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Competing uses of biomass for energy and chemicals: implications for long-term global CO_2 mitigation potential

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Abstract

Biomass is considered a low carbon source for various energy or chemical options. This paper assesses it's different possible uses, the competition between these uses, and the implications for long-term global energy demand and energy system emissions. A scenario analysis is performed using the TIMER energy system model. Under baseline conditions, 170 EJ yr^{-1} of secondary bioenergy is consumed in 2100 (approximately 18% of total secondary energy demand), used primarily in the transport, buildings and nonenergy (chemical production) sectors. This leads to a reduction of 9% of CO_2 emissions compared to a counterfactual scenario where no bioenergy is used. Bioenergy can contribute up to 40% reduction in emissions at carbon taxes greater than 500/tC. As higher CO_2 taxes are applied, bioenergy is increasingly diverted towards electricity generation. Results are more sensitive to assumptions about resource availability than technological parameters. To estimate the effectiveness of bioenergy in specific sectors, experiments are performed in which bioenergy is only allowed in one sector at a time. The results show that cross-sectoral leakage and emissions from biomass conversion limit the total emission reduction possible in each sector. In terms of reducing emissions per unit of bioenergy use, we show that the use of bioelectricity is the most effective, especially when used with carbon capture and storage. However, this technology only penetrates at a high carbon price (>100/tC) and competition with transport fuels may limit its adoption.

Keywords: bioenergy, climate policy, competing biomass applications, cross-sectoral leakage, energy system modelling, scenario analysis

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Introduction

The use of biomass as a renewable source for energy and chemical purposes and as an emission mitigation measure has received much attention (Chum *et al*., 2011; GEA, 2012; IEA, 2013). From an energy perspective, the use of biomass is attractive given its potentially low greenhouse gas emissions and the ability to relatively easily replace fossil fuels in many parts of the energy system. Biomass-based energy carriers (bioenergy) can be used in transport, as heating or cooking fuels in households, or for conversion into electricity. Biomass can also replace fossil fuels in nonenergy purposes as a feedstock for the production of bulk chemicals (biochemicals) (Dornburg *et al*., 2008). Analyses using integrated assessment models (IAMs) have highlighted the importance of biomass use in the energy system to meet emission reduction targets (van Vuuren *et al*., 2007, 2010; van Vliet *et al*., 2009; Luckow *et al*., 2010; Calvin *et al*., 2013; Rose *et al*., 2014). At the same time, however, there are considerable questions with regard to the sustainable potential of biomass given the competition for land, the cost of conversion of biomass-to-bioenergy or biochemicals and the possible direct and indirect greenhouse gas emissions during the production of biomass and its conversion (Beringer *et al*., 2011; Dornburg *et al*., 2010; Haberl *et al*., 2010; Searchinger *et al*., 2008; van Vuuren *et al*., 2009).

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The effectiveness of bioenergy at reducing emissions depends, among others, on which fuel it replaces. Several studies have looked at specific uses of biomass in energy systems and associated emission reductions (Dornburg & Faaij, 2005; Azar *et al*., 2010; Klein *et al*., 2011; Schmidt *et al*., 2011; Taibi *et al*., 2012; Daioglou *et al*., 2014). However, the implications for the remaining energy system are important. Displacing fossil fuels from one use makes them available for use elsewhere, potentially leading to cross-sectoral leakage. The study of leakage has focused on economic equilibrium models with a weak representation of physical parameters such as demand functions and technologies. Furthermore, there is a wide range and uncertainty on the elasticities used in most of these studies (Rajagopal *et al*., 2011; Thompson *et al*., 2011). A more descriptive explanation of leakage may indicate that several dynamic factors play a role, for instance, related to sectors responding differently to different emission taxes and available fuels. Also time-dependent impacts (e.g. related to learning) could further complicate the matter. In other words, a detailed description of the energy system is needed for a better understanding of the share and location of final energy, which can be substituted by bioenergy.

Given the uncertainties and the potentially important role assigned to bioenergy for emission mitigation, a key question is what its best use in the energy system is. It is also important to investigate how competition between different biomass uses may limit its deployment to uses which would provide greater emission reductions. Recently, Creutzig *et al.* (2012) argued that existing assessments are insufficient owing to limitations of system representation, ignoring market factors or narrow exploration of solution space in IAMs.

This study seeks to address some of the above issues by investigating how biomass may contribute to long-term energy and chemical demands and its effect on energy system emissions under different circumstances. We use the TIMER energy system simulation model whose projections of bioenergy and biochemical use and the associated emission reductions are assessed for a number of scenarios. First, total and sectoral (industry, transport, etc.) bioenergy use is projected under a baseline, and the effect of uncertainties on land availability and biomass-to-bioenergy/biochemicals conversion technologies are investigated. Following, to gain insight into the competing applications of biomass and their emission implications, scenario projections where the conversion of biomass is limited to a specific end-use sector are made. This provides insight into how different biomass uses may displace fossil fuels and thus lead to overall emission changes including second order effects such as cross-sectoral leakage. Finally, the marginal emission reduction due to biomass, per end use, is investigated by looking into impacts of increasing a tax on the carbon content of energy carriers. By comparing the results of specific biomass uses with the possibility where it is allowed to be used freely in the energy system, we get insights into the effectiveness of different biomass strategies at reducing emissions, as well as the effect of competition for this limited resource. This analysis is done on a global scale and with a long-term time horizon (2100). Thus, the study takes into account long-term energy use projections as energy demand and supply evolve.

The rest of the paper is structured as follows. First definitions and the system description are outlined followed by a description of the scenarios and indicators used to present the results. Also presented are the energy and emission projections of the baseline scenario. The results section presents the results of the study. Finally, the discussion outlines the uncertainties of the model and the projections, provides a comparison to existing literature and highlights the main results of the study.

Materials and methods

Definitions

Throughout this paper, unless otherwise stated, biomass is defined as a primary energy source. Bioenergy is the use of biomass-based energy carriers (solid or liquid) produced from crops or residues to provide energy services of the end-use sectors. The use of these energy carriers specifically for nonenergy purposes such as a feedstock for the production of bulk chemicals is called biochemicals. According to the TIMER model, the energy system is disaggregated into different end-use sectors: industry, transport, buildings, nonenergy and rest. Nonenergy incorporates the nonenergetic use of energy carriers (as feedstocks) for the production bulk chemicals (ethylene, ammonia, methanol, etc.) while a small fraction of energy carrier also used as a process fuel. 'Rest' includes nonspecified uses as defined by the IEA (excluding residential, commercial and public services). Besides these 'final demand' sectors, we also account for biomass use in the electricity sector, and thus account for its possible conversion into that energy carrier. Note that electricity is not a final demand sector but rather a conversion sector which supplies the final demand. Unless stated otherwise, energy demand is presented in secondary energy terms (i.e. GJ_{sec}) and energy carriers included are coal, oil, gas, bioenergy, electricity and other (includes traditional biomass use in poor households, hydrogen, nuclear, solar, wind, hydropower and waste). Note that the use of traditional biomass, though included in the model, is not analysed in this study as it is assigned to the other energy carrier.

