pathway, as shown in Fig. 2a: mitigation is somewhat reduced for several decades with respect to the base case, and this additional carbon budget is compensated late in the century by achieving globally net negative emissions. This result is consistent with the analysis of IAMs which show a considerable impact on short and mid term emissions pathway of negative emissions technologies (Clarke et. al, 2009).

The impact on the emission trajectory in turn relates to the policy cost, shown in Fig. 2b. Policy cost is presented by the percentage change of global GDP with respect to the BAU projection. DAC reduces the total abatement cost throughout the century before 2100: in the first decades this is due to more lenient mitigation effort, from 2065 it results from the deployment of DAC. The policy cost reaches its peak around 2080, when DAC is available and the same mitigation is foreseen in the two scenarios, and shrinks towards the end of the century when (much) more mitigation is undertaken in the DAC case with respect to the base case.

One of the most appealing features of DAC is its decoupling from the existing energy infrastructure. DAC can be implemented where it is more convenient to do so, accounting for the cost of carbon storage and the energy requirements. As already discussed, in WITCH model the cost of carbon storage is differentiated among the regions according to the availability of the storage field. In principle, DAC could allow for more underground storage of carbon, while at the same time keeping storage costs in check by choosing the most appropriate sites. This is indeed what happens in the model, as shown in Fig. 3a. Compared to the base case, DAC allows to store an additional 500 $GtCO_2$ cumulatively to 2100 at the same cost (around \$100/tCO_2 captured).

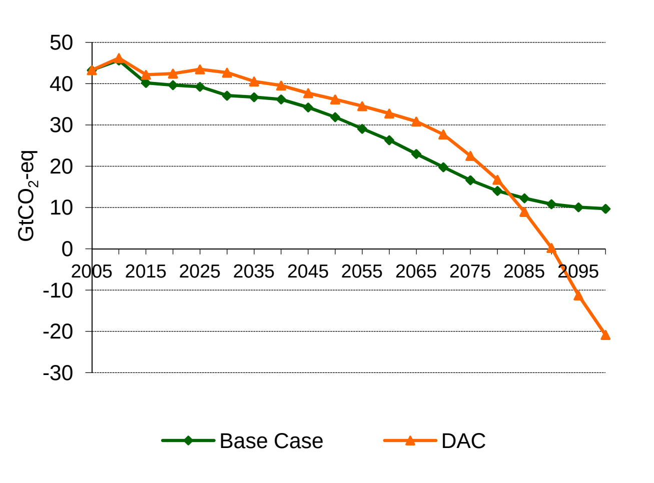


Figure 2a. GHG Emission Path ($GtCO_2$-eq)

