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The value of bioenergy in low stabilization scenarios: an assessment using REMIND-MAgPIE

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Abstract

This study investigates the use of bioenergy for achieving stringent climate stabilization targets and it analyzes the economic drivers behind the choice of bioenergy technologies. We apply the integrated assessment framework REMIND-MAgPIE to show that bioenergy, particularly if combined with carbon capture and storage (CCS) is a crucial mitigation option with high deployment levels and high technology value. If CCS is available, bioenergy is exclusively used with CCS. We find that the ability of bioenergy to provide negative emissions gives rise to a strong nexus between biomass prices and carbon prices. Ambitious climate policy could result in bioenergy prices of 70 \$/GJ (or even 430 \$/GJ if bioenergy potential is limited to 100 EJ/yr), which indicates a strong demand for bioenergy. For low stabilization scenarios with BECCS availability, we find that the carbon value of biomass tends to exceed its pure energy value. Therefore, the driving factor behind investments into bioenergy conversion capacities for electricity and hydrogen production are the revenues generated from negative emissions, rather than from energy production. However, in REMIND modern bioenergy is predominantly used to produce low-carbon fuels, since the transport sector has significantly fewer low-carbon alternatives to biofuels than the power sector. Since negative emissions increase the amount of permissible emissions from fossil fuels, given a climate target, bioenergy acts as a complement to fossils rather than a substitute. This makes the short-term and long-term deployment of fossil fuels dependent on the long-term availability of BECCS.

1 Introduction

Bioenergy is expected to play an important role within the portfolio of long-term greenhouse gas (GHG) mitigation options (Chum 2011; Fischedick 2011). Its combination with carbon capture and sequestration technologies (CCS) allows carbon to be removed from the atmosphere, making it a measure of active carbon management (Obersteiner 2001; Riahi 2007; Tavoni 2013). This feature[1] of bioenergy with CCS (BECCS) alleviates the deep reductions of GHG emissions that are necessary to meet stringent climate change mitigation targets (van Vuuren 2010a, b; Azar 2010; Kriegler 2013, Edenhofer 2010). Another advantage of biomass is its versatility: it can be converted into several types of secondary energy such as electricity, heat, liquid fuels, and hydrogen (Luckow 2010; van Vuuren 2010a). Therefore, it can serve as a flexible measure for mitigation across

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[1] There are other options to generate net negative emissions, e.g., direct air capture technologies and afforestation. In contrast to biomass, they are not usable as primary energy carriers.

different sectors. The combination of both features makes it a valuable and robust mitigation option (Riahi 2007). However, there are major uncertainties regarding the main factors that determine biomass deployment. First, due to uncertainty about future development of land use and agricultural production, there is a wide range of future estimates of bioenergy potential, ranging from less than 50 to several hundred EJ in 2050 (Chum 2011). Furthermore, concerns about the negative impacts of large-scale biomass production on food security, biodiversity and GHG emissions exist (Wise 2009; van Vuuren 2010a; Creutzig 2012; Popp 2011, 2012, this issue). Second, there is major uncertainty about the availability of advanced second-generation bioenergy conversion technologies (Sims 2010). Finally, large uncertainties remain regarding the future deployment of CCS with respect to technological challenges, constraints on storage capacities, and limited social acceptance (Zoback 2012).

This study argues that two key features of bioenergy - versatility and negative emissions - determine its use and value as a mitigation option. Versatility allows bioenergy to be deployed in the way most valuable for decarbonizing energy use (as measured in terms of revenues from its energy production), and its negative emissions capability suggests to use it in a way which maximizes the amount of CO_2 withdrawn from the atmosphere. In the framework of our study, the latter is incentivized by the fact that the carbon price accrues as revenue to BECCS operators for every ton of CO_2 withdrawn (carbon revenue). Concretely, we ask the following questions:

- How do the carbon and energy value of bioenergy determine its overall value for climate change mitigation?
- How does the structure of energy and carbon revenues differ across different bioenergy technologies, and how do these differences affect their deployment for different levels of climate stabilization targets?
- How does biomass deployment interact with the deployment of fossil fuels?

Based on these questions, we aim to characterize the two key economic drivers behind bioenergy use, their interplay and the potential trade-offs between them. To our knowledge, such a detailed characterization has not yet been provided in the literature. To account for the uncertainties about crucial determinants of bioenergy deployment we additionally vary the availability of biomass and CCS technology and study their impact on the mitigation strategy and its costs. We shed light on the crucial factors that determine the choice of bioenergy conversion technology if carbon and bioenergy markets are interlinked, adding to existing studies (Luckow 2010; Calvin 2009; van Vuuren 2010a) on the preferred long-term and large-scale applications of bioenergy under climate policy.

