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Direct air capture of CO_2 and climate stabilization: A model based assessment

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Abstract This paper provides a novel 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 technological specification based on recent estimates by the American Physical Society (APS 2011). Assuming global cooperation on a stringent climate policy we find that: (1) DAC is deployed only late in century, after other low carbon options, though at a very significant scale; (2) DAC has an impact on the marginal and total abatement costs (reducing them) and on the timing of mitigation (postponing it); (3) DAC also allows for a prolonged use of oil, with a positive welfare impact for 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.

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 (Solomon et al. 2010), it immediately appears that the chances of keeping temperature from exceeding threshold such as the 2C signpost

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are strictly intertwined with our ability to achieve net negative emissions at some point in the future, as a way to partly reduce the carbon stock 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. 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 conversion or burning 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 of removing CO_2 directly from ambient air through chemicals (e.g. sodium hydroxide) in cooling-tower-like structures (Bickel and Lane 2010). Unlike other CCS technologies, DAC is not built to capture CO_2 from a particular gas stream. Therefore, it has the advantage of not being directly linked to the existing energy infrastructure that generates CO_2, as other CCS technologies do (Royal Society 2009), and it allows achieving mitigation irrespective of where and how emissions occur. For example, right now half of the emissions come from very distributed or mobile sources (e.g. houses and cars), which are difficult to be captured at the source[1] (Keith et al. 2005). DAC in principle provides some added flexibility, out of its decoupling from emission sources[2]. But since DAC deals with low CO_2 concentrations rather than concentrated streams, its costs are expected to be considerably higher than the currently discussed CO_2 capturing 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 the order of \$1000/tCO_2 (House et al. 2011) based on the current technologies. Some analysis also differentiates the costs of carbon captured (e.g.\$550/tCO_2) and of carbon avoided (e.g.\$780/tCO_2) (APS 2011), considering that to power DAC plants additional emission are likely to occur. APS' estimation is not far apart from the costs in Mazzotti et al. (This Special Issue). As an optimization is performed, the latter provides a slightly lower estimation ranging from \$518/tCO_2 to \$568/tCO_2.

Given the more immediate potential, CCS from concentrated sources has received greater attention than DAC in major assessments like IPCC (2005, 2007) and IEA (2008). Few analyses have 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 abatement cost 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, though this follows quite straight from the

[1] DAC is certainly not the only way to abate the emission at those sources. It is feasible to reduce emission at these sectors via electrifying vehicles and buildings or making use of biomass energy source etc. .

[2] Though it is important to notice that it still needs to be tied to energy infrastructures for its energy consumption.

optimistic assumptions about the DAC cost (between \$100/tCO_2 and \$500/tCO_2). Although House et al. (2011) estimate the cost to be on the order of \$1000/tCO_2, they nonetheless conclude that DAC could conceivably be useful at certain point but (more likely) not before 2050. In fact, APS (2011) and Mazzotti et al. (This Special Issue) note that the commercial case for DAC deployment cannot become compelling until large centralized sources of emissions of CO_2, such as coal and natural gas power plants, have either been equipped with CCS or shut down. Finally, 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 is 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 the role of DAC in climate stabilization along several dimensions. First, we use the most recent and most detailed techno-economic assessment of DAC carried out by APS (2011), which assessed the requirements of DAC in terms of physical capital, operation and maintenance, electricity and high-temperature heat. Second, we incorporate DAC in a fully fledged integrated assessment model, which allows us describing the technology in sufficient detail and comparing 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 mitigation. 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, 2009b)[3]. The model has been designed to study the social-economic aspects of climate change issues. 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 20 main mitigation options 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 be stored underground with costs endogenously related to the cumulative quantity of CO_2 stored in each macro-region via supply cost functions calibrated by Hendriks et al. (2004).

The APS report provides estimates for the physical capital, the maintenance/labour/chemicals cost and the energy requirement to operate a DAC plant able to capture 1 MtCO_2 per year. We break down the DAC costs following APS as Table 1 lists. For capital and maintenance costs, we use as reference the APS' estimation in the 'realistic' scenario and assume that these costs are constant. APS estimates lower costs under an 'optimistic' case too, which we use to compare with the 'realistic' case in terms of DAC level. APS provides

[3] 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.