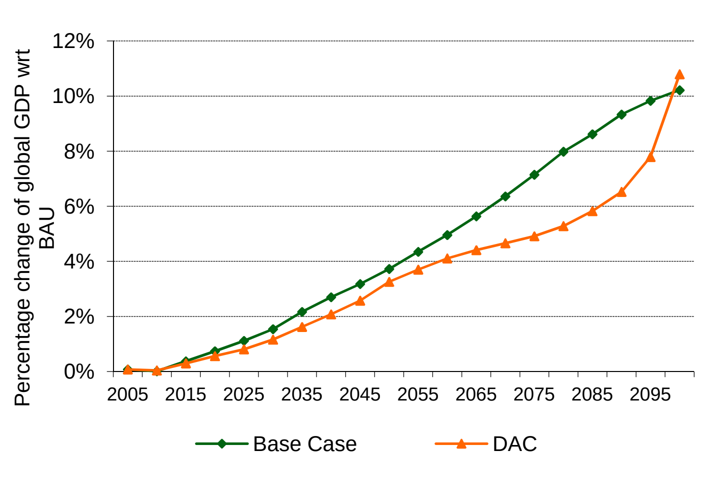


Figure 2b Policy Cost

However, the CO_2 storage flexibility provided by DAC could also be achieved by transporting or shipping the captured CO_2 (from any CCS facility) across macro-regions. In the standard version of the model, this feature is not allowed, and the CO_2 captured in one of the 13 regions needs to be stored in that region. In order to address this issue, we have run an additional model experiment assuming that CO_2 storage sites are perfectly fungible, and thus aggregating the regional cost curves into a single, global one. Once again, we have compared the base case (no DAC) with this additional storage flexibility with DAC scenario (and no storage flexibility). The results indicate that the storage flexibility would allow for considerable more global storage of CO_2, although still lower than in the DAC scenario. The policy costs would also be lowered with respect to the standard case, but would remain higher than the ones with DAC after mid century. This analysis suggests that DAC would be economically attractive even when compared to a situation in which CO_2 can be transported internationally over very long distances.

What is the relationship among DAC and other types of CCS? DAC may crowd out others given the limited storage space, though the flexibility of DAC location might alleviate this substitution effect. On the other hand, as shown above DAC allows more emissions headroom till 2070. Alternative CCS options which are not totally carbon free, i.e. coal plus IGCC, could benefit from the resulting lower carbon prices vis-à-vis with virtually zero carbon sources such as nuclear or renewables. The overall effect is shown in Fig.3b, where we plot the regional differences of the cumulated sequestrated carbon for the DAC case with respect to the base case. DAC is shown to crowd out some biomass with CCS (another negative emission technology in the model) but to induce some additional coal with CCS. The overall crowd-out effect is around 96 $GtCO_2$ as the cumulative number over the century, suggesting that DAC is mostly additional to the other types of CCS.

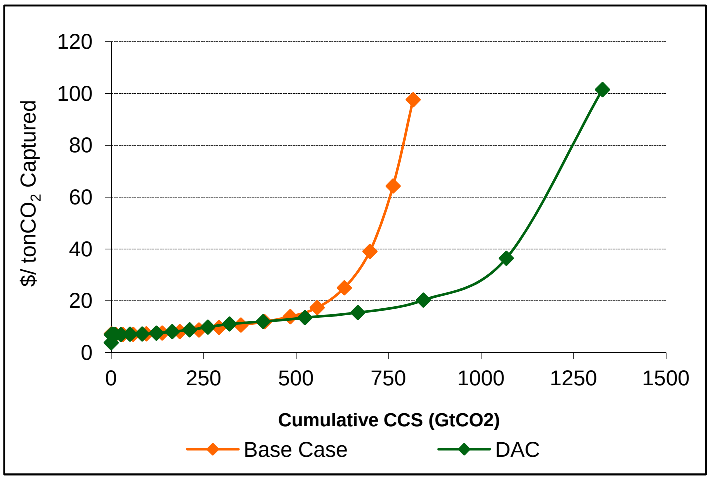


Figure 3a Global Cost Curve of Carbon Storage (2005 – 2100)

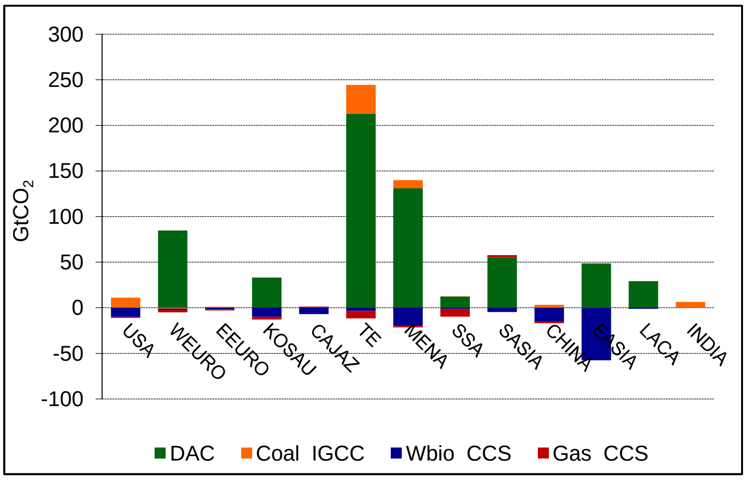


Figure 3b Regional differences in CCS (DAC versus base case, cumulative to 2100)

