Bio-energy and CO$_2$ emission reductions: an integrated land-use and energy sector perspective

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Abstract

Biomass feedstocks can be used to substitute fossil fuels and effectively remove carbon from the atmosphere to offset residual CO$_2$ emissions from fossil fuel combustion and other sectors. Both features make biomass valuable for climate change mitigation; therefore, CO$_2$ emission mitigation leads to complex and dynamic interactions between the energy and the land-use sector via emission pricing policies and bioenergy markets. Projected bioenergy deployment depends on climate target stringency as well as assumptions about context variables such as technology development, energy and land markets as well as policies. This study investigates the intra- and intersectorial effects on physical quantities and prices by coupling models of the energy (REMIND) and land-use sector (MAgPIE) using an iterative soft-link approach. The model framework is used to investigate variations of a broad set of context variables, including the harmonized variations on bioenergy technologies of the 33rd model comparison study of the Stanford Energy Modeling Forum (EMF-33) on climate change mitigation and large scale bioenergy deployment. Results indicate that CO$_2$ emission mitigation triggers strong decline of fossil fuel use and rapid growth of bioenergy deployment around midcentury ($\sim$ 150 EJ/year) reaching saturation towards end-of-century. Varying context variables leads to diverse changes on mid-century bioenergy markets and carbon pricing. For example, reducing the ability to exploit the carbon value of bioenergy increases bioenergy use to substitute fossil fuels, whereas limitations on bioenergy supply shift bioenergy use to conversion alternatives featuring higher carbon capture rates. Radical variations, like fully excluding all technologies that combine bioenergy use with carbon removal, lead to substantial intersectorial effects by increasing bioenergy demand and increased economic pressure on both sectors. More gradual variations like selective exclusion of advanced bioliquid technologies in the energy sector or changes in diets mostly lead to substantial intrasectorial reallocation effects. The results deepen our understanding of the land-energy nexus, and we discuss the importance of carefully choosing variations in sensitivity analyses to provide a balanced assessment.

Keywords Bioenergy · BECCS · Integrated assessment modeling · Land-energy nexus · Climate change mitigation

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1 Introduction

Large scale deployment of bioenergy has been identified as a key long-term option to keep CO_2 emissions limited over the twenty-first century (Popp et al. 2014b; Rose et al. 2013). Bioenergy is particularly valuable in the context of deep emission reductions because it substitutes fossil fuels directly and enables carbon dioxide removal (CDR) from the atmosphere to offset residual emissions by combining bioenergy use with carbon capture and storage (i.e., BECCS) (Klein et al. 2014b; Luderer et al. 2018). The importance of bioenergy for the energy sector is confronted with major uncertainties about the availability, performance, and maturity of advanced bioenergy technologies ABTs (Lomax et al. 2015; Scott and Geden 2018), potential limitations of biomass feedstock supply, and implications on the land-use sector as well as broader issues of socio-economic development and policy implementation (Creutzig 2014). To better inform the debate on bioenergy and climate change mitigation, the EMF-33 study of the Stanford Energy Modeling Forum applies a series of IAMs and performs a broad sensitivity analysis (Bauer et al. 2018b).

This study presents the land-energy coupling approach of the integrated assessment modeling framework REMIND-MAgPIE and applies it to the EMF-33 scenario protocol augmented by additional, more specific sensitivity analysis of context variables covering variations in the land-use sector, socio-economic drivers, and policy implementation. The aim is to enhance the understanding of the coupled land-energy transformation and to study crucial factors and drivers regarding inter- and intrasectorial effects when stringent mitigation targets should be met. We address the question how climate change mitigation increases the intersectoral linkage and which variations lead to (i) intrasectorial effects limited to either the energy or the land-use sector or (ii) to intersectorial effects in and between both sectors. For this purpose, we study quantity and price information derived with the coupled REMIND-MAgPIE model.

The REMIND-MAgPIE model integrates macroeconomy, land-use, and energy systems and computes consistent scenarios implementing varying degrees of climate policies and varying policy frameworks (e.g., evaluation of Nationally Determined Contributions NDCs or optimization of policies to achieve a carbon budget). It participated in various international IAM comparison studies since 2010 (e.g., Kriegler et al. 2014) and contributed integrated economy, energy, land, and climate scenarios to the Shared Socioeconomic Pathways (SSPs) (Riahi et al. 2017). The integrated modeling framework allows investigating a broad range of uncertainties of these assumptions by means of sensitivity analysis to study physical and economic impacts on bioenergy markets and climate policies and thereby study the land-energy nexus in climate change mitigation scenarios.

The integrated assessment part of the EMF-33 study mainly focuses on uncertainties related to ABTs (Bauer et al. 2018b) in the context of energy sector CO_2 emission limitations. ABTs include options to convert ligno-cellulosic biomass into modern energy carriers such as electricity, liquids, and hydrogen (incl BECCS variants). The supply side part (Rose et al., this issue) studies the cost and potentials of biomass feedstocks and related GHG emissions. The present study extends the analysis by varying a broader set of context variables regarding demand and supply side drivers of bioenergy use and use as well as socioeconomic drivers and policy implementation.

We start from a baseline scenario without climate policies applying default assumptions based on the middle-of-the-road narrative and quantification (SSP2). This is compared with mitigation scenarios that implement carbon pricing policies to comply with a prescribed

carbon budget. The carbon pricing system covers all emissions using CO_2-equivalent emission factors. The carbon budget definition follows the EMF-33 scenario protocol and accounts for emissions from the energy sector, including industry. Land-use change emissions and afforestation removals develop according to the carbon price but do not enter the carbon budget. The carbon budget accounts for CO_2 removal via BECCS which offsets CO_2 emissions from energy and industry and, eventually, balances the carbon budget over time. Moreover, to take into account near-term climate policies, we restrict the model up until 2020 to implement only weak climate policies consistent with conditional NDCs.

For the sensitivity analysis, we keep the carbon budget constant and adjust the carbon pricing accordingly. The fourteen variations are sorted in three groups. We vary assumptions on (i) bioenergy conversion technologies and the injectivity of CO_2 into geological formations, (ii) potential and cost in the land-use sector influencing biomass feedstock supplies, and (iii) socioeconomic drivers and climate policies implementation. These variations cover a broad set of factors and drivers affecting the availability of biomass-based mitigation technologies, the supply of biomass, and broader socioeconomic drivers and policy implementation, which influence the energy and land-use sector and their interactions. The integrated scenarios are used to investigate the land-energy nexus in the context of transition pathways with limitations on global energy and industry emissions.