Table 1 Costs and energy consumption of a 1MtCO2 / 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
High-temperature heat consumption	8.1 PJ	8.1 PJ
CO2 transport and storage cost	Based on regional storage capacity, see Table. A1 for supply cost curves	Based on regional storage capacity, see Table. A1 for supply cost curves

APS (2011)

estimates based on today's technology. Lackner et al.(2012) have recently argued that the cost of DAC could well come down to the level that would make it economically interesting, as many other new technologies do when R&D and learning-by-doing could continue to drive the cost down. However, given the uncertainty prospects of technology evolution in this sector, in this paper we take a conservative view and assume investments costs to remain constant in time. This provides a limiting case for the analysis of DAC.

In addition, we model the energy inputs to DAC in terms of electricity and heat. DAC is an energy intensive technology and neglecting the energy demand associated with its deployment – as done so far in most integrated assessment analysis of DAC – could result in a significant underestimation of the total energy supply, if the deployment is vast. For electricity, APS assumes grid power with a specified cost and carbon intensity. Instead, we assume that electricity is generated from zero or low-carbon sources, whose costs are endogenously decided and we leave it to our model to determine whether it is nuclear, renewables (wind and solar), or fossil fuels (coal, biomass and gas) with CCS, or some combination of them, treating this choice as an optimization problem. Regarding heat, which in the APS scheme is required at high temperatures, we follow APS and assume it is provided by natural gas and with CCS. As discussed above, the CO_2 storage cost is a function of the regional capacity of the storage reservoirs: as a result, the different CCS options and DAC will compete against each other since the storage cost will increase as the less costly sites are progressively used. Table A1 (in appendix) provides the regional supply cost curves used in the model.

To provide a reasonable deployment we make an additional assumption about the penetration rate of DAC, assuming that it cannot exceed more than 70 % of the total captured carbon by all CCS technologies, taking into consideration the inertia of the system due to the new requirements of infrastructure and the system re-organization. We relax this assumption (for rates of 50 %, 60 %, 70 %, 80 %) in the sensitivity analysis.

3 The role of DAC in an ideal stringent climate policy

3.1 Scenario set up

We focus first 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 is roughly in line with maintaining global temperature increase below 2C above the pre-industrial levels with some even chances. 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[4], 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 case*** in which DAC is modelled as described in Section 2.

3.2 The global role of DAC

We begin by assessing the potential deployment of DAC for the climate stabilization target considered. The global amount of DAC in Fig. 1 ranges both 'realistic' and 'optimistic' cases. Figure 1 indicates that, for either case, 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 programme, capturing as much as 37 $GtCO_2$/year in 2100[5]. The 'optimistic' cost estimation implies an earlier as well as higher level deployment, although the difference is not big. From now on, we stick to the 'realistic' case for further analysis. We have also tested with more lenient climate objectives, and we found that for climate stabilization target equal or larger than 550 ppm-eq DAC is never deployed over the century. Therefore, DAC is a mitigation strategy only in the case of ambitious climate policies, and only late in the century after other main mitigation options have been put in place and when the cost of removing the final 17 % of global carbon emission is comparatively expensive[6].

To meet the 490 ppm target the scale of deployment of DAC, also as a consequence of the assumed temporal flexibility, is very significant, with about 482 $GtCO_2$ captured via DAC cumulatively over the century. As a result, DAC has a significant impact on the climate mitigation strategy. The possibility of large negative emission substantially affects the optimal mitigation pathway, as shown in Fig. 2a: mitigation is 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 of negative emission technologies on short and mid-term emissions pathway (Clarke et al. 2009). Figure 2a also shows how much mitigation the conventional abatement technologies could do, under the DAC emission pathway (the dashed line). The distance from the base case emission projection indicates 7.2 $GtCO_2$/year less of mitigation by conventional abatement with respect to DAC. Equivalently, following the optimal abatement pathway assuming DAC will be available in the future, only to find out that this will not be the case, would result in an increase of carbon concentrations at the end of the century of 540 ppm.

