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The role of negative CO_2 emissions for reaching 2 °C—insights from integrated assessment modelling

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Abstract Limiting climate change to 2 °C with a high probability requires reducing cumulative emissions to about 1600 $GtCO_2$ over the 2000–2100 period. This requires unprecedented rates of decarbonization even in the short-run. The availability of the option of net negative emissions, such as bio-energy with carbon capture and storage (BECCS) or reforestation/afforestation, allows to delay some of these emission reductions. In the paper, we assess the demand and potential for negative emissions in particular from BECCS. Both stylized calculations and model runs show that without the possibility of negative emissions, pathways meeting the 2 °C target with high probability need almost immediate emission reductions or simply become infeasible. The potential for negative emissions is uncertain. We show that negative emissions from BECCS are probably limited to around 0 to 10 $GtCO_2$/year in 2050 and 0 to 20 $GtCO_2$/year in 2100. Estimates on the potential of afforestation options are in the order of 0–4 $GtCO_2$/year. Given the importance and the uncertainty concerning BECCS, we stress the importance of near-term assessments of its availability as today's decisions has important consequences for climate change mitigation in the long run.

1 Introduction

The transition towards a system with low greenhouse gas emissions (GHG) is one of the greatest challenges facing the energy system today. The projected change in climate

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associated with ‘business-as-usual’ scenarios could very well lead to considerable impacts, such as reduction of agricultural production, biodiversity loss, sea level rise and extreme weather events (Hansen et al. 2008; Hare et al. 2011; Parry et al. 2007). Based on the available scientific evidence, policy makers have proposed to use the so-called 2 °C target (a maximum increase of global mean temperature above pre-industrial levels) as an important objective for international climate policy (UNFCCC 2010). Several studies have indicated the daunting implications of the 2 °C target (Edenhofer et al. 2010; Meinshausen et al. 2006; Van Vuuren et al. 2007): assuming that policies would aim to achieve such a target with a probability of more than 50 % (based on the climate sensitivity uncertainty), global GHG emissions would need to be halved in the next 40 years and to a level close to zero in the second half of the century. In contrast, historical trends so-far have resulted in an almost continuous increase in GHG emissions.

So-far, international negotiations have made little progress in formulating effective international climate policies. While it is even not certain that current pledges to the Copenhagen Agreement will be successfully implemented, they would certainly not lead to the emission levels associated with least-costs ‘2 °C target’ pathways (Den Elzen et al. 2011; Rogelj et al. 2011; Van Vliet et al. 2012). There is also no evidence that ongoing negotiations for policies beyond 2020 will be more successful, although decision-makers proposed a new round of negotiations in Durban. A possible way to deal with this is the consideration of so-called overshoot scenarios (Den Elzen and Van Vuuren 2007; Huntingford and Lowe 2007; Wigley et al. 2007). *Concentration* overshoot scenarios allow, for a limited period of time, for higher concentration levels than those consistent with long-term temperature targets. Such (limited) overshoot scenarios can be attractive as they require less short-term reductions and seem to have only limited additional risks (Den Elzen and Van Vuuren 2007). *Temperature* overshoot scenarios can also be considered, but these clearly bear additional risks as the higher temperature levels will obviously cause climate impacts and it will take considerable time to return to the proposed target (Solomon et al. 2009). Increased temperature levels could cause feedbacks that would result in further climate change (e.g. the temperature feedback on the carbon cycle, that reduces the uptake of carbon by ecosystems (Friedlingstein et al. 2006)).