2 Methodology

2.1 The REMIND and the MAgPIE model

The REMIND and the MAgPIE model are both equilibrium models that apply optimization methods to derive market equilibria. Also, both models cover the time horizon up until 2100 and are global in scope differentiating the world into macro-regions that form markets for food and energy for which market equilibria are computed. Both models rely on the SSPs for assumptions on socioeconomic drivers for demographic, economic, and technological development (Dellink et al. 2017; KC and Lutz 2017). In this study, both models use the SSP2, a middle-of-the-road narrative, to derive a baseline scenario that is used to assess the impacts of climate policies. Assumptions on technological development, resource potentials, etc. in REMIND and MAgPIE follow the SSP2 narrative and documented in the literature (Kriegler et al. 2017; Riahi et al. 2017).

REMIND 1.7 is a Ramsey-type general equilibrium model of economic growth with a hard-coupled detailed energy system model that applies optimization methods to find a general market equilibrium (Bauer et al. 2018a; Bauer et al. 2012; Luderer et al. 2013). Economic agents are assumed to have perfect foresight on future prices, which implies a rational expectations equilibrium on all markets. The macroeconomic system demands labor, capital, and final energy. Final energy use gradually modernizes with growing shares of electricity and gases, whereas shares of liquids and solids decrease. The energy system is a detailed representation of all relevant energy flows from primary to final energy as well as associated GHG emissions. The energy system transformation is consistent with basic energy economic principles of cost competition, but also represents inertia of infrastructures and rigidities to ramp-up new capacities as well as endogenous technological learning. Regions are endowed with fossil fuels, uranium, and biomass that are traded internationally subject to transportation costs and infrastructure expansion rigidities as well as balance of payments constraints. Coal,

gas, and biomass conversion capacities that produce electricity, liquids, and hydrogen can be equipped with CCS. An injectivity constraint limits the annual injection of CO_2 into geological formations to 0.5% of the total potential in each region.

MAgPIE 3.0 is a partial equilibrium model of the land-use sector that finds market equilibrium by minimizing the global costs of production given price irresponsive demands for agricultural products (Humpenöder et al. 2018; Popp et al. 2014a). The model assumes adaptative expectations for evaluation of long-term investment decisions implemented by recursive dynamic model structure. The model is driven by demands for agricultural commodities, which are calculated based on population and income projections for the twenty-first century. For meeting the demand, the model endogenously decides, based on cost-effectiveness, about the level of intensification (yield-increasing technological change), extensification (land-use change), and production relocation (intraregionally and interregionally through international trade). CO_2 emissions from land-use change are calculated based on differences in carbon stocks for different land types. The calculation of N_2O and CH_4 emissions from agricultural production is based on IPCC 2006 emission guideline factors. The optimization process is subject to various spatially explicit biophysical conditions such as yields, water availability, and carbon stocks, which are derived by the global crop growth, vegetation, and hydrology model LPJmL. Due to computational constraints, spatially explicit input (0.5-degree resolution) is aggregated to 700 simulation units for the optimization process based on a k-means clustering algorithm.

MAgPIE simulates two types of biomass feedstock production: 1st- and 2nd-generation biomass feedstocks. First-generation biomass relies on conventional food crops such as maize and sugarcane. Supplies and demands of 1st-generation feedstocks are prescribed by exogenous policies. The largest potential is offered by dedicated herbaceous and woody lignocellulosic bioenergy crops (such as miscanthus, poplar, and eucalyptus), which feature significantly higher energy-specific yields per hectare than 1st-generation crops. Lignocellulosic feedstocks can be converted into electricity, hydrogen, and liquid fuels also in combination with CCS. Conversion into heat, solid energy carriers, and synthetic gases are available, but cannot be combined with CCS. Residues are scaled with production volumes in forestry and agriculture reaching a long-term maximum global potential of 70 EJ/year.

2.2 Coupling approach

The integrated assessment of climate change mitigation policies regarding the interdependencies between the energy and the land-use sector requires the explicit representation and consistent solution of both, quantities of bioenergy and GHG emissions and their associated prices. These variables are key features in transformation pathways of energy and land-use systems. Since the REMIND and the MAgPIE model are each numerically heavy a full integration of both models using a hard-link is not achievable. Therefore, a soft-link approach is implemented to derive consistent scenarios with REMIND and MAgPIE (Bauer et al. 2008; Messner and Schrattenholzer 2000). Basically, the soft-link approach feeds REMIND results iteratively through MAgPIE to deliver information for updating assumptions in REMIND; moreover, both models use harmonized assumptions on narratives and quantitative drivers consistent with SSP2 (see Fig. S1). The iteration is repeated until changes between iterations become negligible. The resulting scenarios of REMIND and MAgPIE are consistent regarding price and quantity of bioenergy and GHG emissions. Variations in climate policies or drivers shift these prices and quantities and the underlying energy and land-use scenarios.

For a convergent solution of the soft-link approach, the interdependencies need to fulfill certain conditions:

1. Higher emissions prices decrease GHG emissions from the energy and the land-use sectors;
2. Higher emissions prices decrease fossil fuel use and increase bioenergy demand (this is not necessarily the case for all IAMs under all circumstances; see Bauer et al. 2018a, b);
3. Higher emissions prices increase biomass supply costs;
4. Higher bioenergy prices decrease bioenergy demand; and
5. Higher biomass supply increases marginal costs of biomass supply and land-use GHG emissions.

The interdependencies suggest a unique solution that can be approximated using an iterative soft-link approach (see Fig. S1). The technical implementation of the iteration process involves (i) a reduced form model that emulates MAgPIE within REMIND and (ii) additional constraints to the solution space to improve the convergence speed and stability of the iterative approach towards the solution.