The availability of DAC brings down the marginal abatement costs and the total abatement costs (measured by the percentage change of global GDP with respect to the BAU projection), as Fig. 2b and c show. In particular, DAC reduces the total abatement cost in the first decades due to more lenient mitigation effort, and from 2065 it results from the deployment of DAC. The difference of policy cost reaches its peak around 2080, when

[4] Permits are allocated to regions based on the Contraction and Convergence scheme, more detail by Bosetti et al. (2008)

[5] Under the "realistic" case, the global deployment of DAC steadily grows in 30 years by 1.2$GtCO_2$/$year^2$. The region that has the fastest growth is Transit Economy in the model, mainly Russia, about 0.3 $GtCO_2$/$year^2$, which is equivalent to adding 300 sites of Sleipner West each year.

[6] At the time DAC arrives only 4 % of total electricity supply is met by fossil fuel power not equipped with CCS.

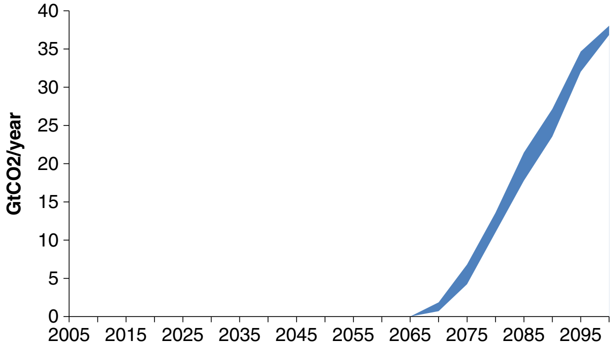

Fig. 1 Global DAC deployment (range of 'optimistic' and 'realistic' cases)

DAC is available and the same mitigation is foreseen in the two scenarios. This distance shrinks towards the end of the century when (much) more mitigation is undertaken in the DAC case with respect to the base case.

3.3 Sensitivity analysis

We conduct series of sensitivity analysis on the deployment of DAC related to model parameters, available competing technologies and certain climatologic consideration.

First, we check the sensitivity of DAC to other competing abatement technologies. These are conventional options, which are featured in the current version of WITCH but with

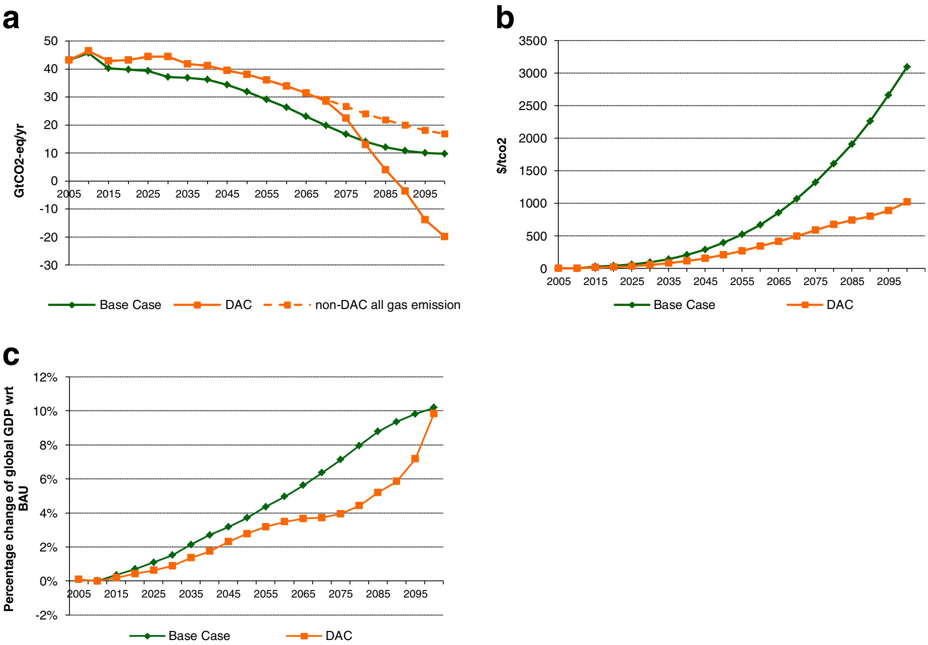

Fig. 2 The Effect of DAC on GHG Abatement and costs *Upper-left*: **a** GHG Emission Pathway; *Upper-right*: **b** Marginal Abatement Cost; *Lower*: **c** Global macroeconomic costs

certain limits. They are: (1) a more efficient capture rate of CCS[7] (2) carbon capture of emissions from coal use not only in power plants but also in the industrial sector, at a cost of \$81.8/tCO_2 (3) a more progressive decarbonisation of mobile emission sources via larger availability of next-generation bio-fuels[8] (4) extra abatement of the residual non-CO_2 GHG emission[9].