2 Methodology

Bioenergy deployment depends on the evolution of both energy and land-use systems. Therefore, an in-depth analysis of future scenarios of bioenergy use requires modeling of the two systems. This study applies the combined model system REMIND-MAgPIE. The integrated assessment model REMIND represents the energy-economy-climate system and covers a wide range of bioenergy and competing conversion technologies. Within REMIND, the land-use sector is represented by an emulation of the high-resolution land-use model MAgPIE. This emulation focuses on bioenergy supply costs and total agricultural emissions.

2.1 The integrated assessment model REMIND

The Refined Model of Investment and technological Development (REMIND) is a global multi-regional model that assesses climate change mitigation policies over the course of the 21st century, while integrating the interactions between the economy, the energy sector, and climate change (Leimbach 2010a, b; Luderer 2012, 2013; Bauer 2012a, b).

REMIND combines a macro-economic Ramsey-type growth model, a detailed bottom-up model of energy production and conversion, and a climate module. The macro-economy endogenously determines the demand for final energy. The final energy carriers and services are produced from primary energy using a broad set of technologies for conversion, transmission, and distribution (cf. supplementary online material (SOM) Table S2). Endogenous technology learning is assumed for solar photovoltaic and concentrating solar power as well as wind turbines (see SOM Section S1 for further information on non-biomass renewables). REMIND assumes a global storage potential for captured carbon of 3600 $GtCO_2$ and a maximal annual injection rate of 0.5 % of the regional total potential (see SOM Section S1.6 for regional potentials). Prices for fossil and biomass resources are calculated from supply cost curves. Regions interact via trading of goods and primary energy carriers, including biomass.

Bioenergy can pursue different technology routes to be converted from primary energy into several types of secondary energy carriers. Dominant technologies are biomass-to-liquid fuels B2L, BIGCC (integrated gasification combined cycle) producing electricity, and biomass-to-hydrogen (B2H2). BIGCC and B2H2 feature high capture rates (80% and 90%, respectively), whereas B2L maintains a lower capture rate (48%) since a significant share of carbon is embedded in the resulting fuel. Detailed information about bioenergy conversion routes and competing technologies and their techno-economic characteristics can be found in SOM Table S3. Biomass is considered a low-carbon energy source with a credit for negative emissions from CCS in the energy system. A detailed description of the assumptions on bioenergy and the interaction of the REMIND and MAgPIE model can be found in Section 2.3 and 2.3.

The techno-economic characteristics of the technologies and the endogenously evolving prices of energy and GHG emissions determine the size and structure of the energy sector. Climate change stabilization targets are implemented by constraining radiative forcing (cf. SOM Section S2.2). The REMIND model computes the cost-effective emission mitigation with full where (abatement can be performed where it is cheapest), when (optimal timing of emission reductions and investments) and what (optimal allocation of abatement among emission sources and greenhouse gases) flexibility. Further key characteristics of the REMIND model can be found in SOM Table S1 and a full model description in Luderer (2013).

2.2 The land-use model MAgPIE

The bioenergy supply prices and land-use emissions represented in REMIND are based on data from the global land-use model MAgPIE (Model of Agricultural Production and its Impact on the

Environment), (Lotze-Campen 2008, 2010). MAgPIE is a recursive dynamic optimization model that minimizes the total cost of production for a given amount of regional food and bioenergy demand. In order to increase total agricultural production, MAgPIE can invest either in yield-increasing technological change or in land expansion (Krause 2012; Popp 2011). Four categories of costs arise in the model: production costs for livestock and crop production, yield-increasing technological change costs (Dietrich 2013), land conversion costs, and intraregional transport costs. A breakdown of total agricultural production costs into these categories can be found in SOM Figure S14. MAgPIE considers regional economic conditions such as demand for agricultural commodities, level of agricultural technology, and production costs as well as spatially explicit data on potential crop yields, land, and water constraints (from the dynamic vegetation model LPJmL, Bondeau 2007) and derives specific land-use patterns, yields, and total costs of agricultural production. The model incorporates N_2O and CH_4 emissions from agricultural production (Bodirsky 2012) as well as CO_2 emissions from land-use change (Popp 2012). Since the demand for food is prescribed exogenously based on the assumed pattern of regional per capita income, there is no price response of food demand. Neither is there any underlying “food-first” policy in MAgPIE. Biomass competes with the production of food crops for land and other agricultural resources. This competition determines the biomass prices that emerge from MAgPIE. Biomass supplies specialized 2nd generation ligno-cellulosic grassy and woody bioenergy crops, i.e. miscanthus, poplar, and eucalyptus.