Many (concentration) overshoot scenarios aim to profit from net negative emissions in the second half of the century (Azar et al. 2006; Azar et al. 2010; O’Neill et al. 2010; Read and Lermit 2005; Van Vuuren et al. 2007). Net negative emissions can be achieved in different ways. Important options include bio-energy combined with carbon capture and storage (BECCS) (Azar et al. 2010; Obersteiner et al. 2001; Read and Lermit 2005), reforestation and afforestation (Canadell and Raupach 2008; Nabuurs et al. 2007; Obersteiner et al. 2006) and forms of geo-engineering, carbon dioxide removal or CDR such as capturing CO_2 directly from the air and ocean fertilization (The Royal Society 2009). Carbon storage in soils through the use of biochar (Galinato et al. 2011) or by producing bio-energy on degraded grasslands could possibly contribute to negative emissions as well (Tilman et al. 2006). Of these options, direct air capture is relatively expensive, while ocean fertilization (and many other forms of geo-engineering) bear serious environmental risks (The Royal Society 2009). As such, BECCS and reforestation would arguably be the most attractive options to create negative emissions. In this paper, we briefly explore the demand and supply of negative emissions by the use of BECCS. For this, we first illustrate the importance of the possibility of negative emissions in future for the decisions policymakers face today using a set of stylized emission pathways. Next, we discuss the possible supply of negative emissions from BECCS by discussing the potential for bio-energy and CCS. Finally, we use the Integrated Assessment Model (IAM) IMAGE to illustrate the implications of BECCS use for the energy system and climate policy in actual IAM based scenarios.

2 The demand for negative emissions

Various studies have shown that the probability of achieving the 2 °C target is correlated with the cumulative CO_2 emissions. Studies by Meinshausen et al. (2009) and Allen et al. (2009), for instance, showed that the CO_2 emission budget in the next four decades would be the best predictor of the probability of achieving the target. Restricted by the available scenario studies at the time, the Meinshausen et al. (2009) study did not consider negative emission scenarios. In a recent study, that uses a similar approach based on the MAGICC model as Meinshausen et al. (2009), negative scenarios have been included (Van Vuuren et al. 2012). The new MAGICC calculations from Van Vuuren et al. (2012) cover a wide range of scenarios with different time profiles as published in recent IAM models. Within this range of time profiles (based on IAM assumption on economic and technical constraints) a clear relationship between the carbon budget and long-term climate targets remains. Different results for non-CO_2 emissions form the single most important factor complicating the relation. But also higher short-term emissions compensated by long-term negative emissions influence a budget approach, clearly for short-term budgets but also for long-term budgets. For instance, higher CO_2 concentrations result in a higher absorption rate of oceans and biosphere, increasing the budget as a function of the level of overshoot (Wigley et al. 1996). Higher temperatures, however, could lead to positive climate-carbon cycle feedbacks such a reduced growth of the biosphere or the release of GHGs from tundra areas (Friedlingstein et al. 2001; Friedlingstein et al. 2006), leading to a lower budget. For the sake of simplification, in the remainder of this section, we assume that the carbon budget is independent of the emission profile. The results of Van Vuuren et al. show that, on average, an ambition to meet the 2 °C target with a probability around 66 % corresponds with a maximum CO_2 emissions budget across the century of 1600 $GtCO_2$. For comparison, the average baseline emission scenario of the recent model comparison study (EMF-22) leads to an emission of more than 5200 $GtCO_2$, i.e. more than 3 times the allowable emission budget (Clarke et al. 2010).

Apart from the long-term climate target, several other factors also determine the emission reduction pathway, including: 1) the rate at which emissions can be reduced and 2) the total reduction potential, as defined by long-term technology development.

1. The emission reduction rate is bounded by several factors (Den Elzen et al. 2010; Kramer and Haigh 2009). First of all, technology has a certain lifetime and premature replacement is expensive. The typical lifetime of a fossil-fuel power plant, for instance, is around 40 years (Philibert 2007). Similar lifetimes hold for plants in industry. While the lifetime of other technologies, such as a passenger car, can be much shorter, also the lifetime of the associated infrastructure can be relevant (fuelling stations; car factories etc.). Other important factors are the inertia in the change of consumer preferences, international negotiation processes, policy formulation and the maximum deployment rate of new technologies. These factors are very uncertain and typically not captured in energy-economic models. Earlier, we found that in existing scenarios for ambitious climate targets hardly any period is found with a reduction rate of 4 %/year (compared to 2000 emission levels) for 10 years or more (Den Elzen et al. 2010). Even a 4 % emission reduction rate requires a decarbonisation rate of 6 %, assuming an average income growth of 2 %. Historically, high global decarbonisation rates are in the order of 2 %/year (achieved over relatively short time periods).
2. A second key factor is the total reduction potential. In some sectors, emissions can be reduced to zero over time. For instance, in the power sector several alternative options exist that can all significantly reduce emissions (renewables, CCS, nuclear power). In

other sectors, however, potential seems to be more limited. For instance, for some transport modes like aviation and freight transport reduction potential seems to be currently limited to energy efficiency and the use of bio-energy (Riahi et al. 2012), while bio-energy use is likely to generate at least some GHG emissions (Searchinger et al. 2008; Smeets et al. 2009). Also for several non-CO_2 emission sources, it will be hard to reduce emissions to zero (Lucas et al. 2007; Van Vuuren et al. 2006).