Fig.3b also provides indication about the regional distribution of DAC, with Transition Economies (TE), and Middle East and North Africa (MENA) being the two biggest DAC players. The main reason is due to the large CO_2 storage availability of both regions and their abundant energy resources, the cost of which accounts for around 30% of the total cost of DAC in 2100[4]. Energy exporting countries (EEX) thus have a comparative advantage in carrying out DAC. Compared with the world without implementing DAC, in 2100 an additional 72 EJ of power and 332 EJ of heat will be needed to fuel the DAC plants, while in the end the primary energy supply is increased by 68%. For DAC plants only, apart from the increased demand of gas, which provides all the heating, the additional electrical demands are mainly met by nuclear and the renewable of wind and solar.

These regional impacts are also important when evaluating the economic impacts of DAC. Fig.4 provides a comparison of the net present value of the climate policy cost with and without DAC. As expected, DAC lowers the global costs of reaching the climate target, since it provides the social planner with an additional mitigation lever. This economic benefit is however mostly perceived by energy exporting countries, as these are the ones where more DAC is implemented in the first place. This cost reduction is particularly important since EEX is the region with the highest policy costs in the model, mostly as a result of having an economy which is very energy intensive and which relies heavily on international energy sales.

[4] See Figure A-1 in Appendix

In other words, oil exporters are the countries that are able to benefit the most from this technology. Nemet and Brandt (2010) mentioned the advantage of DAC as one possibility to preserve the value of reserves in EEX, especially under the stringent carbon policies.

We provide an additional insight on the sources of benefit for EEX in Fig 5. The benefits are twofold. First, DAC allows to preserve the value of oil reserves, something already noted by Nemet and Brandt (2010). The overall effect (Fig 5a) is that the market value of international oil trading does not fall dramatically as in the base case, since more oil is used and traded and its prices is higher. Second, EEX countries also gain from the carbon market. As they implement DAC, they are able to balance their carbon account by importing fewer permits. In fact they are converted from the buyer to the sellers of carbon permits in the international markets. The benefit amounts to 6 trillion$, calculated as the discounted sum of the benefit over the century.

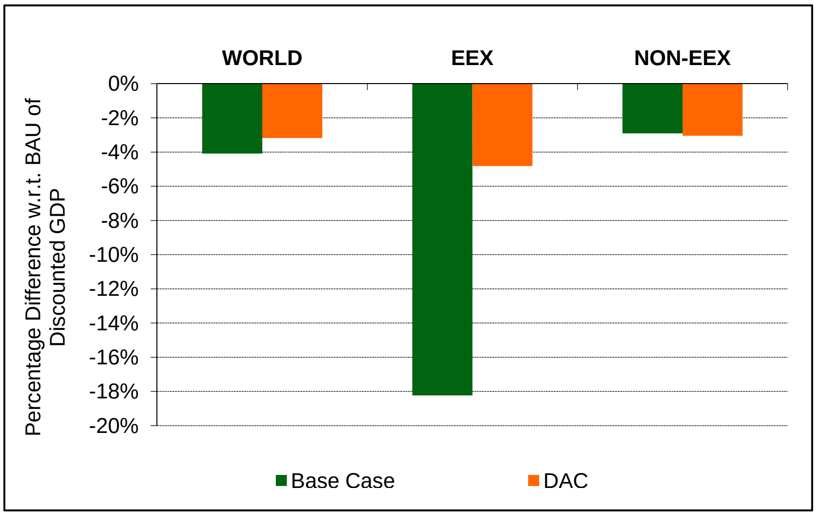


Figure 4 Policy Cost (as the percentage of GDP reduction due to the climate policy)