2.3 Representation of the land-use sector

The supply of purpose-grown ligno-cellulosic biomass in REMIND is represented by regional supply price curves that are calculated based on the price responses of MAgPIE to different biomass demand scenarios (Klein, in prep., SOM Fig. S2). Regional biomass endowments within REMIND are not limited explicitly (apart from a global limit, see below). However, there is an implicit limit, since the biomass supply curves prescribe rising prices for increasing demand. Therefore, the competitiveness of bioenergy with other energy carriers is limited. The emission baselines for CH_4, N_2O, and CO_2 from land-use and land-use changes were also obtained from MAgPIE. They are exogenously prescribed to REMIND and can be reduced according to marginal abatement cost (MAC) functions (Lucas 2007). The MAC function for CO_2 abatement resulting from avoided deforestation was derived from MAgPIE by measuring the response of CO_2 emissions to varying CO_2 prices.

We use different bioenergy supply cost curves for the policy and baseline scenarios in REMIND since carbon pricing not only results in lower land-use emissions, but also increases bioenergy prices. Consistent with Wise (2009) we find that pricing emissions from land-use change induces avoided deforestation. The avoided deforestation leads to an intensification rather than extensification of land for bioenergy production and thus makes it more costly to produce bioenergy. Wise (2009) observes that carbon prices not only reduce deforestation but may even lead to afforestation. However, this option is not available in the current MAgPIE model. In the presence of carbon pricing, deforestation comes to a halt by 2020 in all policy scenarios. The resulting carbon emissions from land use show levels of about 4.4 GtCO2/yr until 2020 and zero emissions thereafter. N_2O emissions from bioenergy production due to fertilization are covered by an emissions factor[2] of 3.7 kg CO_2 eq/GJ in REMIND. By including the emission baselines and emission factors, direct and indirect emissions caused by bioenergy deployment are fully represented and are part of the climate change stabilization target in REMIND. Therefore, emissions from the land-use sector and the energy system are valued equally.

Bioenergy is assumed to be predominantly produced from second-generation, ligno-cellulosic, purpose grown biomass, and ligno-cellulosic agricultural and forestry residues. The traditional use of biomass phases out until 2050, based on the assumption that it is replaced with modern, sustainable, and less harmful fuels as incomes rise, especially in developing countries. First-generation biofuels are expected to contribute only in the short- to mid-term and they are expected to be replaced by second-generation fuels (Sims 2010). Land-use impacts, co-emissions, and competition with food production from first-generation biofuels are heavily debated (Searchinger 2008; Fargione 2008). REMIND assumes that only small amounts of first-generation fuels exist (less than 0.1 EJ/yr globally). The model considers the low-cost potential of ligno-cellulosic agricultural and forest residues, which increases from 20 EJ/yr in 2005 to 70 EJ/yr in 2100 (based on Haberl 2011). Given the concerns about the sustainability implications of large-scale bioenergy production, REMIND assumes, by default, an upper global limit of 300 EJ/yr for second-generation biomass use. This constraint is consistent with the upper end of potential 2050 deployment levels identified in Chum (2011). Based on the current public debate, we consider this constraint to be a reflection of the potential institutional limitations on the widespread use of bioenergy; however, it does not reflect a limitation of bioenergy supply in the MAgPIE model. We have run the scenarios analyzed in this study with unconstrained bioenergy supply and found that bioenergy deployments in 2100 reach 355 EJ/yr in the 550-FullTech scenario and 535 EJ/yr in the 450 FullTech scenario. Therefore, the bioenergy constraint becomes binding at some point in the second half of the 21st century (cf. Section 3 on results).

2.4 Interaction of the models

For the EMF27 scenario analysis the three models REMIND, MAgPIE and MAGICC (Meinshausen 2011) were run consecutively (cf. SOM Figure S4). In a first step REMIND calculates the optimal mitigation strategy for the energy system. Using an emulation of the MAgPIE model REMIND takes into account the bioenergy supply curves, land use emissions and land use based mitigation potentials as described above. REMIND also includes an emulator of the MAGICC model to relate emissions to radiative forcing and temperature. Results from the land use and climate emulation in REMIND and from the subsequent post-runs in MAgPIE and MAGICC are very close to each other. The latter are reported to the EMF27 database.