The REMIND model - represented by the mapping $R(\cdot)$ - derives in each iteration i scenarios for bioenergy use BE and emission prices p^E for 11 regions and 17 time periods; the regions and period indices are ignored to ease readability. The reduced form model consists of the supply function $S_i(\cdot)$ mapping bioenergy prices p^{BE} to quantities BE_i and land-use sector emissions E_i of CO_2, CH_4, and N_2O as exogenous constraints. Given this information in each iteration, REMIND derives a set of emission prices p^E and bioenergy use BE:

$$\left(p_i^E, BE_i\right) = R(S_i(\cdot), E_i).$$

The output of each REMIND run is fed into the MAgPIE model denoted as the mapping $M(\cdot)$ to derive updated information on bioenergy prices and GHG emissions:

$$\left(p_{i+1}^{BE}, E_{i+1}\right) = M\left(p_i^E, BE_i\right).$$

In the initial iteration, REMIND starts with an initial $S_0(\cdot)$ that is derived from a large set of MAgPIE runs, in which the time paths for biomass feedstock production are varied. The function's parameters are updated in each iteration to correct for differences in p_{i+1}^E and BE_i between $S_0(\cdot)$ and actual MAgPIE runs. This corrects for approximation errors of $S_0(\cdot)$. The main reason for updating $S_i(\cdot)$ is that its shape in each period depends on the time path of biomass deployment and the carbon emission price p^E that is endogenously derived in REMIND. For enhanced consistency between REMIND and MAgPIE scenarios, approximation errors $S_0(\cdot)$ are reduced and made consistent with the MAgPIE model.

The updated E_{i+1} is used directly as input for REMIND. The updated p_{i+1}^{BE} is used to recalibrate $S_i(\cdot)$ by shifting the supply curve. The updated supply curve replicates the pairs of BE_i and p_{i+1}^{BE}. Carbon price changes affect biomass feedstock production costs and, therefore, it is necessary to adjust the supply curves to derive consistent sets of price and quantity in the coupled REMIND-MAgPIE model.

The iterative information exchange between both models defines a sequence that converges towards a fixed point $\left(p_E^*, E^*; p_{BE}^*, BE^*\right)$ that is unique for all time steps and regions because of qualitative dependencies 1.-5. mentioned above. The fixed point

characterizes the biomass market equilibrium and equality between marginal emission reduction costs and the emission prices in the energy and the land-use sector. The iterative approach is robust and converges for a broad range of socioeconomic assumptions and emission reduction policies. The Supporting Online Material provides detail on the numerical performance of the iteration process.

Simple implementations of fixed point iterations, such as a cobweb algorithm, are subject to numerical heaviness and computing time. The main reason is the back and forth of relatively similar solutions that converge only after many iteration steps. Such zig-zagging needs to be treated, if computationally heavy models like REMIND and MAgPIE are coupled. Reducing the number of iteration steps is crucial to reduce computation time. Moreover, zig-zag behavior means that the distances between intermediate solutions in the solution space are unnecessarily large and in each iteration step, the optimization algorithm needs to move a large distance to find the solution for the optimum in that iteration. Large updates between iterations also increase the risk that the convergence process becomes instable and is terminated due to infeasibility problems in one of the models. Therefore, it is useful to use additional information that enhances the convergence speed and stability of the iteration but does not change the fixed point's location.

Three features are implemented into the present soft-link approach to stabilize and accelerate the convergence process by constraining the solution space. First, the biomass feedstock supply function implemented in REMIND is derived from the MAgPIE model. In the existing literature on soft-link approaches, general functions such as quadratic supply functions are implemented and updated (Bauer et al. 2008; Messner and Schrattenholzer 2000). Such ad hoc assumptions work because the location of the fixed point does not depend on the shape of the supply function around the fixed point, but convergence is slow because it delivers poor updates of BE. It is significantly improved by estimating a supply function derived from the MAgPIE model (Klein et al. 2014a). The investment of computation time to derive such function pays off, because it is sufficiently robust to parameter changes such as those studied here.

Second, for the initial REMIND run, an appropriate set of biomass supply functions and emission trajectories are selected. Good initialization improves the iteration process with respect to speed and robustness. This is particularly useful because the shape of the biomass supply functions varies with the carbon price levels, which in turn vary largely across stabilization scenarios. Therefore, for the initial REMIND run, an appropriate set of supply functions and emission trajectories is chosen.

Finally, a penalty term is added to the supply function used in REMIND. The penalty is quadratic in the difference $BE_i - BE_{i-1}$, where BE_{i-1} is fixed given the previous iteration. Such penalty dampens the tendency of zig-zagging in the convergence process. The penalty term does not affect the location of the fixed point because the differences get smaller and, thus, the penalty vanishes as the fixed point is approximated.[1]

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[1] It is worth noting that such improvements of convergence processes are not only numerical and technical. Stiglitz (1994, p.11) highlighted that algorithms based on pure market analogous, such as Cob-Web iterations, are inefficient procedures. Based on our experience, the efficiency of iteration processes can be strongly accelerated by initialization and improving update mechanisms. Each update should anticipate reactions of the next iteration to avoid time-consuming zig-zag behavior. The iterative process is very efficient and converges after about five iterations with only small changes for additional iterations.

2.3 The carbon budget framework and sensitivity analysis

The EMF33 study applies a carbon budget framework considering three carbon budgets that cover the time horizon 2011–2100 that are *indicative* for long-term targets of the Paris agreement (Allen 2018; Rogelj et al. 2015). This study focuses on the set of scenarios that complies with the $1000GtCO_2$ budget for energy and industry (land-use change emissions from MAgPIE add another $160GtCO_2$). This scenario is indicative for well-below 2 °C of global warming in 2100 with 66% likelihood in the IPCC's 5th Assessment Report. The most recent IPCC assessment estimates that the corresponding budget at $1300GtCO_2$, and hence, the present study applies a more stringent budget. A very low carbon budget of $400GtCO_2$ and a high budget of $1600GtCO_2$ also investigate the response of bioenergy markets. The long-term carbon pricing policy is subject to short-term policies that freeze the scenarios in 2020 given the expected policy impact of NDCs (see Kriegler et al. 2018).

The carbon budgets are implemented by carbon pricing policies implementing a uniform carbon price across regions (emission taxes or cap-and-trade systems). The carbon price trajectory grows endogenously until 2100 to keep cumulative emissions at the limit defined by the budget. The intertemporal carbon budget framework allows to freely allocate emissions over time, including the possibility to offset a temporary budget overshoot by CDR using BECCS. In the EMF33 set-up, the carbon price penalizes all GHG from all sectors and regions based on 100 year Global Warming Potentials, whereas the carbon budget only accounts for the CO_2 emissions from the energy and industry sector. The consistent pricing of land-use GHG emissions drives the production costs of biomass feedstocks depending on direct and indirect land-use change emissions due to expanding biomass feedstock production (Klein et al. 2014a).

The carbon budget framework sets the main policy context for the sensitivity analysis testing the context variables. Such variations require adjustments of carbon prices to comply with the carbon budget. The carbon price adjustments feed back into the energy and the land-use sector and, thus, the demand and supply for bioenergy and ultimately the shape of the CO_2 emission pathway change.