Clearly, in this discussion the potential to reduce emissions below zero in the long-term plays a critical role (Van Vuuren and Riahi 2011). While compensating for limitation in emission reduction options in some sectors, it also allows to 'transfer' short-term emission reductions to a later point of time. We will illustrate the importance using some very simple calculations.

- First of all, we assume that for reaching the 2 °C target the cumulative 2000–2100 emission budget (land use and energy) needs to be equal to1600 $GtCO_2$.
- We assume that across the century emissions are reduced linearly (as a result of a strategy to spread the emission reduction burden across time) equal to a percentage of 2000 emissions. This maximum rate is maintained until the maximum reduction potential is reached. Quantitatively, we vary this rate between 2 and 4 % (reduction rates below 2 % are incompatible with the emission budget, while higher reduction rates seem to be unlikely based on the discussion above).
- We vary the maximum reduction potential in terms of the the lowest achievable emission level from 5.0 $GtCO_2$/year up to −10 $GtCO_2$/year (the former representing a case of high remaining emissions and the second the use of BECCS).
- Finally, we assume a baseline scenario equal to the average EMF-22 baseline.

Starting from these four key assumptions, it is straightforward to derive the range of 2020 emissions consistent with the total emission budget. It should be noted even small differences in the 2020 reduction target are of key importance given the large share of emissions already 'committed' as part of the current energy infrastructure and existing policies. Figure 1 shows the results of these calculations. In nearly all cases that do not include negative emissions, 2020 emissions need already be reduced significantly. For instance, assuming a maximum reduction rate of 2.5 %/year, global emissions need to be around the 2000 level in 2020 and 10 % below baseline. Only, if a long-term 4 % emission reduction rate is achievable, the 2020 emission reductions could be limited. In all cases without negative emissions, 2050 emissions are around 60–80 % below the 2000 level in order to meet the overall cumulative emission budget. In fact, if emissions cannot be reduced to zero, the need for short-term emission reductions is even more urgent (see panel b). For instance, assuming the emission cannot be reduced lower than 5 $GtCO_2$/year implies that 2020 emissions would need to be reduced to 25 % below the baseline in order to reach the 2 °C target.

The situation changes substantially if negative emissions are assumed to be possible: the urgency for near term emission reductions becomes much less (panel c). We have looked at a negative emission rate of −6 and −10 $GtCO_2$/year. The required 2020 emission reductions are significantly smaller: 0–10 % compared to baseline for assumed emission reduction rates of 2–3 %/year; for a 4 % emission reduction rate it is even possible to allow no reduction in 2020. The 2020 consequences are summarized in panel d.

With these insights, it is useful to look at the IAM calculations where similar results have been obtained. Clarke et al. (2010), for instance, show that those models that are able to meet low GHG concentrations include BECCS in the assumed portfolio. Van Vuuren and Riahi