2.5 Scenario definition

This analysis focuses on the EMF27 scenarios that combine different climate targets with the availability of CCS and high and low bioenergy potential. The EMF 27 scenarios cover three types of climate targets: baseline scenarios without climate protection targets (referred to as “Base”), 3.7

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[2] This emission factor was estimated from MAgPIE results and assuming a global warming potential of 298 for N_2O. Van Vuuren et al. 2010c report a similar value of 2.93 kg CO_2 eq/GJ.

W/m^2 forcing stabilization targets (not to exceed, referred to as “550”), and 2.8 W/m^2 forcing targets with overshoot (referred to as “450”). Scenarios with CCS and an upper limit of 300 EJ/yr for biomass are labeled “FullTech”. Scenarios imposing a limit of 100 EJ/yr on global bioenergy potential are referred to as “LimBio.” If a scenario excludes CCS, it is labeled “NoCCS.” A description of the full portfolio of EMF27 scenarios is given in Kriegler (this issue).

3 Results

The general finding across all scenarios shows that bioenergy is one of the major mitigation options in stringent climate policy scenarios. This paramount importance of bioenergy for achieving low-stabilization targets can be attributed to its two key characteristics: its versatility for producing different secondary energy carriers, and the option to create negative emissions by combining bioenergy with CCS. Section 3.1 and 3.2 focus on the deployment of bioenergy in the energy supply mix, and how this relates to its versatility and negative emissions capability. Section 3.3 and 3.4 investigate the value of and economic drivers behind bioenergy deployment in climate policy scenarios.

3.1 The contribution of bioenergy to primary energy supply

The REMIND baseline scenario is characterized by a strong reliance on fossil fuels. Traditional biomass is used in the first half of the century, but modern bioenergy use remains insignificant. While total primary energy demand continues to increase, deployment of fossil fuels peaks in 2070 due to increasing scarcity and is subsequently replaced with renewable sources. Solar and wind energy contribute to electricity production, whereas bioenergy replaces fossil transport fuels.

As Figure 1 (left and middle) shows, climate policy leads to earlier deployment of bioenergy and much higher long-term deployment, reaching 300 EJ/yr. While bioenergy contributes substantially to global primary energy supply in all scenarios, primary energy mixes vary considerably depending on the stringency of the climate target and the availability of technology. All climate policy scenarios show a reduction of final energy demand compared to the baseline (-16 % to -28 %, cf. SOM Figure S5), which results in a substantial decrease in primary energy demand.[3] In all climate policy scenarios, the use of conventional coal without CCS is phased out quickly after 2010 and decreases to nearly zero by 2040. In addition, only negligible or relatively small coal use with CCS is observed across the scenarios. The 550 FullTech scenario allows for higher deployment levels of oil and gas throughout the whole century compared to the 450 FullTech case. In both FullTech mitigation scenarios, gas with CCS is a mid-term mitigation option with maximal deployment around 2045. At the end of the century, fossil fuels account for approximately 30% (300 EJ) in the 550 FullTech scenario and only 10% (90 EJ) in the 450 FullTech scenario. In all policy scenarios, the expansion of modern bioenergy use begins around 2030, about 30 years

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[3] The direct equivalent method was used for primary energy accounting. Since it accounts one unit of non-biomass renewable or nuclear energy for roughly three units of fossil fuels in electricity production, it tends to understate the contribution of renewables or nuclear in primary energy supply. Reductions in primary energy are partly due to a shift from fossil fuel combustion to non-biomasss renewables and nuclear energy.

earlier than in the baseline, and evolves dynamically thereafter. The maximum potential is reached between 2040 (100 EJ in 450-LimBio) and 2080 (300 EJ in 550-FullTech). BECCS conversion routes are so attractive that bioenergy without CCS is crowded out. New conversion capacities for bioenergy are exclusively built with CCS in all policy scenarios that allow for CCS. In contrast, fossil CCS is less favored as it entails residual emissions in the REMIND model. In both FullTech policy scenarios, BECCS makes up approximately 30% (300 EJ) of primary energy at the end of the century.

In all policy scenarios, the non-biomass renewable energies - solar, wind, and hydro - have a dominant share in the power supply after 2060, of which solar comprises the majority. By 2100, their contribution reaches approximately 41% (550-FullTech) to 76% (450-LimBio) of primary energy supply.

In the 450/550-FullTech scenarios fossil fuels and industry emit 1670/2290 $GtCO_2$ from 2005-2100, of which 830/610 $GtCO_2$ (50/27%) are withdrawn by BECCS, resulting in 840/1680 $GtCO_2$ deposited in the atmosphere by 2100. Together with fossil CCS 950/770 $GtCO_2$ have been captured by 2100 (SOM Section S2.3 and S2.4).