Table 1 provides an overview of the overall set of variations of context variables considered in this study. It is based on the harmonized EMF33 scenario protocols, but also goes beyond that to provide a broader analysis with the REMIND-MAgPIE model. Within the energy conversion sector, five variations of the harmonized EMF33 sensitivities are to test the sensitivity of techno-economic uncertainty of the costs, performance, and maturity of ABTs. This includes the exclusion of (i) all BECCS technologies and (ii) bioliquids production from ligno-cellulosic feedstocks as well as the (iii) delayed availability of all ABTs and (iv) the doubling of their investment costs. The exclusion (ii) is important to consider because of the high competitiveness between alternative bioenergy uses for a limited biomass feedstock supply in climate change mitigation scenarios (see Bauer et al. 2018a, b). Moreover, to test the sensitivity of the annual availability of carbon removal using BECCS, we reduce the CO_2 injection rate into geological storage sites from 0.5 to 0.25% per year of the total available storage capacity. The full exclusion of BECCS technologies is the most significant variation, whereas the other scenarios represent more gradual changes that address specific links along the value chain of bioenergy and CCS deployment.

In the land-use sector, we impose a hard bound that limits modern bioenergy use to 100 EJ/year globally. This scenario is also part of the harmonized EMF33 and the EMF27 study protocol to emulate land-use sector constraints related to broader sustainability targets and food security.

Table 1 Overview on variations of context variables in the sensitivity analysis. The cases "No BECCS" and "Max. 100 EJ/year modern bioenergy" are mentioned as radical sensitivities

	Short	Description	Comment
Default	Full	Default assumptions on socioeconomic drivers (SSP2) and ABT availability	Kriegler et al. (2017)
Bioenergy conversion and CCS	No BECCS	BECCS technologies are fully excluded.	EMF33 standard
	No ABT fuels	Bio-liquid production from ligno-cellulosic biomass feedstocks is excluded to reflect limitations on large scale bioenergy technology facilities	EMF33 standard
	Delayed Readiness	ABT technologies are only available from 2050 onwards reflecting delayed technological maturity	EMF33 standard
	High investment cost	ABT investment costs and Operation & Maintenance costs are doubled to reflect pessimistic economics of ABTs	EMF33 standard
	Low injectivity	Maximum annual CO_2 injection rate is reduced from 0.5% to 0.25% of the remaining geological potential. Reflects barriers in geological storage. Default value based on unpublished expert opinion.	Not tested before
Land-use sector	Max 100 EJ/year modern bioenergy	Maximum annual potential of modern bioenergy use is limited to 100 EJ/year; includes residues, if used in modern modes. In default case, bioenergy use is subject to land-use constraints rather than a direct upper limit.	EMF33 standard, also Kriegler et al. (2014)
	High TC cost	Land-use intensification more challenging due to higher cost to improve yield rates reflecting pessimistic assumptions on technological change.	Humpenöder et al. (2018) studied higher yields.
	Ag-trade fragmented	Trade for agricultural products is fragmented by trade barriers to consider increased food security concerns and national sovereignty (compare SSP3)	Schmitz et al. (2012) studied trade liberalization and GHG emissions. Popp et al. (2017) for SSPs.
	NoGrass	Grassy biomass feedstocks are excluded (e.g., miscanthus). Reflects technological issues to use low-cost, high-yield biomass feedstock.	Similar to Klein et al. (2011)
Socioeconomic drivers and climate policy	SSP1 energy demand	Energy demand as in SSP1. Particularly, lower demand for transportation fuels; electricity in some developing regions even higher. Significant effect on baseline emissions.	Kriegler et al. (2017) introduced SSP scenarios

Table 1 (continued)

Short	Description	Comment
SSP1 fossil fuel (endowment)	Fossil fuel endowments are more pessimistic and correspond to SSP1. Significant effect on baseline emissions and bioenergy use.	Bauer et al. (2016) presents fossil fuel assumptions
SSP1 food demand	Lower food demand reflecting dietary changes towards more sustainable development in accordance with SSP1.	Popp et al. (2010) studies GHG emissions depending on food demand
No LU emission pricing	Carbon pricing is not applied to GHG emissions from the land-use sector. Hence, lower bioenergy production costs.	Popp et al. (2014a), Wise et al. (2009) study GHG emissions and land-use policies
(Flat) C-price path	Carbon price increases with 5%/year until 2060 and linear afterwards. Hence, price starts higher in 2025, but ends lower in 2100 to achieve the prescribed budget.	

The constraint on modern biomass use includes biomass residues, if they are used in modern modes such as biogas conversion. In addition, we study more gradual variations of specific parts of the land-use sector. First, we increase the costs to achieve yield rate improvements for endogenous land-use intensification, which reflects more pessimistic expectations for technical progress in the land-use sector. Second, trade in agricultural products is globally fragmented to reflect food security concerns. This reduces the flexibility to relocate land-use activities. Third, we assume that of ligno-cellulosic biomass only woody feedstocks are available and grassy feedstocks are excluded, which reflects qualitative limitations of feedstock availability due to the difficulty to use grassy feedstocks in energy conversion technologies.

In the broader context of socioeconomic drivers and policy implementation, we perform five variations. First, we assume a more sustainable economic development pattern that reduces energy demand growth consistent with SSP1. Second, we lower fossil fuel availability by assuming slower technological progress; more restrictive regulations are also consistent with SSP1. Third, we lower assumptions for food demand growth reflecting a more sustainable diet and reduced meat consumption. Fourth, we assume that carbon pricing policies are not applied to land-use sector emissions, which mimics the sectoral exemption from climate policies. Fifth, we re-shape the carbon price trajectory assuming a 5% annual growth rate until 2060 and linear growth thereafter. This assumption leads, for a given carbon budget, to a higher CO_2 price in early periods and lower prices in the long run as compared with the default setting. This mimics more ambitious near- to mid-term climate policy, whereas the long-term target is kept constant.

3 Results

3.1 Scenarios with default assumptions

Figure 1 shows global energy and industry CO_2 emissions and total bioenergy use. For the baseline scenario, REMIND-MAgPIE projects relatively high CO_2 emissions up until 2060 before they peak and decline due to increasing fossil fuel scarcity. In the climate change stabilization scenario, net CO_2 emissions over the next decades are also at the upper end of EMF-33 models, but in 2030, it is still lower than the most optimistic NDC estimates (Fawcett et al. 2015; Iyer et al. 2015; Luderer et al. 2016). Around 2050 the net emissions decrease quickly and turn strongly net negative towards the end of the century. The CO_2 price necessary to induce the emission reductions starts at 38USD per ton CO_2 in 2025 increasing at 4.5–5.5% per year (see Fig. S2). The carbon price features a relatively low starting level but grows quickly compared with other EMF-33 models.