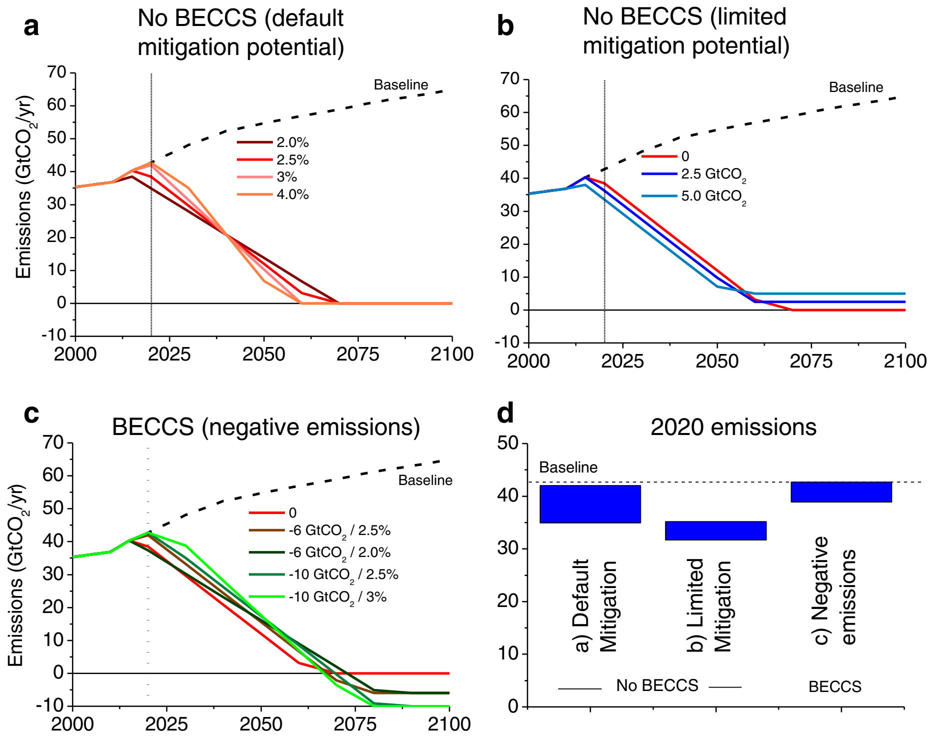

Fig. 1 Illustrative emission pathways based on carbon budget of 1600 $GtCO_2$ and a constant emission reduction rate (expressed as percentage of 2000 emission levels). Panel **a**) shows emission pathways going to zero emissions; panel **b**) shows the results if the emission reduction potential is limited, panel **c**) shows the results if emissions can go negative. Finally, panel **d**) summarizes the emission window for 2020 (emission in 2100 are zero, +5 $GtCO_2$/year and −10 $GtCO_2$/year and a maximum reduction rate of 2–3 % per year. On the high side, the results are constrained by the average baseline scenario from the EMF-22 exercise

(2011) look into this in more detail based on an extensive set of published scenarios. They summarize their results for the three lowest categories defined in the Fourth Assessment Report of IPCC (these categories are defined on the basis of the 2100 radiative forcing level). The lowest category is consistent with a high likelihood of achieving the 2 °C target. Figure 2 shows the scenarios within this category. Given the more complex model dynamics, the results are somewhat less extreme than those shown in Fig. 1. Here, the illustrative calculations above explain why a direct relationship can be observed between 2020 emission levels and the assumptions on long-term negative emissions.

3 The feasibility of negative emissions

A subsequent question involves the potential for negative emissions, in particular from BECCS. While there are some technical constraints in running (BE)CCS plants over conventional fossil fuel plants, these issues seem not to be of overriding importance. Two factors seem to be more important: 1) is it possible to produce sufficient bio-energy and 2) what is the potential for CCS.

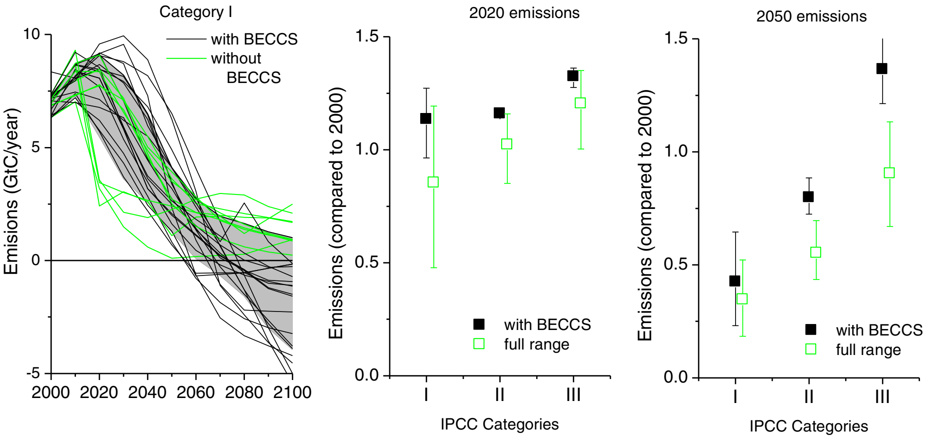

Fig. 2 Overview of scenarios in the literature consistent with the 2 °C target. Scenarios with and without negative emissions. Source: (Van Vuuren and Riahi 2011). Note: The IPCC categories classify scenarios on the basis of their 2100 radiative forcing. The three lowest categories are: I: < 3.0 W/m^2, II: 3–3.5 W/m^2 and III: 3.5–4.0 W/m^2. The left panel shows CO_2 emissions for all scenarios in category I. The middle and right panel show the emissions range across the scenarios in 2020 and 2050 (average and full range)