CO_2 emissions are accounted by assuming that the carbon content of a fossil-based secondary energy carrier is released upon combustion. Thus, given the secondary energy demand of each end-use sector, we can determine each sector's emissions. In the nonenergy sector, fuels are not necessarily combusted and carbon may be 'sequestered' in the form of plastics and chemicals. A detailed description of how the TIMER model deals with this can be found in Daioglou *et al.* (2014). For the end-use sectors (industry, transport, buildings, nonenergy and rest) we only look at direct emissions and thus exclude electricity, which is presented separately to avoid double counting.

To get a complete picture of the emission effects of increased bioenergy/biochemical use, it is interesting to investigate how emissions from the supply of secondary energy may be affected. Thus, we include an additional emission sector called 'energy supply'. The TIMER model includes an 'own energy use' to produce fossil fuels which leads to certain emissions. Concerning biomass, the model takes into account emissions from nonrenewable fuel use in bioenergy production (as presented in Table 1) as well as net emissions due to the displacement of natural vegetation. For the latter, it assumes emissions to be 5–7 kgC/GJ_{Prim}, varying across regions. The emission factor has been determined using the IMAGE model as described by Otto *et al.* (2014). This is done by comparing two extreme runs: in which (i) no biomass is grown, and (ii) biomass is grown on all the available land. The difference in the land-based carbon stocks over the projection period, together with the yield of biomass leads to an emission factor in kgC/GJ_{prim}. Indirect land use change is not accounted for and the interaction of biomass growth with agriculture is beyond the scope of this paper.

System description

The TIMER model is a recursive dynamic simulation model of the energy system. Results depend on a single set of deterministic algorithms, according to which the system state in any future year is derived entirely from previous system states (van van Vuuren *et al*., 2014). The model projects the development of the energy system and its emissions and has been used to assess possible future energy system emission pathways (van Vuuren *et al*., 2007; Rose *et al*., 2014). Energy demand is determined for specific energy functions on the basis of assumptions on population and economic growth, and is met by investments in energy consuming technologies. The model includes key dynamics such as autonomous and price-induced energy efficiency improvements which lower the demand, stock-turnover accounting, trade of energy carriers and learning by doing which leads to cost reductions in technologies. The model has been calibrated to reproduce the IEA energy balances for the period (IEA, 1971-2005).

Energy supply is based on the cost-supply curves of different primary energy carriers (Rogner, 1997; Mulders *et al*., 2006). For nonrenewable sources, these are formulated in terms of cumulative extraction; for renewable sources, these are formulated in terms of annual production. Subsequent equations describe how primary resources are converted to secondary energy carriers at a given efficiency and cost (including capital and operation and maintenance costs). If multiple secondary energy carriers can be used for a given energy function, they compete based on their relative costs (and preference levels), where the cheapest fuel gets the largest market share based on a multinomial-logit model. Electricity demand is met by the power generation sector, which in turn has a demand for energy carriers. Climate policy is modelled by introducing a carbon tax based on the carbon content of the fuels, thus changing their relative costs.

For the production of bioenergy (or biochemicals), the entire supply chain from land availability, biomass production and conversion into energy carriers is modelled. The yields of energy crops and land availability are taken from the IMAGE model and are based on the methodology used by Hoogwijk *et al.* (2005). Biomass can be grown on abandoned agricultural land or 'rest' lands which exclude land used by urban developments, agriculture, natural forests and unsuitable lands. Land availability and crop yields on different land types determine the available biomass resource. As more biofuels are used, energy crops are expanded onto less productive lands, increasing production costs and creating a cost-supply curve. Primary biomass can also be supplied by residues whose potential is exogenously set based on a literature review (Berndes *et al.*, 2003).

Biomass can be converted into solid or liquid secondary energy carriers. Potential bioenergy carriers include Fischer–Tropsch (FT) diesel, wood-based ethanol or methanol, maize ethanol, wheat ethanol, sugar ethanol or oil crop biodiesel. The final makeup of liquid biofuels is determined based on the relative cost of each of the above routes, where the cheapest route gets the largest market share. Solid biofuels can be produced from dedicated energy crops as well as residues. The technoeconomic parameters for biomass conversion technologies used in the TIMER model are shown in Table 1. Literature sources indicate a large range in technoeconomic parameters, especially for future values of conversion efficiency and investment costs. Pessimistic values reported in literature are investigated in the scenario analysis and shown in brackets in Table 1.

For a more detailed description of how the TIMER model represents the energy system, see van van Vuuren *et al.* (2014). For a detailed description of the energy demand functions, see Roorda & Neelis (2006), Boskaljon (2010), Daioglou *et al.* (2012), Girod *et al.* (2012) and Daioglou *et al.* (2014).

Scenarios

In this study we use the TIMER model to do a detailed investigation on the contribution of bioenergy or biochemicals to long-term emission reductions of the energy system. We assess how much they can contribute to total demand, where they are used and how their use is affected by assumptions on primary availability and technoeconomic parameters of biomass conversion. Following, we look into how competing uses may affect its overall effectiveness in reducing emissions.

The role of biomass in the energy system is context dependent: For instance, the question of how effective biofuels are in transport depends on alternative fuel options, total transport energy demand and the cost and efficiency of conversion technologies to produce the biofuels. These factors further depend not only on key interrelationships within the energy system but also on uncertain developments in each demand sector regarding future energy demand and the costs of different technologies. Our analysis, therefore, needs to be done in the context of a baseline scenario. On the basis of this baseline, we run a number of scenarios to investigate the effect of key uncertainties concerning biomass availability and its conversion (System Bioenergy Scenarios). To assess the

Table 1 Technical and cost parameters of the TIMER model for different biofuel production routes*,†

	Year	FT Diesel	Wood Ethanol	Wood Methanol	Maize Ethanol	Wheat Ethanol	Sugar Ethanol	Oilcrop Biodiesel
Conversion Efficiency (%) ‡	Present	40.5	40.7 (34.9)	60.0 (48.0)	53.1	51.1 (48.8)	45.4§	45.2 (33.8)
	2050	48 (40.5)	49.0 (34.9)	57.0 (48.0)	59.0 (53.1)	54.3 (48.8)	54.9 (45.4)	47.6 (33.8)
	2100	51 (40.5)	52.0 (34.9)	57.0 (48.0)	64.2 (53.1)	58.4 (48.8)	65.3 (45.4)	47.6 (33.8)
Investment Costs ($\$_{2005}$/ $kW_{biofuel}$) **	Present	1961 (2199)	1683 (2536)	1024 (1490)	551 (755)	662 (739)	535 (804)	689 (1299)
	2050	1931 (2160)	1655 (2527)	487 (742)	537 (737)	651 (732)	435 (592)	683 (1295)
	2100	1895 (2146)	1597 (2527)	386 (576)	537 (737)	651 (732)	398 (589)	683 (1294)
O&M Costs (% Of Investment Cost)	Constant	1.8	2.3	2.4	3.6	3.2	5.5	4.8
Electricity Demand††	Present	–	0.12	0.07	0.02	–	−0.01	–
	2050		0.08	0.002			−0.06	
Heat Demand ($GJ/GJ_{biofuel}$)	Present	–	–	–	0.55	0.37	–	0.04
	2050					0.3		
Coproduct benefits ($\$_{2005}$/ $GJ_{biofuel}$) ‡‡	Constant	0.9	1.6	–	3.0	3.4	0.4	1.3
Process Emission§§ Factor (kgC/ $GJ_{biofuel}$)	Present	–	5.4	3.2	7.5	4.4	–	0.5
	2050		2.4	0.1	6.0	2.9		0.4

Pessimistic data used in scenario analysis shown in brackets.