In the absence of climate policies, REMIND-MAgPIE projects growing fossil fuel use that drives CO_2 emissions in the baseline scenario. Around the middle of the twenty-first century, traditional forms of biomass phase-out exogenously in the energy system of REMIND. Towards the end of the century, most biomass serves to substitute oil. If fossil fuels are assumed less abundant, bioenergy use increases, while slower energy demand growth reduces its use. In the scenario with carbon budget, the CO_2 price depresses fossil fuel use to significantly decrease emissions. This drives up bioenergy use particularly starting post 2040, when also emissions start to decline quickly. The net negative emissions post 2060 require BECCS deployment. For the very low budget, the bioenergy growth is moved 10 years earlier, but the long-term saturation level is similar. Compared with other studies, the
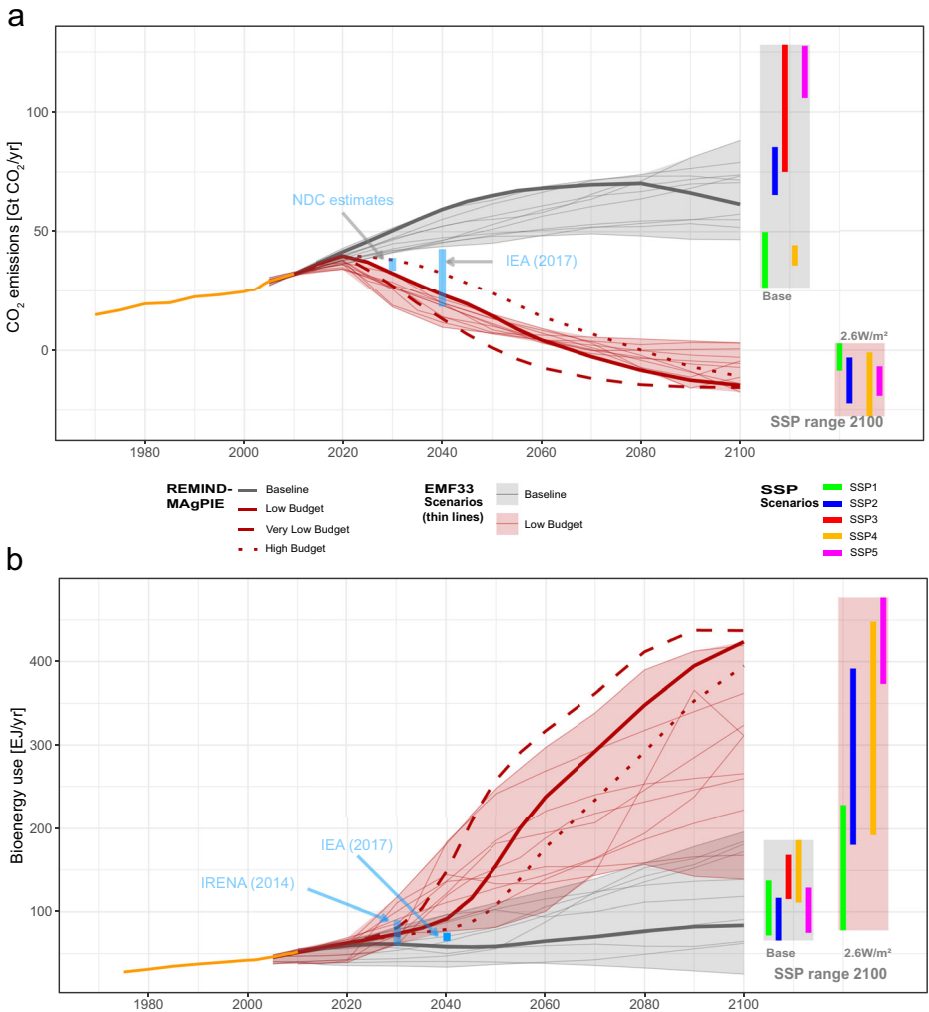
Fig. 1 Baseline and default scenario. Global pathways for CO_2 emissions (left hand side) and total bioenergy use (right hand side) for the baseline and the low budget scenario

REMIND-MAgPIE bioenergy scenarios are in the range of policy pathways in 2030 reviewed by IRENA (2014). Long-term bio-energy use is at the upper end of the EMF33 range. For stricter carbon budgets, reductions in energy and industry CO_2 emissions are associated with higher bioenergy use. The long-term saturation level of bioenergy use is similar for the different carbon budgets, because the bioenergy price increases substantially, additional bioenergy cannot be combined with CCS as the injection constraint becomes binding in most regions and, finally, electrification is the more attractive option (e.g., light-duty vehicles), which relies on other primary energy sources such as renewables.

In the baseline case, the global weighted average of regional bioenergy prices stagnates around 5USD/GJ throughout the century as regional prices vary between 3.5 and 7 USD/GJ (see Fig. S3). This compares with actual prices for wood chips with 20% moisture at 5–6 USD/GJ in today's markets. In the low budget case, the average biomass price increases to 10 USD/GJ by 2050. Hence,

the global primary bioenergy market volume grows to ~ 1500 bil. USD in 2050 or 1.1% of global GDP. This figure changes to 0.6% and 2.6% in case of the high and the very low budget, respectively. The market value of oil decreases instead. Without climate policy, the value is 2.5% of global GDP in 2050. For the high budget case, this value does not change, but for the low budget case, it decreases to 2% and even 1% in the very low budget case.

The biomass feedstock prices are partly driven by the carbon content of the feedstock that becomes valuable as carbon prices grow. In this context, it is worth to note that a price of 100 USD per ton CO_2 implies that the embodied carbon of primary biomass feedstock is equivalent to nearly 9 USD/GJ. Assume a capture rate of ~ 50% for the biomass-to-liquids technology equipped with CCS. Hence, for a carbon price of 164 USD/tCO_2 reached in 2050 in the low budget scenario ~ 7 USD/GJ of the total biomass feedstock price is covered by the remuneration for carbon removal. Hence, climate policies appreciate biomass feedstocks for the embodied carbon, if carbon removal is feasible.