We include these technologies first one at a time and then altogether on top of the standard model[10], see the first part of Table 2. According to this sensitivity analysis, the role of DAC is significantly reduced if these extra technologies are put in place. The peak deployment does not change much, but the average rate of deployment decreases by 38 % from 16 to 10 GtCO_2 per year. When these options are all available, the average deployment further shrinks by 81 % to 3 GtCO_2 per year.

The second sensitivity analysis is on the penetration rate of DAC. When changing the penetration rate from 50 % to 80 %, we do not observe significant differences among the results in terms of the scale of deployment. The variation of the average number is about 2 GtCO_2.

Our third sensitivity analysis relates to the inter-generational discount rate. As WITCH assumes perfect foresight, policy makers look forward to negative emissions (Fig. 2b), and the result is more emissions in the near term and fewer in the long run. The preference for the present versus the future is captured in the model through the social rate of time preference (SRTP). By default, WITCH sets SRTP to 3 % initially (in 2005) and it decreases by 0.25 % at each 5-year time step[11]. Intuitively if the SRTP is set to zero, which means that the future welfare will be equally important as it is now, the emission would be more equally distributed across the time-span. The comparison in Table 2 suggests that when time preference is zero and no discount is applied to future mitigations costs vis à vis with current ones, we can observe significantly lower deployment of DAC.

Finally, since DAC changes the CO_2 concentrations in the atmosphere quite rapidly, it might change the global carbon balance. Climatologists look into the carbon cycle to consider the oceanic feedback as a response to large-scale carbon dioxide removal (CDR) from the atmosphere. Given the carbon exchange between the atmosphere and the ocean, the sudden removal of carbon from the atmosphere would cause the outgassing from the ocean to restore the natural carbon balance (Gruber et al. 2009; Vichi et al. this volume). Our DAC scenario simulates a continual CDR action during the last 30 years of the century, resulting in 61 ppm negative emission. According to Vichi et al. (this volume), who quantify the outgassing effect caused by CDR actions, 65 ppm constant CDR within 30 years induces 8.5 ppm (18 GtC) of outgassing. If this effect is taken into consideration, we expect that about 15 % of the carbon removed by DAC would go back to the atmosphere. Taking the outgassing effect into consideration, our simulation result shows less deployment of DAC, by roughly 30 % (141 GtCO_2) less in total over the 30 years.

[7] Carbon capture rate is currently assumed to be 90 %; to allow extra abatement, we progressively increase this rate to reach 99 % from mid-century onwards. The costs of CCS are the same for the two cases.

[8] The model currently finds the market share of this decarbonisation option not to exceed 5 % of the total fuel supply. Here we increase the maximum market share to 50 %, to allow more progressive substitution of the zero-carbon technologies to the conventional fuels.

[9] Currently the model assumes a piecewise cost curve of the non-CO2 GHG abatement (the highest cost category is defined to be \$200/tC), with a certain amount of GHG remaining unabated. Now we allow this part of GHG be abated but at a relatively high cost of \$136.4/tCO2 (\$500/tC).

[10] By ‘standard’ we mean the model that excludes these extra options but includes DAC.

[11] The same SRTP is used later to calculate the discounted sum of the policy cost.