References: (Hamelinck & Hoogwijk, 2007; Macedo *et al.*, 2008; Chum *et al.*, 2011; Seabra & Macedo, 2011; Gerssen-Gondelach *et al.*, 2014).

*Data show that installations with high capacities have lowest costs and highest efficiencies, and vice-versa for small capacity installations (Gerssen-Gondelach *et al.*, 2014). Unless otherwise stated, default values of table quotes values based on average capacities, pessimistic values based on small capacities.

†For *Investment Costs*, and *Process Emission Factor*, parameters may vary across regions. Global averages are presented.

‡Based on Higher Heating Value. Future improvements largely based on increased capacity.

§Studies for autonomous distilleries producing only ethanol shows current ethanol yields at 86.3 $l_{ehtanol}/t_{cane,wet}$ and future yields at 91 $l_{ethanol}/t_{cane,wet}$. We convert to energy terms assuming a sugarcane HHV of 4.5 $MJ/_{kgcane,wet}$.

**Projections are based on endogenous learning by doing. According to the projections, wood methanol has the largest cost reductions, since it is the preferred technology.

††Electricity and heat demand is allocated to production of fuel, i.e. no allocation to possible by-products and based on values from Hamelinck & Hoogwijk (2007). No values for electricity or heat requirement quoted for FT diesel. Sugarcane ethanol cogenerates electricity from surplus bagasse.

‡‡Based on sale of coproducts such as glycerin, animal feed and cogenerated electricity in the case of sugarcane ethanol. Price of electricity based on TIMER projections.

§§Emission of conversion process only. Based on electricity and heat demand multiplied by emission factors of electricity and heat as projected by the TIMER model.

effectiveness of different biomass uses and how competition may limit this, we run a set of scenarios where bioenergy is limited to a specific end use, including biochemicals (BioSector scenarios). We compare all projections to a counterfactual scenario that assumes no use of biomass at all. The complete list of scenarios is:

1. Baseline: All end-use sectors compete for biomass. Economic and demographical projections are based on the OECD Environmental Outlook baseline (OECD, 2012). The main assumptions and projections of this scenario are described in *Baseline Projections*.
2. System Bioenergy Scenarios
   - BioLowPot: Same as *Baseline* with half land and residue availability.
   - BioLowTech: Same as *Baseline* with pessimistic parameters for biomass-to-bioenergy conversion technologies (Table 1).

3. Sectoral Bioenergy Scenarios: Potential and technoeconomic assumptions same as *Baseline* scenario. Collectively referred to as *BioSector* scenarios.
   - BioBuildings: Bioenergy is only used in the buildings sector. This includes the residential and service sectors, where it may be used as a heating or cooking fuel.
   - BioNon-energy: Biomass is only used as a feedstock or process fuel for the production of bulk chemicals such as ethylene, ammonia, methanol, waxes and lubricants (Biochemicals).
   - BioElectricity: Biomass is used for electricity production (which may then be used in energy consuming sectors). This option also allows for bioelectricity with carbon capture and storage (BECCS).
   - BioIndustry: Bioenergy is only allowed in the industry sector. This option also allows for BECCS – as part of cement, steel and heavy industry production processes.
   - BioTransport: Bioenergy is only allowed in the transport sector.
4. NoBio: This is a counterfactual to the baseline where bioenergy is not allowed in the energy system. It acts as the reference case to which all other scenarios are compared to investigate the effect of bioenergy use.

We run all cases described above with carbon taxes ranging from 0 to 700 US$/tC, applied to the carbon content of all energy carriers used within the entire system. As these taxes increase, the competitiveness of bioenergy changes in different sectors as each sector has varying emission abatement or fuel substitution possibilities. The experiments thus provide insight into the marginal energy choices and emission reduction potential of each sector for different tax levels. It is assumed that the carbon tax is applied instantaneously in 2015 and remains constant for the entire simulation period. The model outcomes induced by these taxes are presented in cumulative terms for the period 2015 to 2100.

The BioSector scenarios (and all tax scenarios) are stylised scenarios in the sense that they are not intended to show expected developments of the energy system, but rather to highlight potentials and feedbacks under specific circumstances. Instead of looking at the 'optimal mix' of bioenergy use, we conduct a systematic analysis of bioenergy and its specific uses.

Indicators

For each scenario, we calculate the differences in sectoral or total (sum of all sectors) emissions with respect to the NoBio scenario; referred to as the Cumulative Emission Change (CEC). The Total Cumulative Emission Change (TCEC) indicates the sectoral and total emission changes due to different uses of biofuels. It is calculated via Eqn (1).

$$\mathrm{TCEC}_s = \sum_{2015}^{2100} \mathrm{Emis}_{\mathrm{s,Scen}} - \sum_{2015}^{2100} \mathrm{Emis}_{\mathrm{S,Nobio}} \tag{1}$$

where Emis is the annual CO_2 emissions, S denotes the emitting sector (including total) and *Scen* refers to the specific scenario. The marginal effects of the carbon tax are captured by the Marginal Cumulative Emissions Change (MCEC). This is the value for the TCEC by running the sectoral scenarios for different carbon taxes. It is described by Eqn (2).

$$\mathrm{MCEC}_s = \left[\sum_{2015}^{2100} \mathrm{Emis}_{\mathrm{s,Scen}}\right]_{\mathrm{tax}} - \sum_{2015}^{2100} \mathrm{Emis}_{\mathrm{S,Nobio}} \tag{2}$$

The MCEC shows emission reductions due to changes in the energy system as a whole. Thus, in addition to an increase in biomass use, it also includes emission reduction methods such as fuel switching to clean(er) fuels and structural changes leading to reduced demand. To correct for this and to be able to isolate the contribution of biomass, the Bioenergy Marginal Cumulative Emissions Change (BMCEC) is also calculated. This compares the CEC of each scenario at different carbon taxes with respect to the *NoBio* case with the same tax. BMCEC is described by Eqn (3).

$$\mathrm{BMCEC}_{\mathrm{Scen,s,tax}} = \sum_{2015}^{2100} \mathrm{Emis}_{\mathrm{s,Scen,tax}} - \sum_{2015}^{2100} \mathrm{Emis}_{\mathrm{S,Nobio,tax}} \tag{3}$$