3.2 Bioenergy: a versatile energy carrier

Due to its versatility, bioenergy assumes a unique position among non-fossil energy carriers. In contrast to nuclear or non-biomass renewables, it can be converted into different types of secondary energy. Figure 1 (right) depicts the demand of primary bioenergy for those types of secondary energy cumulated for 2005-2100. Modern bioenergy is mainly deployed in the second half of the century. The exogenously prescribed phase out of traditional biomass is not varied across scenarios.

In almost all scenarios including the baseline, bioenergy is predominantly used to produce liquid fuels. In the baseline scenario, biofuel is a substitute for increasingly scarce and costly oil in the second half of the century. Under climate policy, biofuel production with CCS has two purposes. First, it lowers emissions in the transportation sector, for which other decarbonization methods, such as electrification, are rather costly. Second, it produces negative emissions, which offset emissions from other sources (cf. Section 3.3). Only the 450-ppm scenarios (FullTech and LimBio) show capacities for dedicated electricity production from biomass using BIGCC with CCS. In all other scenarios the small amounts of bioenergy demand for electricity accompanying the dominant demand for liquids is due to the fact that electricity is a byproduct of the biomass liquefaction process represented in REMIND (cf. SOM Table S2). The BIGCC and B2H2 processes feature higher capture rates and, therefore, enable the higher negative emissions that are required in the more stringent mitigation scenarios. In general, tightening the climate target or restricting the bioenergy potential increases the deployment of technologies with higher capture rates, in order to maximize negative emissions per unit of primary bioenergy used. Consequently, the shares of BIGCC (80% capture rate) and/or hydrogen production (90% capture rate) increase from 550-FullTech to 450-FullTech, from 550-FullTech to 550-LimBio, from 450-FullTech to 450-LimBio, and from 550-LimBio to 450-LimBio. Kriegler (2013) also observe a higher share of B2H2 and BIGCC compared to B2L due to tighter bioenergy supply limited to 200 EJ/yr.

3.3 The value of bioenergy for climate change mitigation

The following sections show that bioenergy has a high value for climate mitigation. As a direct reflection of this, mitigation costs, an indicator of the economic challenges resulting from climate policy, rise sharply if bioenergy or CCS are limited (Figure 2). This indicates that without bioenergy and CCS, it is difficult to achieve low stabilization targets.

Aggregate mitigation costs are expressed in terms of consumption losses between a climate policy scenario and the corresponding baseline, in net present value terms for the period 2005-2100 and discounted at 5% per year, as a share of net present value consumption in the baseline. We find that mitigation costs depend strongly on the climate target as well as the abundance of bioenergy and the availability of CCS technologies. Increasing the stringency of the climate target from 550 ppm to 450 ppm results in almost a doubling of mitigation costs from 1.8% to 3.1%. The unavailability of CCS increases mitigation costs more (to 2.7% for 550-ppm and 10.5% for 450-ppm) than lowering the bioenergy potential from 300 EJ/yr to 100 EJ/yr (to 2.3% and 5.7% respectively). The costs for all 550-ppm scenarios lie below the 450-ppm policy costs. In the 450-ppm scenario, costs almost double (to 5.7%) if bioenergy supply is limited to 100 EJ/yr and more than triple (to 10.5%) if CCS is not available. The value of bioenergy and BECCS increases with the stringency of the mitigation target, and is particularly important for low stabilization at 450 ppm CO_2e.

BECCS is particularly valuable because its negative emissions provide an additional degree of freedom for the amount and timing of emission reductions (Kriegler 2013). Since emissions from fossil fuel combustion in earlier periods can be compensated by negative emissions at a later stage (up to 50% in the 450-FullTech scenario), negative emissions allow for the postponement of some emission reductions in the short-term and the preservation of some residual emissions in the long run. This is even more significant if overshooting of the stabilization target (in terms of radiative forcing) is allowed before 2100. Figure 2 illustrates this emission dynamics and the challenges associated with climate stabilization with full and limited technology portfolios. The graph shows CO_2 emissions over time from fossil fuel and industry with (top left) and without accounting (top right) for negative emissions from BECCS as well as the resulting CO_2 prices (bottom left). Pathways of net emissions do not depend on the availability of biomass or CCS in the 550-ppm case. In the 450-ppm scenario, BECCS in the second half of the century compensates for the emissions of the preceding decades. Limiting the bioenergy potential to 100 EJ/yr or excluding CCS strongly reduces this inter-temporal flexibility. An immediate and rapid restructuring of the energy system is required in the early decades since strong overshooting of the forcing target (by 0.7 W/m^2 as observed in the 450-FullTech scenario), is no longer possible (0.3 W/m^2 in the 450-NoCCS scenario). Consequently, carbon prices as high as 120 $/t$CO_2$ in 2020 (520 $/t$CO_2$ with NoCCS), compared to 50 $/t$CO_2$ in the FullTech scenario, are required to trigger this early transformation and to reach the 450-ppm target.