Table 2 Sensitivity analysis on the deployment of DAC

Scenarios and parameters	Cumulative deployment ($GtCO_2$)	Average deployment ($GtCO_2$/year)	Peak deployment ($GtCO_2$/year)
Alternative abatement technologies availability			
DAC alone (standard)	482	16	37
+ CCS with higher capture rate	439	14	37
+ extra carbon capture from coal combustion in power plants and industry sectors	416	13	33
+ extra decarbonisation of mobile emission sources	386	15	36
+ extra abatement of non-CO_2 GHG	316	10	33
All Options	89	3	16
Penetration rate of DAC			
50 %	476	14	33
60 %	483	14	36
70 % (standard)	482	16	37
80 %	489	16	36
Social Rate of Time Preference (SRTP)			
Standard time preference (standard)	482	16	37
No time preference	334	7	11
Feedback of natural carbon balance			
Without considering oceanic outgassing (standard)	482	16	37
Considering oceanic outgassing	341	11	32

3.4 A regional assessment of DAC

One of the most appealing features of DAC is its decoupling from the specific emission sources: it 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 the cost of carbon storage is differentiated among the regions according to the availability of storage reservoirs. In principle, DAC could allow for more underground storage of carbon, while at the same time keeping storage and energy costs in check by choosing the most appropriate sites. This can be illustrated by Fig. 3a: compared to the base case where 815 $GtCO_2$ are stored cumulatively to 2100, DAC allows the storage of an additional 788 $GtCO_2$ at a similar storage cost (around \$100/tCO_2 captured).

However, the CO_2 storage flexibility provided by DAC could also be achieved by transporting 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 is assumed to be stored regionally, an assumption justified by the coarse geographical detail of the model. In order to address this issue, we have run an additional model experiment, assuming that (1) DAC is not available (2) CO_2 storage sites are perfectly fungible, thus aggregating the regional cost curves into a single, global one. We find that 1240 $GtCO_2$ is stored over the century, which can be compared with 815 $GtCO_2$ when no storage flexibility is allowed. This storage value is slightly lower than the case where DAC is allowed but the storage is regional (1603 $GtCO_2$). The total abatement cost would also be lowered in the case with storage flexibility

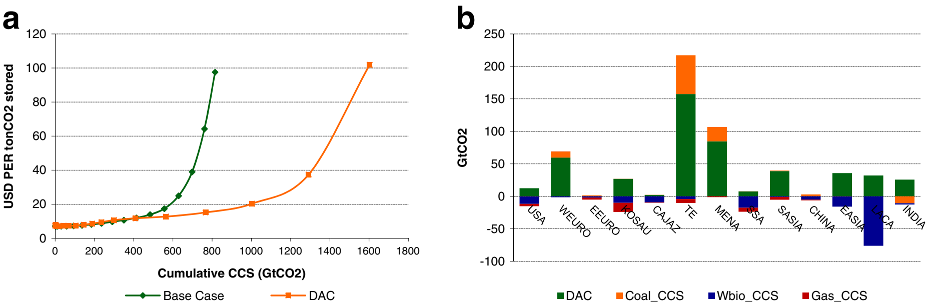

Fig. 3 **a** Global Cost Curve of Carbon Storage (2005 to 2100) **b** Regional differences in CCS (DAC versus base case, cumulative to 2100)

compared to the base case, but storage flexibility without DAC results in higher abatement cost than regional storage with DAC after the mid-century. This analysis suggests that DAC would be economically attractive even when compared to a situation in which CO_2 can be freely transported and stored in any region where it is economical to do so.

What is the relationship among DAC and other types of CCS? DAC may crowd out others given the limited CO_2 storage space, though the flexibility of DAC location might alleviate this substitution effect. On the other hand, as shown in Fig. 2a DAC allows more emissions headroom till 2080. Therefore, alternative CCS options which are not totally carbon free, i.e. coal with CCS, could benefit from the resulting lower carbon prices vis-à-vis with virtually zero-carbon technology like nuclear power or negative-emission technology like biomass CCS. The overall effect is shown in Fig. 3b, where we plot the regional differences of the cumulative sequestrated carbon for the DAC case with respect to the base case. In most regions DAC is shown to crowd out some biomass with CCS but to induce some additional coal with CCS. The overall crowd-out effect is around 111 $GtCO_2$ over the century, suggesting that DAC is mostly additional to the other types of CCS.