Note that at a 0 tax level, TCEC = MCEC = BMCEC. Finally, to determine the effectiveness of bioenergy at reducing total emissions, we determine total emission reductions (due to bioenergy) per unit bioenergy use. This effectiveness changes across carbon taxes as abatement technologies such as BECCS become cost-effective:

$$\mathrm{BioEff}_{\mathrm{Scen,total,tax}} = \frac{-\mathrm{BMCEC}_{\mathrm{Scen,total,tax}}}{\text{Cumulative Bioenergy Use}_{\mathrm{Scen,total,tax}}} \tag{4}$$

Baseline projections

The baseline assumptions (population, economic growth and primary potential of energy sources) are based on the OECD Environmental Outlook (OECD, 2012). In this baseline, the total potential of primary woody biomass and residues in 2050 is projected to be 174 $\mathrm{EJ_{prim}\ yr^{-1}}$ and 72 $\mathrm{EJ_{prim}\ yr^{-1}}$, respectively. By 2100 these increase to 299 $\mathrm{EJ_{prim}\ yr^{-1}}$ and 81 $\mathrm{EJ_{prim}\ yr^{-1}}$. These increases in primary potential are driven by increased yields of woody and food crops, changes in land availability and assumed increases in residue availability (Berndes *et al.*, 2003; Hamelinck & Hoogwijk, 2007; van Vuuren *et al.*, 2009).

Key projections of this baseline are shown in Table 2. The tenfold increase in economic activity coupled with an increasing population leads a secondary energy demand of approximately 920 EJ $\mathrm{yr^{-1}}$ in 2100. The overall increase in energy demand coupled with resource scarcity drives up the projected energy prices as seen by the increase in the price of oil, gas and to a lesser extent, coal and primary biomass. Note that all these prices are determined endogenously (System Description). The relatively constant price of coal is due to its large resource base.

Figure 1 shows the development of secondary energy demand (left) and emissions (right) per sector for the baseline. We also show the total electricity produced to highlight its important role in future energy systems. Secondary energy

Table 2 Key indicators of the baseline. Prices of primary energy carriers based on projections of TIMER

Year	Gross World Product (Trillions $\$_{2005}$)	World Population (Millions)	Price of Oil ($\$_{2005}/GJ_{Prim}$)	Price of Coal ($\$_{2005}/GJ_{Prim}$)	Price of Gas ($\$_{2005}/GJ_{Prim}$)	Price of Biomass ($\$_{2005}/GJ_{Prim}$)
2010	50	6927	8.2	1.6	3.4	4.5
2020	72	7691	9.9	1.8	3.8	4.3
2030	100	8321	11.0	2.1	5.4	4.5
2040	137	8810	11.4	2.2	6.2	5.0
2050	182	9154	11.9	2.2	6.4	5.3
2060	240	9502	14.5	2.2	6.9	5.5
2070	308	9683	16.7	2.2	7.7	5.8
2080	387	9725	18.3	2.3	8.5	6.1
2090	473	9661	18.9	2.3	9.9	6.5
2100	565	9555	19.6	2.3	10.5	6.6

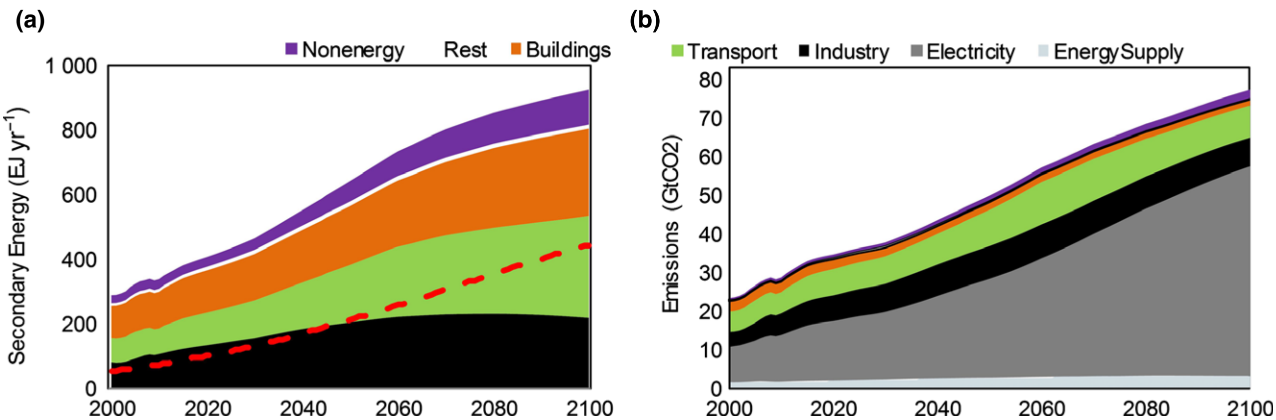

Fig. 1 Baseline scenario. (a) Global secondary energy demand per sector and total electricity demand (dashed red line). (b) Energy-system emissions per end-use sector and electricity generation.

demand is driven by large increases in the buildings and transport sectors, which together account for almost two-thirds of the total demand. The baseline projection shows that both nonenergy and industry see modest growth, which flattens out towards the end of the century.

The results show that in the baseline oil loses its dominant position in the second half of the century, making up only 19% of total secondary energy use (detailed results shown in Table S1 baseline scenario). However, it is still widely used in transport and industry. Gas, bioenergy and coal represent 12%, 18% and 6% of all secondary energy use. Bioenergy use is driven by its competitiveness with oil and gas, leading to significant use in the transport, buildings and nonenergy (biochemicals) sectors, which have many oil and gas-based energy functions. By 2100, it is projected that over 40% of the secondary energy demand is due to electricity demand used significantly in buildings, industry and transport. Electricity is increasingly generated by coal which makes up almost 70% of the fuel share by 2100.

Total emissions are projected to increase from approximately 31 $GtCO_2\ yr^{-1}$ today to 77 $GtCO_2\ yr^{-1}$ in 2100. Most emission increase is projected to come from coal-based electricity which by 2100 is responsible for almost 54 $GtCO_2\ yr^{-1}$. The transport sector, being the major energy demand sector, is the second main contributor to emissions at 8 $GtCO_2\ yr^{-1}$, or 11% of total emissions in 2100. In the latter part of the century, a shift towards electric transport (driven by the rapid increase in oil prices) means that despite an increase in energy demand for transport, the annual emissions (at point of consumption) stabilise and decrease slightly towards the end of the century. Heavy industry is the third largest emitter (7 $GtCO_2\ yr^{-1}$ in 2100) due to its large size and significant use of coal. Fuel use in the nonenergy, buildings and 'rest' sectors contribute very little to global emissions either because they depend mainly on electricity, the energy use of the sectors is small or, in the case of nonenergy, not all fuel use leads to emissions. Due to increased electrification as well as bioenergy use, the buildings sector is projected to reduce its direct emissions.

Results

In the following sections, we outline the results of the scenario analysis. Quantitative results for all scenarios are summarised in the Supplementary Information.

Baseline and uncertainty scenarios

In the *NoBio* scenario, total cumulative CO_2 emissions are 5099 $GtCO_2$ while in the Baseline scenario these are lower at 4652 $GtCO_2$, representing a 9% decrease in emissions due to bioenergy. This difference mainly comes from the transport and buildings sectors; here emissions are projected to be 26% and 50% lower, respectively due to bioenergy use. This is an absolute reduction of 267 GtCO2 and 170 $GtCO_2$ for transport and buildings, respectively. Emissions from the energy supply sector increase from 174 $GtCO_2$ (*NoBio*) to 237 $GtCO_2$ (*Baseline*) due to the production of bioenergy.