3.2 Sensitivity analysis

Figures 2 and 3 summarize sensitivity analysis results for the low budget case. The impacts on cumulative gross energy emissions and annual bioenergy use are shown in Fig. 2, whereas Fig. 3 shows changes of carbon and bioenergy prices. The scenario with default assumptions is highlighted as a black marker serving as the reference for comparisons. Additional information is provided in the Supporting Material.
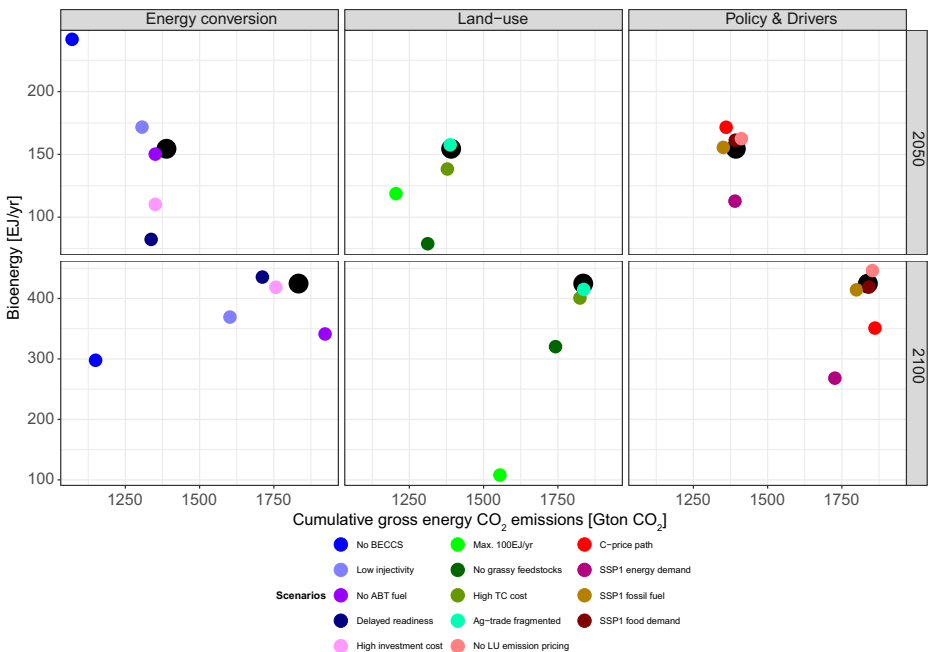

Fig. 2 Sensitivity cumulative gross CO_2 emissions and bioenergy use for the low carbon budget. The large black dots represent the default case that serves as reference case. The emissions exceeding the low carbon budget of 1000 GtCO_2 in 2100 equal the amount of CDR. The same does not hold true for the 2050 due to the intertemporal flexibility. Bioenergy use is total global bioenergy
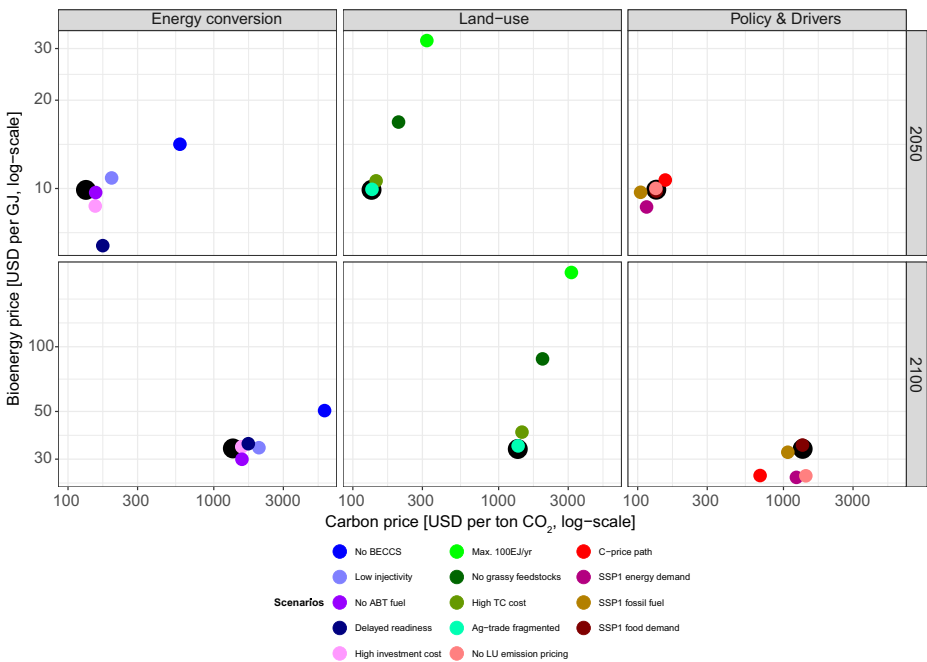
Fig. 3 Sensitivity bioenergy and carbon prices for the low carbon budget. The large black dots represent the default case that serve as reference cases. Note the log-scale for both axes

Energy conversion sector The parameter variations considered in the energy conversion sector tend to weaken ABTs and thus their deployment. Generally, this results in lower gross CO_2 emissions by 2050 and higher carbon prices. Reactions on bioenergy markets are ambiguous, but generally, the effects are larger in 2050 than in 2100, whereas cumulative gross CO_2 emissions react more strongly in the long-term. The largest impact is realized by excluding BECCS technologies, in which by 2050 more bioenergy is used at higher prices, because fossil fuel use needs to decrease to a larger extend and bioenergy serves as a substitute. A similar, though more gradual, sensitivity test is provided by the reduced CO_2 injectivity case. The qualitative effect remains the same but it is quantitatively muted: bioenergy use and prices in 2050 only increase by +43% and +10%, respectively. By 2100, bioenergy use is lower in both sensitivity cases, but prices are still higher than in the default case because higher carbon prices are necessary to limit CO_2 emissions in the energy sector, which feed back into the land-use sector increasing biomass feedstock supply costs (see, e.g., Klein et al. 2014a).

The full exclusion of BECCS or its gradual limitation by reducing the CO_2 injectivity reduces the amount of CDR. Halving the injectivity rate from 0.5 to 0.25%/year increases the value of removed carbon in 2050 because the carbon price increases more strongly than the CDR amount decreases. This indicates that the energy sector becomes economically more dependent on carbon embodied in bioenergy, since the expenditures for permanent carbon removal increases although the quantity decreases. Moreover, the accelerated use and increasing price of bioenergy in the midterm is due to the immediate need to substitute more fossil fuels. If the capability to remove and store the carbon embodied in bioenergy is reduced, a higher carbon price is needed to comply with the carbon budget. The higher carbon price feeds back into the energy system. It signals further reduction of fossil fuel use and, thus, bioenergy

use increases to substitute fossil fuels. This policy feedback effect on bioenergy use is observed in many EMF33 models for the case of full BECCS exclusion (Bauer et al. 2018b). The effect is muted if the CO_2 injectivity is reduced, but qualitatively the same.

