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Steven K. Rose, Elmar Kriegler, Ruben Bibas, Katherine Calvin ...+4 more authors

Institutions: Electric Power Research Institute, Potsdam Institute for Climate Impact Research, Joint Global Change Research Institute, Utrecht University ...+2 more institutions

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Bioenergy in energy transformation and climate management

**Steven K. Rose · Elmar Kriegler · Ruben Bibas ·
Katherine Calvin · Alexander Popp ·
Detlef P. van Vuuren · John Weyant**

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Abstract This study explores the importance of bioenergy to potential future energy transformation and climate change management. Using a large inter-model comparison of 15 models, we comprehensively characterize and analyze future dependence on, and the value of, bioenergy in achieving potential long-run climate objectives. Model scenarios project, by 2050, bioenergy growth of 1 to 10 % per annum reaching 1 to 35 % of global primary energy, and by 2100, bioenergy becoming 10 to 50 % of global primary energy. Non-OECD regions are projected to be the dominant suppliers of biomass, as well as

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S. K. Rose (✉)
Energy and Environmental Analysis Research Group, Electric Power Research Institute, 2000 L Street NW, Suite 805, Washington, DC 20036, USA
e-mail: srose@epri.com

E. Kriegler · A. Popp
Potsdam Institute for Climate Impact Research, Potsdam, Germany

R. Bibas
Centre International de Recherche sur l'Environnement et le Développement (CIRED), Nogent-sur-Marne, France

K. Calvin
Pacific Northwest National Laboratory, Joint Global Change Research Institute at the University of Maryland–College Park, College Park, MD, USA

D. P. van Vuuren
PBL Netherlands Environmental Assessment Agency, Bilthoven, The Netherlands

D. P. van Vuuren
Department of Geosciences, Utrecht University, Utrecht, The Netherlands

J. Weyant
Stanford University, Palo Alto, CA, USA

consumers, with up to 35 % of regional electricity from biopower by 2050, and up to 70 % of regional liquid fuels from biofuels by 2050. Bioenergy is found to be valuable to many models with significant implications for mitigation and macroeconomic costs of climate policies. The availability of bioenergy, in particular biomass with carbon dioxide capture and storage (BECCS), notably affects the cost-effective global emissions trajectory for climate management by accommodating prolonged near-term use of fossil fuels, but with potential implications for climate outcomes. Finally, we find that models cost-effectively trade-off land carbon and nitrous oxide emissions for the long-run climate change management benefits of bioenergy. The results suggest opportunities, but also imply challenges. Overall, further evaluation of the viability of large-scale global bioenergy is merited.

1 Introduction

How important could bioenergy be to future energy transformation and climate change management? This study analyzes the potential role of bioenergy using the models designed to explore potential global energy transformations. Since the beginning of humanity, biomass has been an important energy resource, serving heating and cooking needs. Over time, with the development of modern society, energy demand has expanded, with society's broader set of needs increasingly met by fossil fuels. Fossil fuels are an energy dense and relatively abundant resource. However, their combustion also leads to a net addition of greenhouse gases into the atmosphere, in particular carbon dioxide. Biomass, on the other hand, is a renewable resource that can be grown, converted for energy, and re-grown. During this cycle, biomass grows and naturally sequesters carbon dioxide from the atmosphere through photosynthesis.

Growth and carbon sequestration are an important distinction between biomass and fossil fuels, as sequestration offsets the emissions released during conversion of biomass to energy. However, the net emissions associated with biomass use for energy services is a complex issue due, in particular, to potential changes in land use and land management (e.g., Searchinger et al. 2008; Wise et al. 2009; Popp et al. 2011). There are also potential social implications for commodity markets and other environmental end-points (e.g., Hertel et al. 2010; Berndes 2002). The extent of these effects depends on a host of factors, including the type of biomass and numerous uncertainties—biophysical (e.g., carbon density, land productivity) and economic (e.g., land conversion, yield responses).

Biomass is also a flexible resource that can service many end-uses—transportation, power, heat, hydrogen production, and materials. For the power sector, biomass is also appealing because it can serve base load electricity demand, while variable renewable resources such as wind and solar require more integrated solutions to service substantial load. In addition, there is considerable interest in the prospects of combining biomass-based energy conversion processes with carbon dioxide capture and geologic storage capability (BECCS). BECCS could be an energy technology with net negative emissions that sequesters carbon during growth and captures and stores conversion emissions underground indefinitely (Azar et al. 2006; Fisher et al. 2007). As a negative emissions technology, BECCS could be particularly helpful for attaining low greenhouse gas concentration targets (e.g., Van Vuuren et al. 2007).