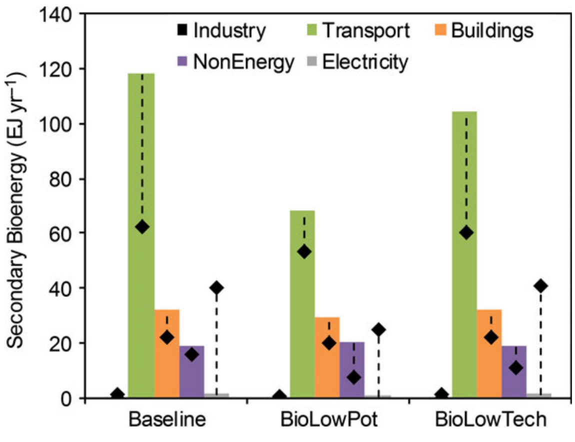

Fig. 2 Sectoral bioenergy use in 2100 for the Baseline, BioLowPot and BioLowTech scenarios. The dashed black lines show the effect of a 700$/tC tax.

In the *Baseline* scenario, the use of bioenergy is projected to be 74 EJ yr^{-1} in 2050 and 170 EJ yr^{-1} in 2100, or 18% of total secondary energy demand. This is approximately 46% and 70% of the primary potential in 2050 and 2100, respectively. Energy crops (mostly woody) account for 71% and 79% of primary biomass in 2050 and 2100, respectively, the rest coming from residues. This leads to a land requirement of 209 Mha in 2050 and 462 Mha in 2100. From the total bioenergy use, 69% is used in the transport sector, 19% in buildings, nonenergy accounts for 11% and 1% is used for electricity production.

As shown in Fig. 2 (more details are provided in Table S1 in the appendix), in the *BioLowPot* scenario where biomass potential is halved, total bioenergy use is limited to 118 EJ yr^{-1}. This affects energy use and emissions of transport, with negligible changes in buildings and nonenergy. Total cumulative emissions with respect to *NoBio* decrease by 7% (Table 3). For the *BioLowTech* scenario, the changes are similar but less pronounced, which shows that the baseline projections are more sensitive to the overall biomass availability than the techno-economic parameters. In this case, total cumulative emissions with respect to *NoBio* decrease by 8%.

Table 3 Sectoral and Total cumulative emission (2015-2100) as well as BMCEC for NoBio, Baseline, BioLowPot on BioLowTech scenarios, with and without a 700$/tC tax ($GtCO_2$). Table does not contain energy supply emissions*

Sector	Industry	Transport	Buildings	Nonenergy	Electricity	Rest	Total
NoBio	696	1021	340	118	2707	43	5099*
Baseline	680	754	170	108	2661	43	4652
BioLowPot	681	873	179	108	2676	43	4766
BioLowTech	680	803	168	108	2668	43	4699
With tax							
NoBio + tax	335	662	251	52	267	24	1713
Baseline + tax	324	581	142	38	−313	20	1019
BioLowPot + tax	326	585	139	44	−108	22	1189
BioLowTech + tax	324	574	141	41	−343	23	991
BMCEC							
Baseline	−16	−267	−170	−11	−46	0	−447
BioLowPot	−14	−148	−161	−10	−31	0	−332
BioLowTech	−16	−218	−172	−10	−39	0	−400
With tax							
Baseline + tax	−11	−81	−109	−15	−580	−4	−694
BioLowPot + tax	−9	−77	−112	−8	−375	−2	−524
BioLowTech + tax	−11	−88	−110	−11	−610	−1	−722

*Included in the Total but not shown in this table are the emission changes in the energy supply sector. These are 174GtCO2 *(NoBio)*, 237GtCO2 *(Baseline)*, 206GtCO2 *(BioLowPot)* and 229GtCO2 *(BioLowTech)*.

To simulate significant emission mitigation efforts, we apply a 700$/tC tax on the cost of energy carriers. The energy system reduces emissions via fuel switching, reduced demand, or adoption of technologies such as carbon capture and storage. Cumulative emissions for the NoBio + tax case reduce to 1713 $GtCO_2$. The *Baseline + tax* scenario can further reduce emissions to 1019 $GtCO_2$ via the increased use of bioenergy. While all sectors reduce emissions due to bioenergy use, there is a huge change in the electricity production sector. At high tax levels, BECCS becomes an important mitigation technology leading to large emission reductions in this sector. Similar dynamics but to a lesser extent are seen in the *BioLowPot + tax* scenario whose cumulative emissions are 1189 $GtCO_2$. Interestingly, in the *BioLowTech + tax* scenario, the cumulative emissions are lower than the *Baseline + tax* scenario (991 $GtCO_2$) as more negative emissions due to electricity with BECCS are achieved. Reduced possibilities to produce liquid biofuels increase the availability of biomass for electricity generation. The effectiveness of bioenergy use under competing possibilities is the focus of the remainder of this paper.

BioSector scenarios

By systematically limiting bioenergy use to a specific end-use sector, we can investigate the indirect effect of fossil fuel leakage between different end-use sectors. Figure 3 shows the TCEC for the *Baseline* and each of the cases when bioenergy use is limited to a single sector (*BioSector*). In *BioIndustry* and *BioTransport*, much of the expensive oil in these sectors is easily replaced by bioenergy. As the displaced oil is still too expensive to be used in the remaining sectors, leakage is limited. Furthermore, bioenergy in transport also reduces total electricity demand leading to a small reduction in the electricity sector as well, while the large production of liquid biofuels leads to a significant increase in energy supply emissions. For the *BioBuildings* case oil and gas are replaced leading to leakage towards electricity and transport. For *BioNon-energy* bioenergy primarily replaces gas (and smaller amounts of coal and oil). This leads to more oil use in transport (increasing its emissions), and more gas use in electricity (decreasing its emissions by replacing coal). Also, the large decrease in overall gas demand leads to significant reduction in energy supply emissions. The overall reduction in the nonenergy sector is low because of its small size, and specifically for this sector the carbon contained in fossil fuels is not necessarily emitted and may be stored in the form of plastics and chemicals (see Definitions). In the BioElectricity case, there is some leakage of oil towards transport and coal towards industry. These however only partially counteract the large emission reduction in the electricity sector.

In almost all scenarios, the transport sector shows emission increases due to leakage of fossil fuels induced by bioenergy use elsewhere. This sector is quite large and depends heavily on oil and to a lesser extent gas, which tend to be the marginal fuels replaced in the rest of the energy system. In the cases where coal or gas is replaced, the electricity or industry sectors accept the leaked fuel.