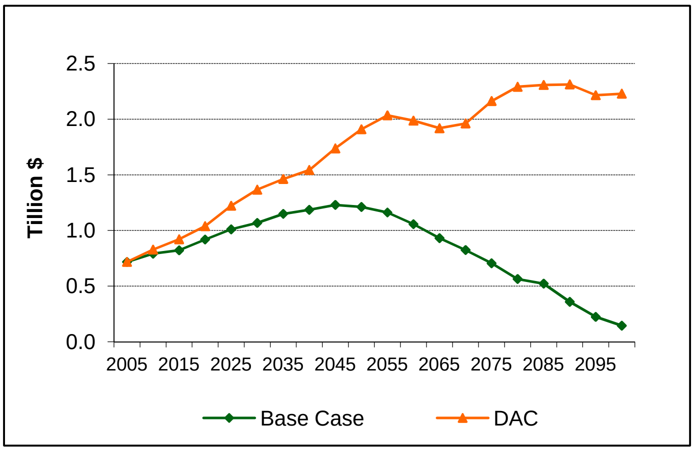
4 'Clean Oil' and the Incentive for EEX to Abate

The results shown so far suggest that EEX would be the biggest winners of implementing DAC. Yet, even in this case they would bear almost twice the cost that the Non-EEX do. Although international climate policy has mostly focused on trying to involve emerging economies like China and India, securing the participation of energy rich countries might be particularly problematic. Considering that these countries are characterized by fast growing demographics and CO_2 emissions and have the ability to influence international energy policy, they have direct consequences on climate policies too. Therefore, finding schemes which are incentive compatible is a major – though underinvestigated – research and policy challenge. In principle, DAC could provide with such an opportunity[5].

In order to assess this issue, we depart from the assumption of global cooperation and simulate a case in which the EEX are not part of the climate agreement (they have no mitigation obligation nor can they participate in carbon trading). As a first important outcome, we find that achieving the same climate

[5] The possibility of Middle East becoming a hub for carbon storage has been recently discussed at the 2012 World Future Energy Summit.

target (490 ppm-eq) is impossible[6] when EEX do not commit to any abatement obligation, even if DAC is available, as a result of the excessive mitigation burden which would fall on the remaining countries. This highlights the relevance of the EEX countries and the importance of their engagement if a stringent climate policy is to be attained.