Figure 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. These energy exporting countries (EEX) have a comparative advantage in carrying out DAC because of the large CO_2 storage availability and abundant energy resources that can be used for power and high-temperature heat at the DAC facilities, the cost of which accounts for around 30 % of the total cost of DAC in 2100 (see Fig.A1 in appendix for a breakdown of DAC costs). Compared with the base case, in 2100 an additional 65 EJ of power and 298 EJ of high-temperature heat will be needed to fuel the DAC plants, resulting in an increase of 84 % in primary energy supply. For DAC plants only, apart from the increased demand of gas, which provides all the heating, the additional electrical demand is mainly met by nuclear (36 % in 2100) and renewables (wind and solar, 57 % in 2100).

These regional impacts are important when evaluating the economic impacts of DAC. Figure 4, which compares the net present value of the climate policy cost with and without DAC, shows that DAC lowers the global costs of reaching the climate target since it provides social planners with an additional mitigation lever. This economic benefit is mostly captured by EEX, as these are the ones where more DAC is implemented in the first place. This cost reduction is particularly relevant since EEX is the region with the highest policy costs in the model, mostly as a result of having an energy-intensive economy which relies heavily on international energy sales.

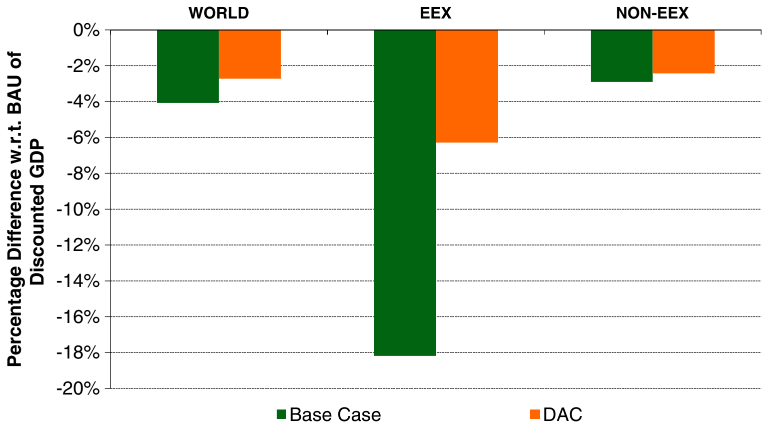

Fig. 4 Policy Cost (as the percentage of GDP reduction due to the climate policy)

In other words, EEX is the region able to benefit the most from this technology. The source of benefit for EEX is two-fold. First, DAC allows the preservation of the value of oil reserves, as noted by Nemet and Brandt (2012). The size of the oil market in 2100 (measured by the market value) is 5-time larger in the DAC case than the base case, and the overall effect is that the market value of international oil trading does not fall as dramatically as in the base case, since more oil is used and traded and its price is higher (See Fig.A2-a in appendix). 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 turn from buyers to sellers of carbon permits in the international markets (See Fig.A2-b for the breakdown of the benefit).

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, as they start out the biggest losers. Yet, even in this case they would bear almost three times the total abatement cost that the non-EEX countries do. While 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 population and CO_2 emissions and have the ability to influence international energy policies, they have a direct impact on climate agreement. Therefore, finding schemes which are incentive compatible is a major – though underinvestigated – research and policy challenge. In principle, DAC could provide such an opportunity[12].

In order to assess this issue, we depart from the assumption of global cooperation and simulate a case in which EEX countries are not part of the climate agreement (they have no mitigation obligation nor can they participate in carbon trading, so their carbon price is zero). As a first important outcome, we find that achieving the same climate target (490 ppm-eq) with the assumed economic growth in non-EEX is impossible[13] when EEX do not commit to abatement obligations even if DAC is available. The infeasibility results from the excessive

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

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

mitigation burden which would fall on the remaining countries. EEX has cumulative emissions in the BAU of 1098 $GtCO_2$ against the global carbon budget of 2861 $GtCO_2$. and this highlights the relevance of the EEX countries and the importance of their engagement if a stringent climate policy is applied.