When looking at the emissions of specific sectors, Fig. 3 also shows how the sectoral emission reduction potential may be affected by competing uses of bioenergy. As expected, for any given sector, its emission reductions are greater in the BioSector than in the Baseline scenarios (as the availability of bioenergy is not shared with the rest of the energy system or it does not accept leaked fossil fuels). This can best be seen for the electricity sector where bioenergy availability decreases the cumulative emissions by 46 $GtCO_2$ in the *Baseline* case (with respect to *NoBio*), while in BioElectricity it reduces by 217 $GtCO_2$. Total emissions reduction, however, is largest in the Baseline case where both transport and buildings can mitigate emissions significantly.

Marginal emission changes

Figure 4 shows the marginal sectoral emission changes (MCEC and BMCEC) between *NoBio* and *Baseline* as the carbon tax increases. Detailed results on energy use for the baseline at all tax levels are shown in Table S2. The MCEC shows that as carbon tax increases, a very large contribution eventually comes from the power sector. This is in contrast with low tax levels where emissions reductions come from transport and buildings. The power sector has the largest abatement potential for three reasons; (i) it has the largest demand for energy and thus largest potential for substitution, (ii) it is the largest emitter due to the heavy use of coal and (iii) it can adopt carbon capture and storage (CCS) technologies at high carbon prices (greater than 100$/tC). While at high tax levels, transport, buildings and industry also contribute to the mitigation potential; their contribution to total mitigation is much smaller than the power sector.

The BMCEC (bottom panel, Fig. 4) shows that bioenergy contributes to the marginal emission reduction in buildings and transport; however, this decreases with increasing taxes. As the tax level increases, the share of bioenergy use increases in nonenergy, electricity and to a lesser extent industry (see Table S2). Increased use of bioenergy in these sectors means that its use decreases in buildings and transport. The main reason is that bioenergy is an attractive substitute (especially in combination with CCS) for coal in the electricity, industry and nonenergy sectors. Buildings and transport instead shift towards other energy carriers (gas and electricity, respectively) and also reduce total demand at high carbon prices.

At tax levels above 100\$/tC, biomass use with carbon capture and storage (BECCS) in industry and electricity starts becoming increasingly important. This leads to the possibility of negative emissions (see Table S3). Overall, as the carbon tax increases (700\$/tC), secondary energy demand decreases to 640 EJ yr^{-1} in 2100. The fraction of bioenergy for nonelectric uses decreases from 18% to 16%. At high taxes (greater than 500\$/tC), biomass and other nonfossil energy sources make up over 80% of electricity sources.

Table 4 shows the change in the energy system cumulative emission (MCEC) due to taxes for the *NoBio*, *Baseline* and *BioSector* scenarios. As expected, the *NoBio*

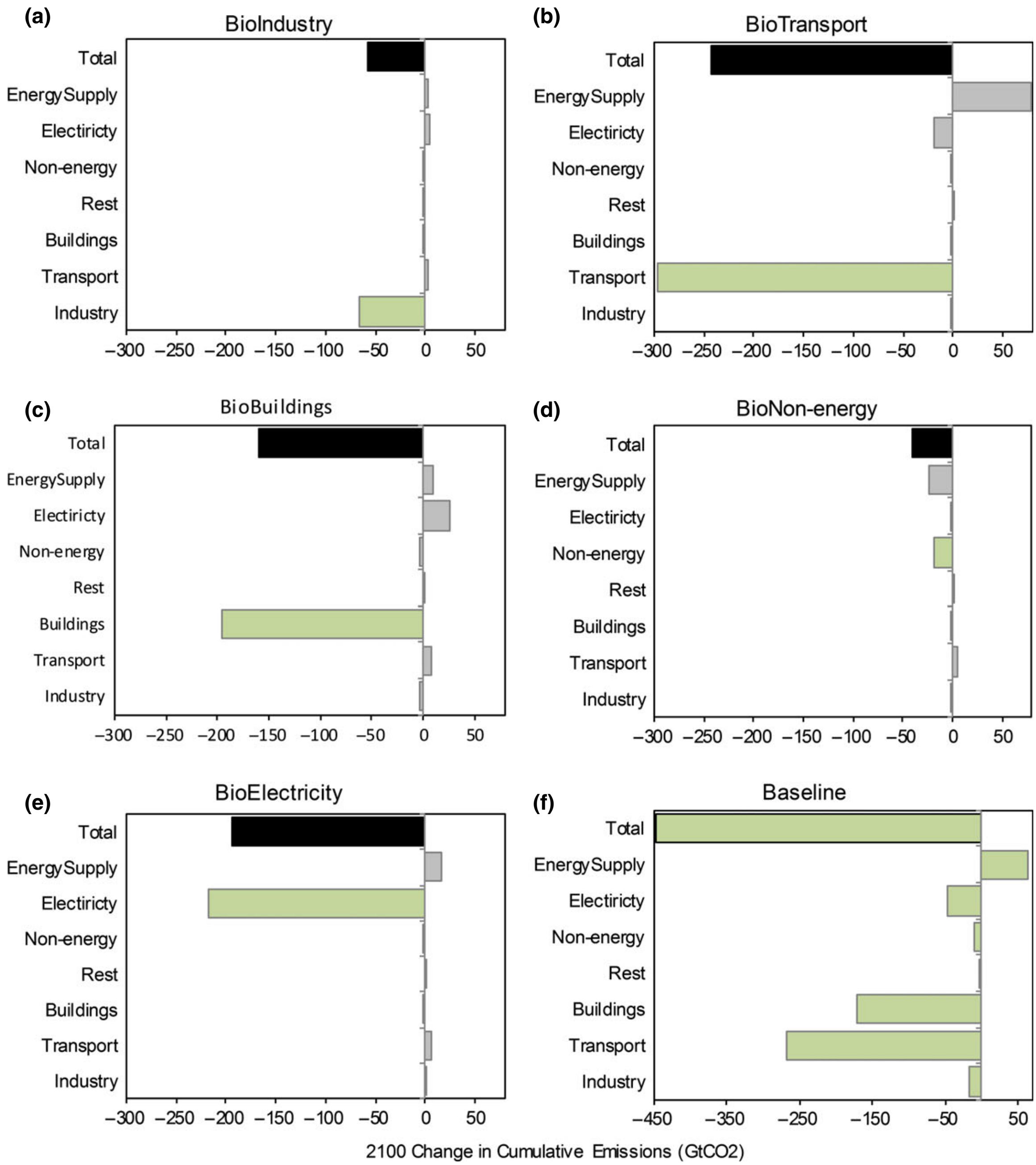

Fig. 3 TCEC in $GtCO_2$ per sector and total. Results for scenarios (a) BioIndustry, (b) BioTransport, (c) BioBuildings, (d) BioNon-energy, (e) Bioelectricity and (f) Baseline. A negative value means an emission reduction. Note different scale for (f).