The other three energy technology variations lead to diverse sensitivity patterns. By 2050, the diminished technology performance leads to smaller cumulative emissions at higher carbon prices and lower bioenergy use and prices. In particular, the delayed readiness of ABTs shows the most notable impact on bioenergy markets (-47% price and -35% quantity) followed by the variation of investment costs (-29% and -12%, respectively). In 2100, the sensitivity patterns differ. Only the case with higher investment costs still shows more relaxed bioenergy markets, but the impact is relatively small because fuel costs rather than capital costs are the dominant cost driver in future bioenergy markets (Daioglou et al. 2020). In case of delayed technology readiness, bioenergy use and prices exceed the default case in 2100 to partially make up the delay implying a stronger sector interaction. Different to that, the exclusion of ABTs for liquid fuel production relaxes bioenergy markets, but at the same time, cumulative emissions and carbon prices are higher ($+5\%$ and $+15\%$, respectively), which is an exception to the general result of decreasing gross emissions. This is due to within sector flexibility to restructure the energy sector. If bioenergy cannot be used for liquid-fuel production anymore, it is reallocated to electricity and hydrogen production with CCS, which both feature relatively high carbon capture rates. The additional CDR is used to offset CO_2 emissions from increased fossil fuel use to overcome the shortfall in liquid fuel production. Under default assumptions, liquid biofuel production with CCS is the most competitive option to utilize the energy and the carbon value of biomass feedstocks. It is not allocated to other conversion routes because liquid fuel production increases the bioenergy price. At these high bioenergy prices, other alternatives (e.g., renewables in the power sector) are the relatively more competitive alternative.

The results highlight that worsening assumptions of costs, maturity, and performance of bioenergy technologies and CO_2 injectivity interfere with the complex and dynamic interactions between the energy and the land-use sector. It is crucial how the variations specifically affect the energy and carbon flows and how the valuation changes. Particularly, worsening the carbon capture capability does not imply that less bioenergy is used and, thus, the intersectorial relations do not necessarily become weaker; for instance, in 2050, more bioenergy is used in cases with low injectivity or full exclusion of BECCS. Also, the sector coupling can decrease in terms of physical bioenergy use, but the overall willingness to pay for the embodied carbon by the energy sector could be boosted, which reinforces the intersectorial coupling in economic terms. Therefore, general statements on how assumptions about bioenergy technologies affect the sectorial interrelationship via emissions and bioenergy markets are not possible. The effects depend on the specific changes of assumptions as well as the complex and dynamically changing market context.

Land use sector The variations that we tested constrain biomass production systems. These variations lead to similar sensitivity patterns that differ in quantitative extent. Directly limiting biomass feedstock supply for modern use to 100 EJ/year leads to the strongest impact. The exclusion of grassy biomass feedstocks also impacts bioenergy markets (in 2050 $+70\%$ price and -50% quantity), which is due to lower energy yields per hectare and higher costs of woody biomass production. In both sensitivity cases, gross cumulative emissions are reduced, because less carbon is embodied in the bioenergy and thus less CDR is realized. Therefore, higher carbon prices are required to reduce cumulative gross CO_2 emissions from energy and

industry. Moreover, due to price irresponsive bioenergy demand the total revenue for bioenergy grows, because the relative quantitative reduction of bioenergy delivered to the energy sector is overcompensated by the relative increase of bioenergy prices. Hence, stronger economic coupling between the sectors is the result of weaker quantitative sector interaction. If land-use sector limitations reduce bioenergy use, this also leads to structural effects of bioenergy use. The reduced quantity of bioenergy is reallocated from liquid fuel production to hydrogen and electricity generation to better exhaust the value of carbon embodied in bioenergy by choosing technologies with higher carbon capture rates.

Assuming higher costs for yield improvements hardly affects carbon and bioenergy markets, whereas within the land-use sector total cropland is extensified (additional 125 Mio ha in 2050 and 330 Mio ha in 2100 compared with 2000 and 2300 million hectare, respectively, in the mitigation scenario with default parameterization). Consequently, net cumulative land-use CO_2 emissions increase ($60GtCO_2$ by 2100). Similarly, stronger restrictions on agricultural goods trade trigger adjustments of regional production patterns within the land-use sector that buffer effects on global bioenergy use. These two sensitivity tests lead mostly to adjustments within the land-use sector, whereas the effects on the energy sector are negligible.

Socioeconomic drivers and climate policy Varying socioeconomic drivers towards more sustainable pathways also show different qualitative and quantitative reactions. Less optimistic assumptions on fossil fuel availability reduce carbon prices (22%), but bioenergy use is hardly affected because final energy demand remains unchanged. Conversely, slower growth of final energy demand reduces bioenergy use and prices substantially (− 27% and − 13% in 2050, respectively). The relaxed sector coupling results from a combination of lower demand for both, bioenergy and carbon offsets. Assumptions on dietary changes are of little importance for bioenergy and energy CO_2 emissions, but the pressure within the land-use sector is substantially reduced: in 2050 total cropland decreases by 250 Mio ha while cropland for bioenergy plantations increases by 65 Mio ha. The lower pressure on land systems decreases N_2O emissions by 19% and cumulative CO_2 emissions from land-use change by 2100 are $50GtCO_2$ lower.

The shape of the carbon price trajectory is an important factor governing the timing of CO_2 emissions and removals, which in turn influences bioenergy use. Higher carbon prices in 2050 increase bioenergy use and prices (+ 11% and + 8%, respectively), whereas lower carbon prices in 2100 relax the market situation (− 17% and − 25%, respectively). Hence, achieving the long-term target with higher near-term ambition also leads to a stronger sector interaction by mid-century and weaker sector coupling in the long-term. The exemption of land-use change emissions from the carbon pricing regime leads to mildly higher bioenergy use at much lower prices (+ 5% and − 25% in 2100, respectively). However, this exemption leads to serious impacts on the land-use sector. By mid-century, land-use is intensified by increased fertilization, which increases N_2O emissions by 32%. Towards the end of the century, land-use is extensified by 100 Mio ha cropland leading to additional $90GtCO_2$ emissions.