Figure 3 (left) shows that these emission dynamics directly translate into a relationship between the pathways of fossil fuels and bioenergy deployment making the short and long-term deployment of fossil fuels dependent on the long-term potential of biomass. Figure 3 (right) depicts the cumulated amounts (from 2005-2100) of fossil fuels and bioenergy for scenarios with different bioenergy availabilities scaled to the 450-FullTech scenario. Comparing the 450-LimBio with the

450-FullTech case shows the simultaneous increase of cumulated fossil fuel and bioenergy demand. Due to the creation of negative emissions, more biomass use allows for higher deployment of fossil energy. This leads to the following conclusion: while biomass is an important substitute for fossil fuels in climate mitigation scenarios, given a climate target it also displays characteristics of a complement to fossil fuels.

Figure 4 shows the additional 450-HighBio scenario (not part of EMF27 portfolio) which omits the 300 EJ/yr constraint on global bioenergy deployment. Although the bioenergy demand strongly exceeds 300 EJ/yr the corresponding amount of fossil fuels does not increase further. This is the consequence of assuming a physical limitation of the injection rate for captured carbon in REMIND. Since this limit is reached in 2060 (450-FullTech), removing the bioenergy-constraint in the 450-HighBio scenario cannot provide additional negative emissions and there is no room for additional fossil fuels. Thus, the short to long-term deployment of fossil fuels and BECCS technologies additionally depend on the rate at which CO_2 can be sequestered into geological reservoirs.

3.4 The relation between bioenergy and carbon markets

Maintaining today's fossil fuel deployment over the next decades under stringent climate policies induces a strong demand for BECCS in the second half of the century. This is reflected by the strongly increasing prices for biomass. While bioenergy prices in the Base-FullTech scenario range between 1 $/GJ in 2010 and 12 $/GJ in 2100, prices reach 32 $/GJ in the 550-ppm scenario and 73 $/GJ in the 450-FullTech scenario in 2100. Limiting bioenergy potential or excluding CCS increases bioenergy prices to 105 $/GJ and 431 $/GJ, respectively. Average production costs of bioenergy are much lower (around 6 $/GJ) indicating substantial revenues for bioenergy producers.

Figure 4 (left) reveals a strong correlation between carbon prices and bioenergy prices. This is not surprising: with increasing carbon prices, the incentive to replace fossil fuels with bioenergy increases, as do potential revenues from BECCS-generated negative emissions. The dependence of bioenergy prices on carbon prices is stronger in scenarios with CCS and somewhat weaker in the NoCCS scenario. In the climate mitigation scenarios, the value of bioenergy is determined by both its energy value *and* the value of potential negative emissions. An analysis of the revenues gained from biomass conversion demonstrates that under stringent climate targets, and in the presence of BECCS, the value of negative emissions tends to dominate over the value of the energy.

Figure 4 (right) shows the revenues from secondary energy production and captured carbon per unit of primary energy input for different BECCS power plants in 2050 and 2100 for the US and for the 450 and 550-FullTech scenario. In both scenarios, a major share of revenues from BIGCC and B2H2 plants is gained from capturing carbon, whereas revenues from energy production are relatively low. This effect is stronger at higher carbon prices (550 vs. 450 and 2050 vs. 2100). Compared to electricity and hydrogen, revenues from diesel are significantly higher since the transportation sector has fewer low-carbon alternatives to biomass than the electricity sector. Fossil liquids prices increase due to entailed carbon emissions. This drives up the demand for biofuels and the resulting prices for biofuels (cf. SOM Fig. S12 and Fig. S13 for a regional breakdown of revenues and liquid fuel prices). Thus, the B2L technology is attractive despite its lower capture rate. Only in scenarios with high carbon prices (LimBio vs. FullTech, 450ppm vs. 550ppm) technologies with higher capture rates become more favorable. The driving factor for building bioenergy conversion capacities for electricity and hydrogen production are the revenues generated from negative emissions, rather than from energy production.