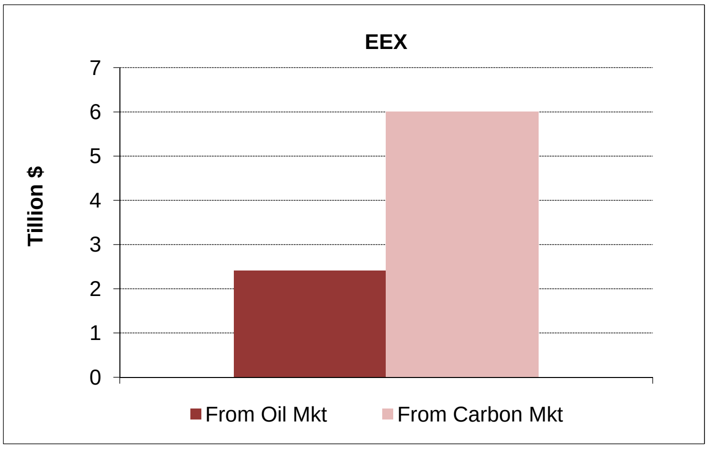


Figure 5a The market value of the Oil Market

Figure 5b Economic benefits of DAC in the EEX regions

As a potential alternative, we simulate a policy in which EEX countries can be involved via a "clean oil" market in which oil decarbonised through DAC in EEX can be sold to non-EEX. As shown previously in the paper, EEX have comparative advantage in carrying out DAC and might find this arrangement profitable. The rest of world could also benefit since it needs low carbon fuels given the strict mitigation target confronted. We price the two types of oil by setting up and clearing two distinct oil markets. Contrary to the case of a climate agreement without the participation of EEX, this fragmented cooperation on clean oil allows us solving the model and finding a solution which attains the given climate objective. Fig. 6 shows the trade of the traditional and clean oil over time. Around 2060, DAC is implemented in EEX countries and they start selling the decarbonised oil, allowing them to use the remaining resources and to profit from the international energy market sales. Clean oil sells at a price about 3 times higher than the traditional one (335$/bbl versus 100$/bbl), given its additional value and the costs associated with its decarbonisation. The timing and the size of the DAC programme associated with this policy is comparable to the one analysed in the previous sections under the full cooperation policy, with roughly 540 $GtCO_2$ cumulatively captured via DAC.

[6] Impossible is here meant in modeling terms, since no feasible solution could be found for this scenario.

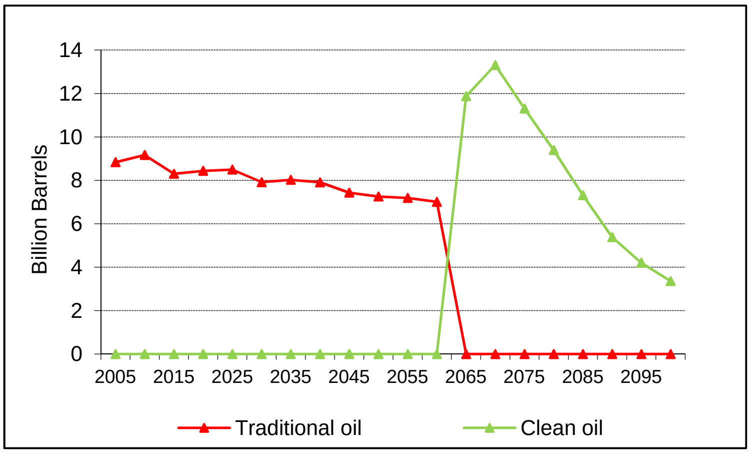


Figure 6 EEX Net Export of Traditional and Clean Oil

In economic terms, this policy would be roughly neutral for energy exporters, who would bear a minimum policy cost as shown in Fig.7. On the other hand, the remaining regions would face a significant penalty, as a result of the inevitable efficiency losses due to the non equalization of marginal abatement costs of a partial agreement. At least, this policy would allow reaching the climate objective, though it will not solve the free riding incentives which have been shown to represent a major impediment to the stability of self enforcing climate agreements (Carraro and Siniscalco, 1993, Barrett 1994; Bosetti et al., 2009).

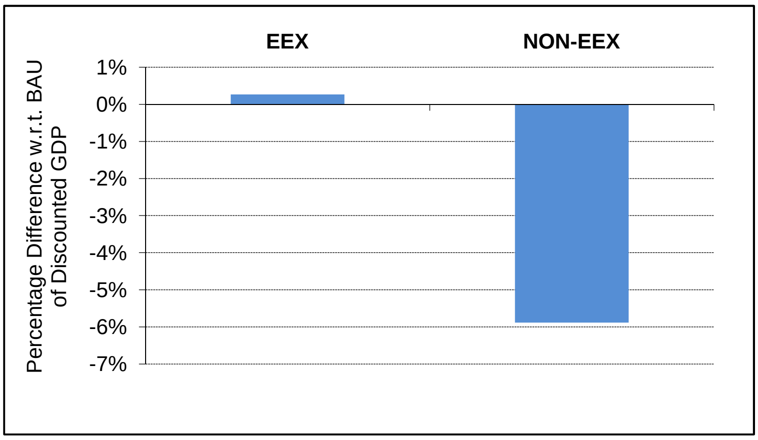


Figure 7 Costs of the 'clean oil' policy

5 Concluding Remarks

This paper has provided one of the few comprehensive assessments of the long term prospects of Direct Air Capture. Using novel estimates of the techno-economic specifications of DAC, we have implemented this novel mitigation option in a fully fledged integrated assessment model. We have tried to capture all of the most salient features of DAC, including its high capital and operating costs, its significant demand for both electricity and heat, and its reliance on appropriate CO_2 storage sites. This integrated framework has allowed us comparing and contrasting DAC vis-à-vis with the main alternative mitigation options.