3.1 Availability of large-scale bio-energy

There is a fierce debate on the sustainable potential of bio-energy (Dornburg et al. 2010; Melillo et al. 2009; Searchinger et al. 2008). Several concerns have been raised. First of all, there are competing claims on scarce land resources from food production, timber production and bio-energy production. In the next four decades, it is likely that an increase of agricultural production of around 60 % will be required in order to feed 9 billion people with increasingly meat-intensive diets (IAASTD 2009; Smith et al. 2010). At the same time, there are indications that even producing relatively small amounts of bio-energy have contributed to lifted food prices (Rosegrant 2008). Assuming that a sustainable bio-energy potential should not threaten food security, the potential for bio-energy strongly depends on the development in the agricultural system (in particular its productivity increase). Equally important are limitations posed by biodiversity protection, water scarcity and prevention of soil degradation. Finally, also the potential GHG emissions associated with bio-energy production need to be taken into account (Crutzen et al. 2007; Dornburg et al. 2010; Searchinger et al. 2008; Smeets et al. 2009; Wicke et al. 2012; Wise et al. 2009). The ability of BECCS to result in net negative emissions obviously depends on the size of these emissions. For production of woody bio-energy for use in power stations, the conversion emissions are typically low: relatively little processing of the biomass is needed (compared to for instance the production of biofuel), and woody bioenergy can (depending on the management system) be produced with very little fertilizer input (Van Vuuren et al. 2010b). The net impact on GHG emissions, therefore, mostly depends on land-use change associated CO_2 emissions, either directly (at the location of woody bio-energy production) or indirectly (displacement of other activities). Estimates of these emissions vary strongly: they can be as high as the emissions associated with fossil fuels or even be negative if bio-energy production contributes to improvement of degraded soils (Nijsen et al. 2011; Searchinger et al. 2008; Tilman et al. 2006) .

Van Vuuren et al. (2009; 2010a) looked into the sustainable bio-energy production potential under various assumptions. They show that the sustainable potential in 2050 may vary between 0 and 200 EJ/year depending on a range of assumptions regarding the factors mentioned above. A typical value would be around 150 EJ/year for the sum of purpose-grown bio-energy and residues (assuming sites would produce around 5–10 ton dry matter per hectare per year). By 2100, this value may be around 250 EJ/year. The literature review by Dornburg et al. (2010) shows a comparable range. Assuming that 1) all bio-energy would be used in BECCS plants, 2) a capture efficiency of 90 % and 3) a land-use related emission factor associated with the production of bio-energy of 15 kg CO_2 per GJ, it is easy to calculate that the absolute maximum total potential for negative emissions would be in the order of 10 $GtCO_2$/year in 2050 and 20 $GtCO_2$ in 2100. An emission of 15 kg CO_2 per GJ is based on some review of the literature and calculations using the IMAGE model, and reduces the net effectiveness of BECCS by about one fifth (but as discussed above there is a considerable uncertainty range). It should be noted that the BECCS potential is likely to be smaller as a result of competition with other forms of bio-energy use such as the transport sector and the production of materials.

3.2 Availability of CCS potential

Also the availability of CCS can be constraining. First of all, the storage capacity for CO_2 is uncertain: while there is some certainty about the safety of storing CO_2 in empty fossil-fuel reservoirs, the potential of safe storage in other categories (such as coal-beds, saline aquifers or even in the ocean) is more uncertain. Second, societal acceptance is at least as an important constraint (Johnsson et al. 2009). Local communities have successfully opposed CCS projects, based on (perceived) risks (Brunsting et al. 2011).