The impact of choosing a flatter carbon tax trajectory on near-term emissions and bioenergy markets is consistent with the finding that tighter climate policies increase bioenergy use, because it implies lower emissions and, thus, stronger need to substitute fossil fuels with low carbon fuels such as bioenergy. Moreover, since the carbon budget is not changed, but reallocated over time, more fossil fuels can be used towards the end of the century which

consequently levels bioenergy use off. The exemption of land-use sector GHG emissions increases the pressure on land by first intensification and later also extensification. Hence, it is crucial to implement the climate policy in a comprehensive way covering both sectors and all emissions. Note that in this study, these additional land-use emissions are not balanced by emission reductions in the energy sector, which would reinforce the pressure on the land-use sector (Wise et al. 2009).

The impacts of the sensitivities discussed here depend on the strength of the carbon budget. If the emission limitations are stronger, the impacts of the changes in the assumptions increase. The supplementary material provides detailed information and discussion.

4 Concluding discussion

The energy-land nexus is interesting for researchers and policy makers in the context of climate change mitigation because both sectors will become more closely integrated in a complex and dynamic interaction. The interaction involves substantial physical quantities and economic values of bioenergy and emissions that are studied by the integrated energy and land-use sector model REMIND-MAgPIE. Large scale deployment of modern bioenergy, incl. BECCS, is projected to take off around mid-century, if global mean temperature increase shall be limited to well-below 2 °C above pre-industrial levels. For the stronger 1.5 °C target, bioenergy use would start to increase earlier, whereas the scale of long-term deployment varies little. Biomass feedstocks produced in the land-use sector are valued in the energy sector for the potential to substitute fossil fuels and to remove the carbon embodied permanently from the atmosphere by deploying BECCS. Both features make biomass feedstocks increasingly valuable over time in climate change mitigation scenarios and lead to a stronger interlinkage of the energy and the land-use sector. At the same time, the increasing demand for biomass feedstocks and the pricing of land-use GHG emissions increase the pressure on land systems. These crucial interaction channels are included in the soft-linked energy and land-use sector model REMIND-MAgPIE, which both also rely on the same socioeconomic drivers and derived the associated assumptions from the same narrative of a middle-of-the-road pathway (SSP2, see Bauer et al. 2017; Popp et al. 2017). The soft-link applied for the REMIND-MAgPIE coupling covers the most essential interactions. It is known that soft-links are not fully considering all interactions and are subject to approximation errors (Bauer et al. 2008). However, for the energy-land-nexus, the bioenergy and the emission links are crucial and need analysis in integrated frameworks with spatial and technological detail.

The earlier EMF27 study (Kriegler et al. 2014; Rose et al. 2013) identified the potential value of biomass feedstocks and its system-wide role in the coupled energy-land system and the Fifth Assessment Report of the IPCC highlighted these results. The EMF27 study tested the sensitivity of large scale bioenergy deployment strategies. The full exclusion of CCS technologies (incl. BECCS) has been identified as the single most important factor for the achievability and mitigation costs of the well-below 2 °C target. Moreover, gradually limiting modern bioenergy use to 100 EJ/year ranked second for the mitigation costs. The potential and techno-economic performance of wind and solar energy technologies or the gradually faster improvement of economy-wide energy intensity lead to smaller impacts on mitigation costs.

The EMF33 scenario protocol focuses on large scale bioenergy deployment and climate change mitigation and studies radical sensitivity cases; these include the full exclusion of

BECCS technologies as well as the hard limit on modern bioenergy use. On top of that, EMF33 also includes more gradual sensitivity tests for the availability, maturity, and performance of ABTs. The latter leads to smaller sensitivities than the full exclusion of BECCS technologies (see also Bauer et al. 2018b). We find that the changes in prices and quantities of bioenergy and emissions are heterogeneous depending on which characteristic of bioenergy technologies is specifically changed. It is crucial whether the energy or the carbon-related aspect of bioenergy technologies is changed. This means that the gradual sensitivities are not only muted versions of the radical sensitivity of excluding BECCS technologies altogether, but they lead to qualitatively different results. Techno-economic variations to explore the carbon value of bioenergy increase carbon prices but temporarily increase bioenergy use, whereas limitations on producing high-value liquid fuels reduce bioenergy use while carbon prices also increase. Therefore, sensitivity tests of bioenergy technologies require careful design and analysis of energy and carbon-related aspects. It is worth noting that the injection rate turned out to be a crucial parameter. The default value applied here is based on expert opinion. The sensitivity of this parameter suggests that improved knowledge could strongly reduce uncertainties.

In this study, we also expanded the sensitivity analysis beyond the hard limit of 100 EJ/year on modern bioenergy use to more gradual sensitivity tests of key assumptions such as agricultural trade and yield improvements. Different to the sensitivity tests regarding bioenergy technologies the sensitivity patterns for prices and quantities of bioenergy and emissions are qualitatively the same and only differ in magnitude. The more gradual constraints on biomass production systems lead to much smaller changes in the intersectorial interactions (particularly bioenergy markets) than the hard bound on modern bioenergy use. The more gradual sensitivities lead to intrasectorial adjustments that buffer the intersectorial effects. The intrasectorial effects on intensification and extensification of land-use are, however, substantial. Similar results are expected for variations of other key assumptions in the land-use sector that indicated only small changes in bioenergy prices (see Humpenöder et al. 2018, for more information).

The differentiated analysis presented here puts sensitivity tests into perspective. For instance, the sensitivity with respect to energy demand growth appears relatively small when compared with the radical variations regarding bioenergy use and BECCS availability. However, moving the focus towards the more gradual sensitivities narrows the difference and can even reverse the ranking. The 27% lower bioenergy use in 2050 due to lower final energy demand is more substantial when compared with gradual rather than radical sensitivities of bioenergy technologies and supply, especially in terms of bioenergy and carbon price changes. Hence, the radical sensitivities are without doubt interesting for diagnostic purposes and these can be implemented relatively easily into different IAMs for the purpose of harmonized model comparisons. However, for a fair and balanced assessment of climate change mitigation, the set of sensitivity tests has to be chosen carefully to avoid biases in results. The present study systematically compares radical and gradual sensitivity tests and highlights that the radical sensitivities induce substantial variations in results. The very strong intersectorial impacts get much smaller for the gradual sensitivities. This is mostly due to the intrasectorial adjustments that partly insulate sectors. These intrasectorial flexibilities, however, can imply very strong effects on the transformation of energy use or land-use changes. Nonetheless, the energy-land nexus becomes more intense for stronger climate change mitigation targets and, thus, the intersectorial coupling becomes tighter via emissions and bioenergy markets.

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