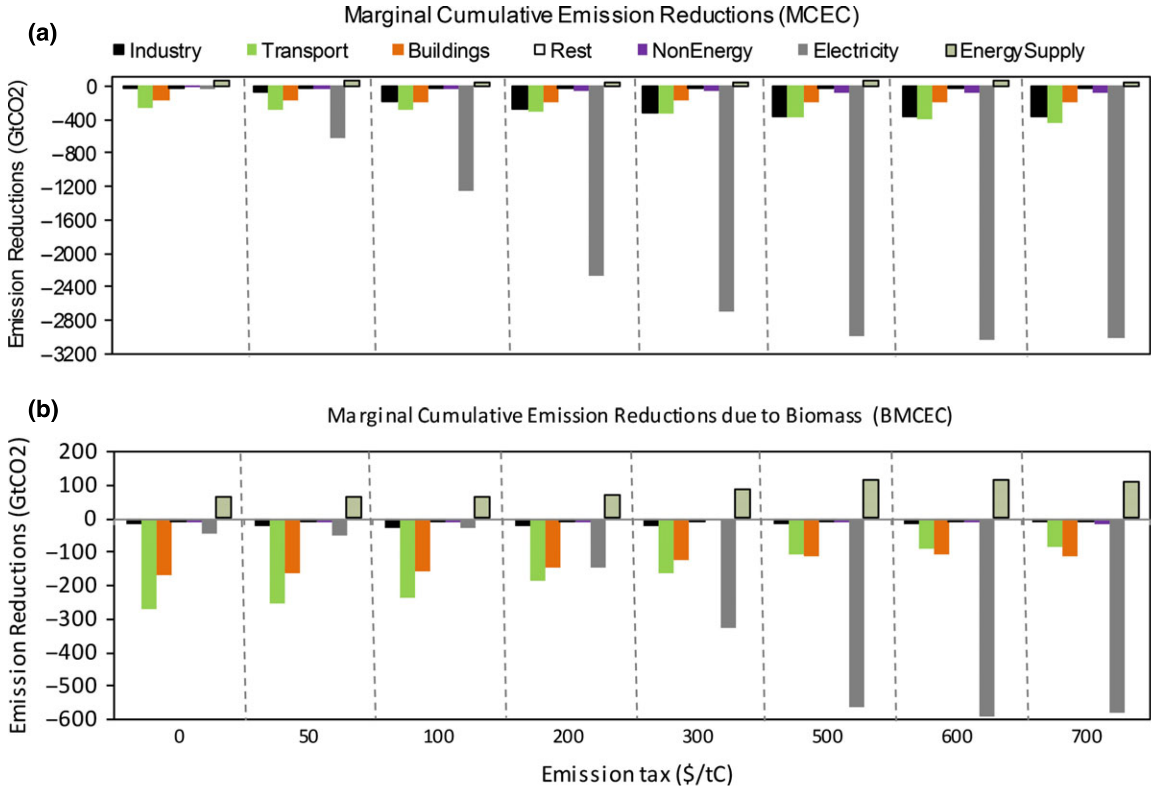

Fig. 4 Marginal cumulative emission reductions per sector with increasing carbon taxes on the baseline scenario. Panel (a) shows the MCEC as calculated by Eqn (2). Panel (b) shows the BMCEC as calculated by Eqn (3). MCEC includes emission reductions due to all fuel switching operations including bioenergy, efficiency improvements, reduced demand, and fossil fuels use with carbon capture and storage. BMCEC shows the contribution of bioenergy to the MCEC.

scenario has the lowest emission reductions. At low tax levels, the emission reduction is greatest for the *Baseline.* However, at taxes greater than ≈200$/tC, limiting bioenergy to the electricity sector leads to overall greater emission reductions. Since bioenergy is not shared with transport (as in the *Baseline* case), the electricity sector can use more bioenergy to substitute coal and apply CCS technology. It should be noted that TIMER is a simulation model and therefore does not fully optimise bioenergy use. This makes it a useful tool to identify such situations of suboptimal use.

Emission reduction effectiveness of bioenergy

Table 5 shows the effectiveness of bioenergy in reducing emissions, according to Eqn (4), for the BioSector and Baseline scenarios with increasing taxes. Without carbon taxes, bioenergy is most effective in reducing emissions when its use is limited to electricity production. As shown above, this does not necessarily mean that the emissions are reduced more than in the unconstrained case, but rather that less bioenergy is used for the given reduction. This finding is thus important for scenarios with more stringent constraints on biomass supply. BioNon-energy has the lowest effectiveness due to cross-sectoral leakage of fossil fuels and low emission reduction potential of that sector. At higher taxes, limiting the use to electricity production provides the greatest emission reduction per unit bioenergy due to the use of BECCS. The same holds true but to a lesser extent for the Baseline case. For BioTransport and BioIndustry, at higher taxes bioenergy increasingly replaces electricity thus not contributing to direct emission reductions. For this reason the effectiveness of BioTransport and BioIndustry decrease as taxes increase, with BioIndustry increasing its effectiveness eventually due to the adoption of BECCS. Interestingly, BioLowTech has a more effective use of bioenergy with respect to the Baseline at high taxes, since pessimistic assumptions on technoeconomic parameters reduce the competition between the transport and electricity sectors for bioenergy use.

Discussion

This study compares a number of model-based projections to assess the possibilities of biomass use for emis-

Table 4 Energy System MCEC ($GtCO_2$) under Baseline and BioSector scenarios with increasing taxes

	Tax Level				
Scenario	0	100	200	500	700
NoBio	0	−1520	−2608	−3254	−3386
Baseline	−447	−1915	−3049	−3951	−4080
BioBuildings	−159	−1648	−2731	−3386	−3518
BioNon-energy	−40	−1554	−2638	−3291	−3428
BioElectricity	−194	−1726	−3246	−4380	−4520
BioIndustry	−58	−1599	−2677	−3329	−3468
BioTransport	−242	−1720	−2756	−3352	−3477

Table 5 Total emission reductions per unit of bioenergy use in all scenarios for carbon tax levels of 0, 300 and 700$/tC ($cumMtCO_2/cumEJ_{Bioenergy}$)

Tax	0	300	700
Scenario			
Baseline	57	75	90
BioLowPot	57	69	90
BioLowTech	57	54	99
BioBuildings	61	61	62
BioNon-energy	26	23	23
BioElectricity	143	211	211
BioIndustry	82	55	69
BioTransport	51	39	27

sion mitigation. We have used a long-term global simulation model with detailed representation of the energy system to systematically analyse the implications of bioenergy and biochemicals. Endogenous dynamic projections of demand from an energy function perspective and depletion of energy sources makes the model suitable to assess scenarios of fuel substitution measures. The TIMER model, being a simulation (as opposed to optimisation) model, is well suited to investigate how competing uses may influence the effectiveness of bioenergy use. However, to get insights into the robustness of these results under different system representations, such a detailed scenario analysis investigating the uncertainties and trade-offs between different bioenergy uses should be repeated with other energy system models (including optimisation or general equilibrium models).