4 Summary and Conclusion

The potentially negative carbon content of biomass has far-reaching consequences for mitigation strategies, mitigation costs and bioenergy deployment. Our analysis shows that BECCS can be a crucial mitigation option with high deployment levels and a high technology value, particularly for low stabilization targets. In our model results, modern bioenergy is exclusively used with CCS if this technology is available. Not having BECCS available strongly increases mitigation costs.

BECCS has impact on the timing and dynamics of emission reductions over the course of the century. Negative emissions are valuable because they increase the amount of permissible carbon emissions from fossil fuels and therefore allow postponing some emissions reductions in the short-term. Thus, for a given climate target, bioenergy acts as a complement to fossils rather than a substitute. Postponing emission reductions turns this inter-temporal flexibility into a commitment since the prolonged *short-term* deployment of fossil fuels rely on the *long-term* potential of biomass *and* the availability of CCS. Given the uncertainties about CCS technology and the concerns about the sustainability of large-scale production of bioenergy, a strong reliance on the availability of these two options could be a risky strategy.

The potential of biomass to provide negative emissions establishes a strong link between bioenergy prices and carbon prices. For low stabilization scenarios with BECCS availability, we find that the carbon value of biomass tends to exceed its pure energy value. This has consequences for the choice of BECCS technologies: with rising carbon price the capture rate becomes the crucial deciding factor in terms of which conversion routes are taken. High carbon prices (as observed in the LimBio scenarios) induce investments in technologies that would not be built for the purpose of energy production. In our scenarios these are electricity and hydrogen. However, except in the 450-LimBio scenario exhibiting higher carbon prices than all other CCS-scenarios, bioenergy is predominantly used to produce low-carbon fuels, since the transport sector has significantly fewer low-carbon alternatives to biofuels than the power sector.

The price link has another consequence: as this study shows, imposing stringent climate targets induces a strong demand for BECCS and a high willingness-to-pay for biomass. Postponing emission reductions will further increase this demand-pull for biomass. Thus, a high pressure on the agricultural sector can be expected under stringent climate policy even if production costs of purpose-grown biomass were high. In our analysis, biomass prices exceed average production costs, giving rise to considerable land rents for producers. The resulting large-scale bioenergy production potentially has unintended negative impacts on land-use systems, such as competition with food production, reduction of biodiversity, and additional GHG emissions (Wise 2009, Searchinger 2008, Fargione 2008). Imposing sustainability constraints on the production of bioenergy likely will limit the potential of bioenergy (Haberl 2010, van Vuuren 2009) as a mitigation option. Therefore, further research is needed to study the potentially far-reaching implications of connecting agricultural, energy and carbon markets. In particular, unintended side effects should be included into the assessment of bioenergy as a mitigation measure. The investigation of this climate policy induced land-energy nexus requires an integrated assessment based on fully coupled energy-economy and land use models.

5 Acknowledgements

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6 Figures

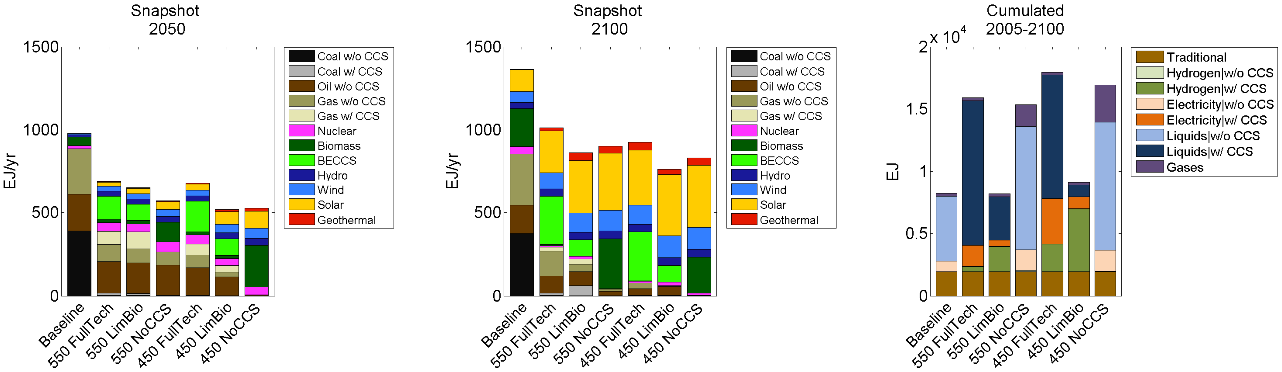
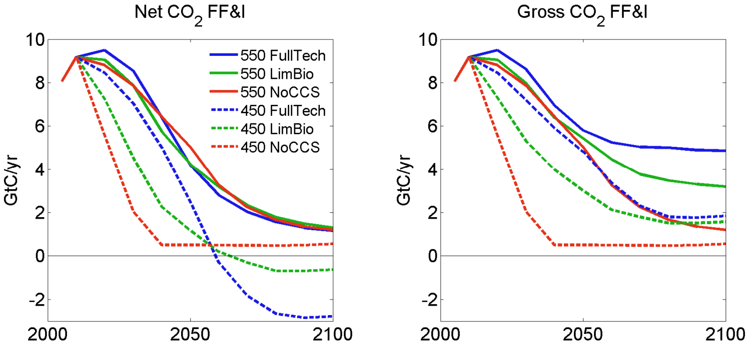