Starting from the assumption of global cooperation on a stringent climate objective of 490 ppm-eq, our results indicate that DAC would be an important technology but only in the far distant future. DAC would be deployed well after all the other main abatement options have been put into the place, though the scale of deployment could be vast and reach several hundreds of $GtCO_2$ by the end of century. For a less stringent climate objective, of about 550 ppm-eq, DAC would no longer be profitable, suggesting that DAC is relevant only when significant emission reductions are needed. This might still be the case even for less stringent climate stabilization objective but assuming that global emission reductions start later than hypothesized in this ideal policy setting, a possibility which is more likely every day given the slow progress of international climate policy.

DAC could also prove important in the case of a partial agreement in which full cooperation is difficult to sustain. This paper has assessed the potential role of DAC in providing energy exporting countries with incentives to participate into emission reduction activities, assuming that DAC can be used to decarbonize oil. Our analysis has indicated that this arrangement would be incentive compatible for EEX countries, a relevant result considering the reluctance of oil exporters to carry out any mitigation activity given the potential welfare losses associated with a shrinking energy trade. It will not however solve the problem of how to sustain cooperation and limit free riding incentives.

Similar to other negative emission technologies, DAC would have a rather visible impact on the costs and timing of mitigation, reducing the policy burden and shifting the mitigation activities forward in time. Though this might pose a problem of moral hazard (McLaren, 2011), it could also help to achieve climate stabilization if the current emission trends continue in the future, as it seems likely to be the case. Already today, enough carbon intensive capital has built and will not be easy or economical to retrofit. DAC would offer an opportunity to mitigate distributed and locked in sources of emissions.

Although the analysis presented in this paper represents a step forward in terms of modelling DAC, several caveats remain, and call for additional work. For example, we have assumed that the cost specifications of DAC remain constant over time. In fact, technical change might be able to reduce it, and even earlier or higher level of the deployment of DAC could be expected should the cost decrease over time (though at the costs of additional upfront investments in R&D). The role of DAC could also change if uncertainty – on future technology performance, policy decisions, etc. – is taken into account.

In general terms, our analysis suggests whether DAC could or could not be an important carbon mitigation option, alongside with several other way to capture CO_2 from the atmosphere (biological, on oceans, etc.), depending on the level of climate safety that we would like to achieve, and the rate of progress in getting started with mitigation. It doesn't seem to be, however, a game changer for the kind of short term options which should be undertaken, nor have the ability to affect the rules of engagement in the common cause against climate change.

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Appendix

Table A-1: The Regional Capacity of Carbon Sequestration

Carbon Price ($/t$CO_2$)	Cumulative CCS (GtCO_2)													
	USA	WEURO	EEURO	KOSAU	CAJAZ	TE	MENA	SSA	SASIA	CHINA	EASIA	LACA	INDIA	World (storage flexibility)
20	61.86	83.28	10.19	65.18	18.52	228.48	137.38	37.88	50.83	76.86	63.63	117.20	50.83	1002.12
30	71.96	99.00	11.13	75.96	21.39	319.54	202.15	42.75	58.70	90.12	75.28	130.06	58.70	1256.74
40	78.34	109.09	11.72	82.79	23.19	371.92	240.76	45.76	63.65	98.55	83.23	138.40	63.65	1411.06
50	82.95	116.46	12.15	87.72	24.49	408.37	268.13	47.90	67.21	104.67	89.24	144.50	67.21	1521.02
75	90.73	129.03	12.89	96.06	26.67	468.02	313.71	51.46	73.21	115.03	99.87	154.92	73.21	1704.81
100	95.87	137.41	13.37	101.57	28.11	506.49	343.58	53.78	77.15	121.90	107.20	161.87	77.15	1825.46

Fig. A-1 Component of DAC Cost