The GCAM model, an integrated assessment model, has been used to determine the potential biomass uses under stringent climate targets (Luckow *et al.*, 2010). Their baseline runs are very similar in terms of emissions (80 GtCO2 yr^{-1} compared to 77 $GtCO_2$ yr^{-1} in this study). Both models show that bioenergy is used in the baseline and becomes more important in mitigation scenarios. Concerning emissions reduction, Luckow *et al.* (2010) agree that heavy industry and buildings have a limited contribution to emission reductions, which are mainly driven by fuel switching in transport and electricity generation, and if possible CCS. Even though the models agree on the importance of BECCS at reducing emissions, according to Luckow *et al.* (2010) at tax levels greater than 700$/tC, almost all of the bioenergy is used with CCS. In this study, even at high taxes bioenergy is still also used without CCS as a transport fuel, in the *Baseline* scenario. A key difference is that in GCAM the production of liquid biofuels (for transport) with CCS is included as an option, while in TIMER CCS is limited to electricity production and partly the industry sector. Intermodel comparisons have shown that the production of liquid fuels with CCS is also used in other models which allow for this technology (Calvin *et al.*, 2013). Given the possibilities of biorefining (fuels and chemicals) with CCS, the potential of BECCS may be significant over the entire energy system. Given the importance of liquid fuels for transport, it is important for further research to focus on the competition between different options which include CCS.

A comprehensive review of studies on leakage of oil due to biofuels has found that depending on assumptions and modelling technique a range between −20% (1 GJ biofuel replaces 1.2 GJ of oil) and 120% (1 GJ biofuel increases oil use by 0.2 GJ). However, most of the values fall within 30% and 60% (1 GJ biofuel replaces 0.3–0.6 GJ oil) (Smeets *et al.*, 2014). One of the main uncertainties across all studies (including this one) is the elasticity of substitution of different fuels. The study of leakage has focused on economic equilibrium models with a weak representation of physical parameters (demand functions and technologies). This study seeks to offer a descriptive assessment given a technologically detailed energy system simulation model and also accounting for all fossil fuels, as opposed to just oil. Our results are in agreement with previous studies stating that a unit of bioenergy does not replace one unit of fossil fuels. This is true for any alternative energy supply option and thus outcomes on net mitigation impacts depend on overall mitigation targets for the entire economy.

A number of aspects of the model have to be highlighted to put the results of this paper in context. Land use change (LUC) emissions have been included by attaching an emissions factor to crop based primary biomass. Due to the complex and uncertain nature of land use change, there is a large variance in the related emission factors across studies (Wicke *et al.*, 2012). Since in this study almost all of the biofuels produced are second generation, the indirect land use change emissions are expected to be low (assuming that sustainability criteria are in place). Our method does not reflect that increasing use of biomass may lead to marginal increases in LUC, since we use a constant land emission factor. Coupling this study with detailed land allocation modelling would allow studying the land-based carbon fluxes and emission mitigation (Gillingham *et al.*, 2008; Wise *et al.*, 2009; Havlik *et al.*, 2011; Rose *et al.*, 2012). This would provide an overall picture of the emission implications of bioenergy use when used together with energy system emission studies such as this one. A similar approach could also be made for the effects on water or biodiversity for a better overall sustainability assessment of large scale use of biomass for energy and chemical purposes. Another area of significant uncertainty concerns the availability of residues as a resource for bioenergy. In this study, primary residue potential is based on a literature review and set at 72EJ yr^{-1} in 2050 and 81EJ yr^{-1} in 2100. Furthermore, it is assumed that it is available at low price and has no emission effects or feedbacks on agricultural and forestry systems. Due to the important role that residues play in bioenergy use (according to our projections 21% of bioenergy use in 2100 come from residues), it is important to consistently assess the availability, costs and limits of the large scale use of this resource.

This study investigates the potentials and uncertainties of biomass as a renewable source for energy and chemical purposes, and highlights the sensitivities and dynamics of its emission mitigation possibilities. The following important observations are made:

Bioenergy is likely to play an important role in future energy systems

Under the baseline projections 170 EJ yr^{-1} is projected to be used in 2100. Much of this is used in the transport sector where it can easily replace expensive oil. The buildings and nonenergy sectors also replace fossil fuels, but to a much lesser extent. Overall, bioenergy use helps reduce baseline cumulative emissions by 9% to 4.7 $TtCO_2$ when compared to a counterfactual baseline with no bioenergy. The results are shown to be sensitive to assumptions for both bioenergy potential and bioenergy production technologies, with the former having a stronger impact on results. Halving the bioenergy potential reduces bioenergy production to around 118 EJ yr^{-1} and cumulative emissions increase to 4.8 $TtCO_2$ while adopting pessimistic conversion technologies results in bioenergy production of 156 EJ yr^{-1} and cumulative emissions of 4.7 TCO_2.

In the TIMER model, emission reductions from bioenergy use come mostly from the transport and electricity sectors

At taxes greater than 100\$/tC, bioelectricity with CCS leads to significant emissions reductions. At a tax level of 700\$/tC, overall emissions are projected to be 1 $TtCO_2$. Assuming no bioenergy use, emissions would stand at 1.7 $TtCO_2$ implying that bioenergy can contribute to a further reduction in emissions by up to 40% at high emission taxes. This emission reduction potential is affected if biomass potential is halved (1.2 $TtCO_2$ in 2100). The LowTech case with high tax yields emissions slightly lower than the base case due to increased used of bioelectricity with CCS.

Cross-sectoral leakage can reduce the emission reduction potential and depends on what energy carriers bioenergy substitutes

Any policies aiming at specific bioenergy uses have to account for the possibility of cross-sectoral leakage. This is driven by the volume and competitiveness of displaced fuels at providing alternate energy services. This in turn depends on how elastic sectors are at making fuel choices. Nonenergy and buildings have the highest leakage rates since displaced coal, gas and oil from these relatively small sectors are easily absorbed in the large electricity transport sectors. When bioenergy is limited to the transport sector it replaces oil and electricity use. The expensive oil is not readily consumed elsewhere and the electricity sector also reduces its emissions. Bioenergy use in the electricity sector displaces large volumes of coal which cannot be fully absorbed by the remaining sectors. Thus, the large reduction in emissions in the electricity sector counteracts any leakage.

Competing uses of bioenergy potentially limit its effectiveness at reducing emissions

The most effective use of bioenergy for emission reduction is in the electricity sector. This is because this sector is projected to increase its share in total emissions due to its large size and use of coal. Furthermore, bioenergy use with carbon capture and storage at high carbon taxes leads to sharp emission reductions. Nonenergy uses of biomass do not offer significant emission reductions due to leakage and the fact that part of the carbon content of feedstocks is sequestered in the form of chemicals. With increasing carbon taxation, additional emission reductions due to the use of bioenergy mainly come from changes in the electricity generation mix and to a lesser extent from transport, buildings and heavy industry. As carbon taxes increase, transport demands large volumes of bioenergy since it is the only cost-effective substitute for oil. However, this limits its use in the electricity sector where the use of BECCS can lead to greater emission reductions. Further research is needed to assess how BECCS in liquid fuel production influences the effectiveness of different bioenergy CO_2 mitigation options.

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Table S1. Secondary energy carrier share for the NoBio, Baseline, BioLowPot and BioLowTech scenarios, per sector and total in 2100.
Table S2. Shares of secondary energy carrier use, total secondary energy use, annual emissions and cumulative emissions in 2100. Each sector and total for Baseline scenario.
Table S3. Sectoral and Total cumulative emissions (GtCO2), total energy use, and sectoral fraction of bioenergy. For all scenarios and carbon taxes.