Figure 1. Demand for primary energy: in 2050 (left) and 2100 (middle); demand for bioenergy across technologies cumulated from 2005 to 2100 (right).



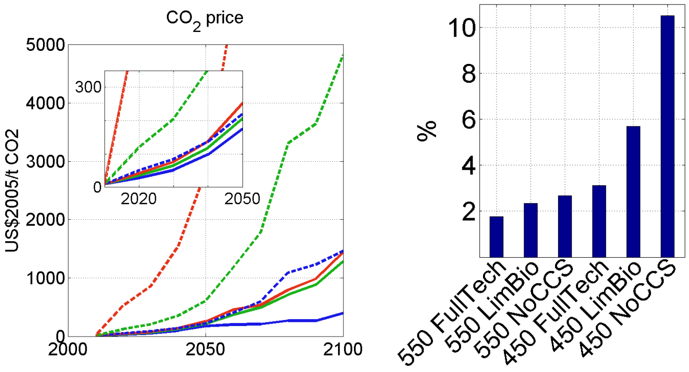


Figure 2. Dynamics of mitigation across scenarios: CO_2 emissions from fossil fuel and industry (FF&I) including negative emissions (top left) and without negative emissions (top right); CO_2 prices over time (bottom right); mitigation costs (discounted and cumulated consumption losses 2005-2100), (bottom right).

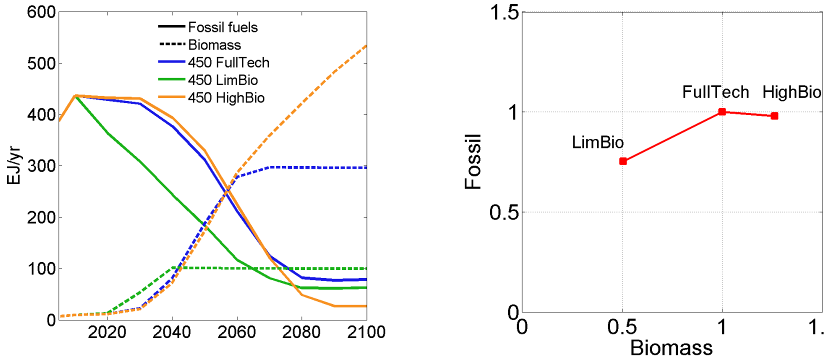


Figure 3. Demand for bioenergy and fossil fuels over time (left) and cumulated from 2005-2100 scaled to the 450-FullTech scenario (right).

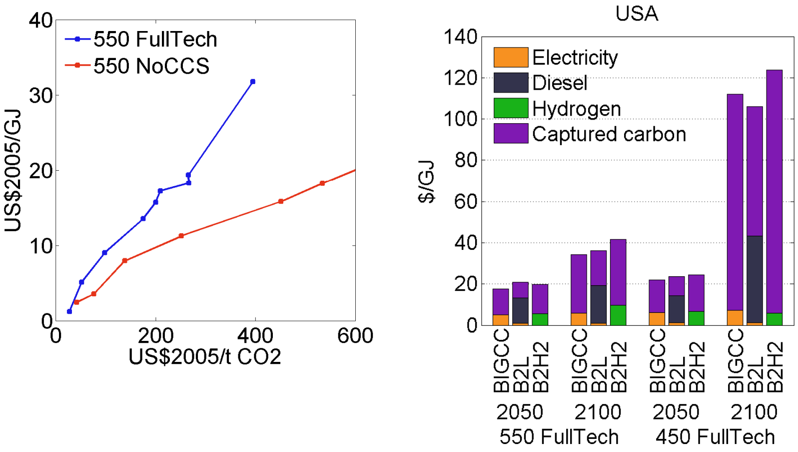


Figure 4. Value of energy versus value of carbon: global average bioenergy price versus carbon price (left). Revenues from energy production and negative emissions across technologies for USA (right);

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