From a fully technical perspective, Hendriks et al. (2004) estimated the global storage capacity based on different assumptions to range from 500 to around 10,000 $GtCO_2$ (Fig. 3). Fossil-fuel reservoirs capacity (the most certain part) range from 500 to around 3000 $GtCO_2$. A recent study of the International Energy Agency finds somewhat lower numbers in most regions, but considerably higher numbers in the USA (IEAGHG 2011). As a result, their total global estimate is slightly higher, while the fossil fuel part was estimated at 600 to 2500 $GtCO_2$. Assuming that CCS is mostly used in the second half of the century, the total capacity use of empty oil and gas fields allows for an average annual storage rate of 10 to more than 65 $GtCO_2$/year. Including coal seams and aquifers would move the high-end

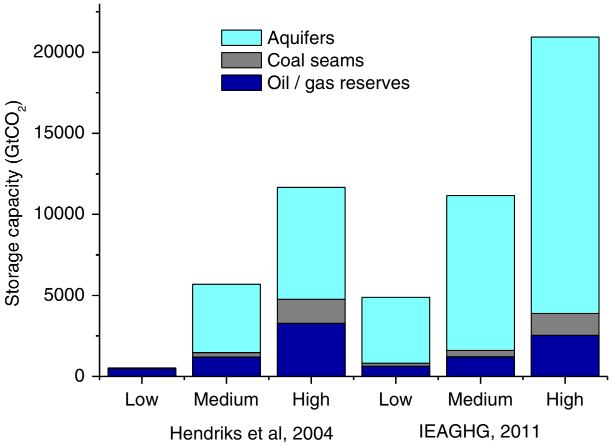

Fig. 3 Estimates of storage capacity (Hendriks et al. 2004 and IEAGHG 2011)

range upwards considerably. The same reservoirs, however, could also be potentially used to store the CO_2 generated from fossil-fuels, lowering the available space for BECCS. This implies that under the most optimistic estimates, the storage capacity will not be limiting BECCS capacity at the global level (although capacity could run out in specific, densely populated, regions such Korea, Japan and India). Under pessimistic assumptions, however, the potential for BECCS could be seriously constrained by the storage capacity (technically maybe 10 $GtCO_2$/year, but social acceptance could reduce this number to zero). Also the maximum storage rate and CCS costs could play a role in the uncertainty. The latter are determined by the capture, transport and storage costs, and quite some progress is still needed to increase the competitiveness of BECCS (see, for instance, IPCC 2005; GCCSI 2011).

3.3 The potential for afforestation and reforestation

The importance of BECCS also depends on the availability of other negative emission options. Afforestation/reforestation (AR) forms a reasonable alternative to BECCS, although negative emissions can only be achieved after first substantially reducing current deforestation emissions. Studies on potential from AR report both technical and economic potential and more realistic estimates taking into account all kind of practical limitations. Kindermann et al. (2008) report that substantial emission reductions can be obtained from reducing deforestation. Strengers et al. (2008) report a mitigation potential from afforestation up to 10 $GtCO_2$/year in the 2010–2050 period under the most optimistic assumptions, but indicate that a number around 4 $GtCO_2$/year would be more realistic. In pessimistic cases, however, there would be no realistic potential. These numbers are reasonably consistent with the estimate of 1.3–4.2 $GtCO_2$-eq/year reported by the IPCC 4th Assessment Report. Obviously, bio-energy potential and AR potential may compete for the same land. Another point is that both bio-energy and afforestation measures could, if introduced at a large scale, not only lead to carbon sequestration but also to biophysical impacts on climate, such as albedo changes. These impacts are still uncertain given our current understanding of the interaction between land-use change and climate (e.g. impacts of deforestation and land-use change in the Amazon rainforest or Africa). There is more consensus on the impact of land-use change in snow-covered areas in the temperate zone, where large scale reforestation measures could lead to a net warming impact (Betts 2000; Schaeffer et al. 2006).

3.4 Assessment of total potential

The above considerations imply that optimistic estimates on the negative emissions might be in the order of 10–20 $GtCO_2$/year for BECCS and around 4 $GtCO_2$/year for forestry related options. More realistic estimates, however, are likely to be half this potential or less.