As a potential alternative, we simulate a policy in which EEX can be involved via a "clean oil" market in which oil produced by EEX is "decarbonised" by DAC (production of one barrel of oil requires approximately 0.34 tCO_2 reduction) and can be sold abroad. As shown previously in the paper, EEX has 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 infeasible climate agreement without EEX's participation, this fragmented cooperation via "clean oil" allows us solve the model and find a solution which attains the given climate objective. Figure 5 shows the international trade of traditional and clean oil. Around 2070, DAC is implemented in EEX countries and they start selling the decarbonised oil, allowing them to use the remaining resources and profit from the international energy market sales. Clean oil sells in 2070 at a price 3.5 times higher than the traditional one (379$/barrel versus 109$/barrel), given its additional value and the costs associated with its decarbonisation. The size of the DAC programme associated with this policy is roughly 512 $GtCO_2$ cumulative to 2100, among which 123 $GtCO_2$ are captured in EEX. DAC comes online in non-EEX in 2050, 15 years earlier than the previous sections under full cooperation. The net trade of clean oil is decreasing towards the end of the century due to a high cost in terms of decarbonisation, and also because of less oil demand caused by a more stringent carbon budget.

In the economic term, this policy would be roughly neutral for energy exporters, who would not bear policy cost. On the other hand, the remaining regions would face a significant penalty that amounts to 5.7 % of cumulative GDP, as a result of the inevitable efficiency losses due to the non equalization of marginal abatement costs of a partial agreement (See Fig.A3 in appendix). At least, this policy would allow the climate objective to be reached, 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. 2009a).

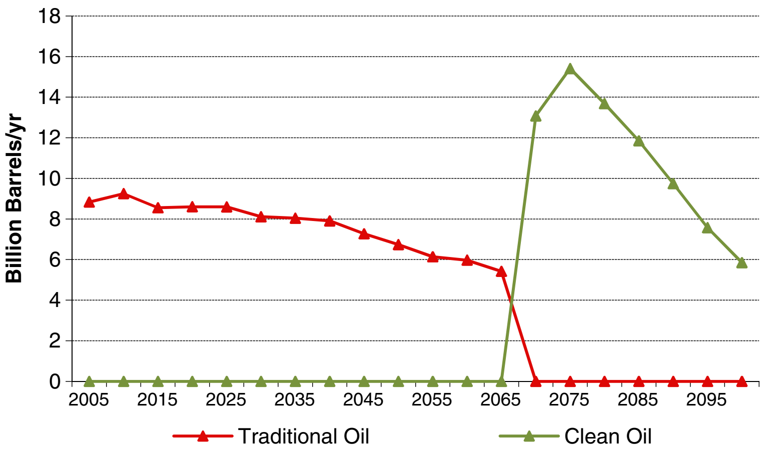

Fig. 5 EEX net export of traditional and clean oil

5 Concluding remarks

This paper has provided one of the few comprehensive modelling assessments of the long term prospects of Direct Air Capture technology. Using novel estimates of the techno-economic specifications of DAC, we have implemented this 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 high-temperature heat, and its reliance on appropriate CO_2 storage sites. This integrated framework has allowed us to compare and to contrast DAC vis-à-vis 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 distant future. DAC would be deployed well after several other main abatement options have been put in place, but the scale of deployment could be vast and reach several hundreds of $GtCO_2$ by the end of century. The sensitivity analysis shows that the scale of DAC deployment also depends on the alternative abatement options that are available. Moreover, DAC (and negative emission technologies in general) are affected by the way the future is discounted into present terms; lowering the social rate of time preference would reduce the scope of DAC since it would counteract the tendency to shift policy costs onto future generations. For a less stringent climate objective, of about 550 ppm-eq, DAC would no longer be profitable, suggesting that DAC is relevant only when extremely demanding emission reductions are needed. However, large scale deployment of DAC would result in a sharp decline of carbon concentrations which would, according to the climatic papers in this special issue, results in a CO2 outgassing from the oceans; our analysis has shown that such outgas could reduce the usefuleness of DAC.

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 in emission reduction activities, assuming that DAC can be used to "decarbonise" oil. Our analysis has indicated that this arrangement would be incentive-compatible for EEX, 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; moreover, the free riding incentives might actually be reinforced once counties realize the magnitude of the transfers occurring from non-EEX to EEX countries.

Although the analysis presented in this paper represents a significant step forward in terms of modelling DAC, some 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, this paper analyzes whether DAC could become an important carbon mitigation option, alongside several other ways to capture CO_2 from the atmosphere (biological, on oceans, etc.). The answer depends on the level of climate safety that we would like to achieve and the rate of progress in getting started with mitigation. It does not 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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