4 Assessing the role of BECCS using the IMAGE integrated assessment model

In order to explore the potential for BECCS further, we have run a set of alternative climate policy scenarios: i.e. stabilization cases at 2.6 and 2.9 W/m^2 (450 and 480 ppm CO_2-eq.) using the IMAGE model with and without BECCS (IMAGE can directly be run under radiative forcing targets, and thus does not need cumulative emission targets). The IMAGE model provides a description of various systems relevant for global environmental change (Bouwman et al. 2006). The climate system is represented by parts of the MAGICC6 model, while the carbon cycle is represented by a detailed description of the interaction between the biosphere, oceans and the atmosphere. In the energy system, technologies are chosen based on relative costs (using multinomial logit equations), which in turn are determined by depletion and technology learning dynamics. Biomass can be used in the transport sector, in the power sector (with and without CCS) and other sectors. As a baseline for our calculations we used the recently developed scenario for the OECD Environmental Outlook 2012 (OECD 2012), assuming that no new climate policies are introduced. In this scenario energy-related CO_2 emissions increase from nearly 30 $GtCO_2$/year today to around 55 $GtCO_2$/year in 2050 and more than 80 $GtCO_2$ in 2100. Climate policies are induced by introducing a CO_2-equivalent price. The calculations assume full participation of regions and sectors after 2012, and use a discount rate of 5 %. The use of BECCS is limited by similar constraints as discussed in Section 3 (note that afforestation and deforestation measures are not included in these IMAGE calculations).

In the scenarios in which the use of BECCS is allowed, this technology indeed plays an important role. While the costs are seemingly high (it combines the additional costs of the bio-energy feedstock and the costs of CCS technology), the technology produces two services: production of electricity and storage of CO_2. As a result, the technology is very competitive for moderate to stringent climate targets. In the scenarios shown here, the carbon price is high enough from 2030 onwards to induce large scale BECCS application (see Fig. 4). The total negative emissions in 2100 amount to about 4 $GtCO_2$-eq/year. This is a net result of the negative contribution of BECCS (10–15 $GtCO_2$/year) and remaining emissions in other sectors (like international transport). Already in the 2050–2060 period, the emissions of the power sector become net negative, reducing the mitigation pressure in other sectors.

The influence of BECCS can also be seen from comparing scenarios with and without this technology. The 2.6 W/m^2 target, in fact, becomes infeasible in the current model set-up. This is reported also for several other models (Clarke et al. 2010). For the 2.9 W/m^2 target, the removal of BECCS leads to a cost increase. Moreover, with BECCS emission reductions can be somewhat postponed. Without BECCS, short-term emission reductions, in fact, need to be similar to the 2.6 W/m^2 scenario (with a sharp peak in 2020). Figure 5 shows the impacts on the energy mix: to compensate for the lack of BECCS, the model needs to further increase energy efficiency and to decrease unabated fossil fuel use. This is done by

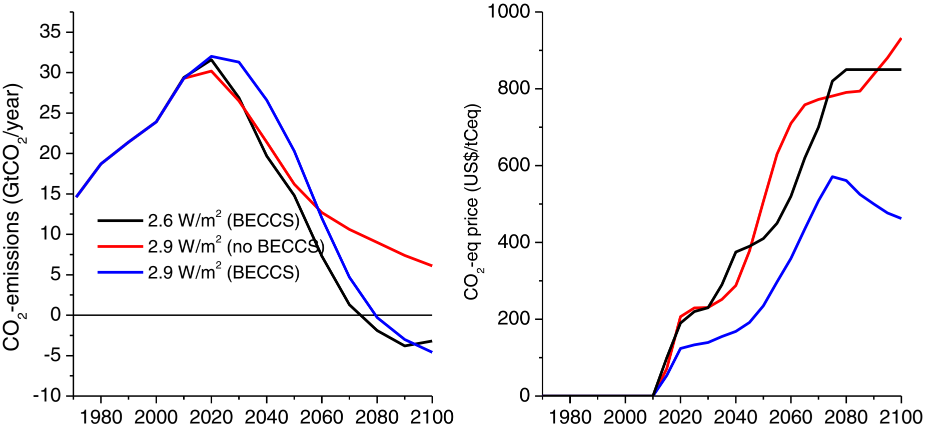

Fig. 4 Emission trajectory of scenarios with and without BECCS leading to stabilization at 450 and 480 ppm CO_2-eq

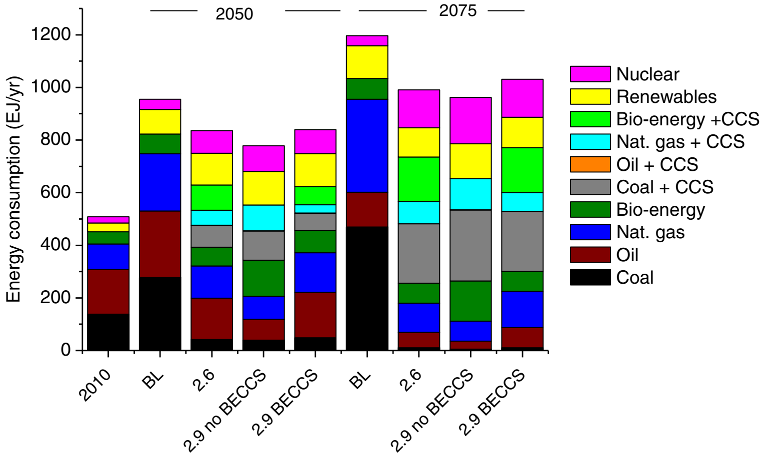

Fig. 5 Primary energy consumption

significantly increasing natural gas and coal use with CCS and nuclear power. In addition, also the remaining oil use in (international) transport is reduced further.

In the BECCS scenarios, the majority of bio-energy is used in conjunction with CCS – and thus the use of bio-energy in the transport sector is significantly reduced (shown by a reduction of bio-energy use without CCS). At the same time, the total bio-energy consumption increases. For 2050, from 75 EJ/year in the baseline to 140 EJ/year in the mitigation run without BECCS and 150–170 EJ in the runs with BECCS (in all cases including residues). In 2075, these numbers are 80, 150 and 250 EJ/year. This also leads to corresponding changes in land use. In our scenario land for food production is projected to peak around 2025 (driven by a slowdown in population growth combined with further productivity improvement in the agricultural system). In the mitigation cases, the additional land for bio-energy amounts to around 0.3-0.6 Gha during the second half of the century or about 20-30 % of the area required for crop production (1.4-1.7 Gha). As discussed earlier, these numbers are subject to considerable uncertainty, both in terms of the required area (depending on the assumed technology improvements in the production of bio-energy and yields) and associated GHG emissions.

5 Discussion and conclusions

In this article we discussed the demand and scope for negative emissions by using BECCS. The analysis leads to the following conclusions:

BECCS can have an important impact on the timing of emission reductions Using a set of stylized emission pathways, we explored different emission pathways that would lead a cumulative emission of 1600 $GtCO_2$ in the 2000–2100 period (providing a high chance of meeting the 2 °C target). Without negative emissions, each of these pathways imply almost immediate emission reductions, certainly if we assume that not all emission sources can be reduced to zero. If BECCS is allowed as part of the emission reduction portfolio, it is likely to have an important impact on the timing of emission reductions: less near-term emission reductions are required.

The potential for BECCS depends on critical uncertainties with respect to bio-energy and CCS The potential for bio-energy and CCS is difficult to assess as it does depend on technical uncertainties, but also on more elusive factors such as social acceptance, political choices and the development of the agriculture system at large. The assessment made in this article shows that negative emissions from BECCS would most likely be in 2050 at best somewhere between 0 and 10 $GtCO_2$/year, while in 2100 this might be 0–20 $GtCO_2$/year.

Short-term emission targets in the context of the 2 °C target need to be assessed based on expectations with respect to short-term emission reductions and costs, and expectations on long-term technology development and associated costs In the short-term, emissions are clearly not only bound by economic and technical factors but also by the ability to agree on climate policy at the (inter)national level. The availability of BECCS in the long-term may allow for less reductions in the short-term. However, while economically attractive given the double contribution to mitigation, this requires a near-term assessment on the availability and impacts of BECCS in the long-term. In our discussion in Section 3, we have also indicated that the availability of BECCS technology is not certain at all. Current decisions therefore need to be taken in the context of this uncertainty. More reductions in the short-run (with additional costs) allow for a more flexible portfolio in the long run. It is important to note that the bio-energy markets would be heavily influenced by the use of BECCS. Without BECCS most of the bio-energy gets used in the transport sector. With BECCS, a substantial part of bio-energy is shifted towards the power sector.

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