To date, a variety of individual studies have reported on large-scale bioenergy deployment in climate management scenarios (e.g., Wise et al. 2009; Rose et al. 2012; Reilly et al. 2012; Popp et al. 2011; van Vuuren et al. 2010). Some have focused explicitly on BECCS

Table 1 Bioenergy modeling details for the models analyzed

Label	Model					Bioenergy									
		Biomass feedstocks[1]				Power		Liquid fuel		Hydrogen		Biogas[2]	Biomass heat	Explicit land use	
		1st gen	Dedicated lignocellulosic	Residues	Sustainability considerations	w/o CCS	w/ CCS	w/o CCS	w/ CCS	w/o CCS	w/ CCS			General	For bioenergy
U	AIM-Enduse	x	x	x	x	x	x	x		x	x	x	x		
B	BET	x	x	x	x	x	x	x				x			
D	DNE21	x	x	x	x	x	x	x		x	x				
L	ENV-Linkages[3]					x									
F	FARM		x	x	x	x	x						x	x	x
G	GCAM	x	x	x	x	x	x	x	x	x	x	x		x	x
Gr	GRAPE			x	x	x	x	x						x	
Im	IMACLIM	x	x	x	x	x	x	x							
I	IMAGE	x	x	x	x	x	x	x		x	x			x	x
Me	MERGE		x	x	x	x	x	x							
M	MESSAGE		x	x	x	x	x	x	x	x	x	x	x	x	x
P	POLES	x	x	x	x	x	x	x	x	x	x	x			
R	ReMIND/ MAgPIE	x	x	x	x	x	x	x	x	x	x	x	x	x	x
T	TIAM-WORLD	x	x	x	x	x	x	x	x			x	x		x
W	WITCH	x	x	x	x	x	x	x							

[1] See Supplemental Material for additional detail on feedstock and sustainability considerations

[2] An "x" in this column indicates that the model explicitly tracks and reports the biogas energy produced. Some models include landfill GHG mitigation but do not track energy output

[3] In ENV-Linkages, no particular feedstock is specified. However, there is a natural resource input to bioelectricity production that is representative of biomass

(e.g., Azar et al. 2010; Lemoine et al. 2012). And, assessment products have summarized the literature and reported potential bioenergy annual deployment ranges (Fisher et al. 2007; Chum et al. 2011). This paper advances understanding of bioenergy's potential role in climate change management with a focused and comprehensive bioenergy deployment assessment with the latest modeling. Specifically, this study takes stock of the full bioenergy perspectives of 15 models running comparable scenarios. Recent community-wide model development, including the revision of past bioenergy modeling and introduction of new bioenergy technologies into many models (e.g., BECCS) provides an opportunity for a broad assessment that yields insights into potential alternative long-run roles for bioenergy. The comprehensive assessment, from biomass feedstocks to bioenergy deployment across economies and regions, offers a glimpse into what might be possible and encourages reflection and research on future technology, implementation, and policy opportunities and challenges.

In this paper, we characterize the potential future dependence upon bioenergy and the value of bioenergy in transformation of the energy system. The paper is complemented by Popp et al. (2013) who explore the land-use and emissions implications of bioenergy and land-use policies in transformation pathways for three specific models, and Luderer et al. (2013) who evaluate the overall energy transformation role of renewable energy technologies with an emphasis on non-bioenergy renewables.

We begin with an overview of the models and scenarios considered. We then present results quantifying the dependence and value of bioenergy. We conclude with key insights and research directions.

2 Models and scenarios

The overall Energy Modeling Forum Study 27 (EMF-27) is an exploration into the cost and societal transformation implications of different technological and climate policy futures (see Kriegler et al. (2013) for an overview). The EMF-27 study includes 19 models. Our study evaluates 15 of the models—those that reported global biomass primary energy results. Table 1 of the provides a structural overview of bioenergy modeling within each model. The models consider different sets of biomass feedstocks and bioenergy conversion technologies. Almost all of the models have an option to produce electricity from biomass-fueled power plants with CCS. Some also have biofuel and hydrogen options with CCS. About a third of the models have biogas technology, and even fewer have biomass-based heat. Differences in bioenergy options could affect results as they represent differences in competition for biomass feedstocks, as well as one of many differences in modeled alternatives for decarbonizing the various parts of the economy. Less than half of the models explicitly consider land-use. Of those that do not, some implicitly consider land-use via bioenergy cost and/or sustainability constraints on biomass supply (e.g., allowable land-use). See the Supplemental Material (SM) for additional detail on feedstocks modeled and sustainability considerations.

In this study, we consider seven scenarios—the model baseline and six climate policy scenarios. The baseline represents business as usual without additional climate policy. The climate policy scenarios are defined by the stringency of the climate target and bioenergy-related technology assumptions. Specifically, we consider (i) 2100 CO_2 equivalent atmospheric concentration targets of 550 and 450 ppm, (ii) default and constrained biomass supply variants, and (iii) variants with and without CCS. The concentration targets are associated with 2100 radiative forcing targets of 3.7 and 2.8 W/m^2. The 3.7 W/m^2 policy does not allow the forcing target to be exceeded at any point in time, while the 2.8 W/m^2 target allows overshoot prior to

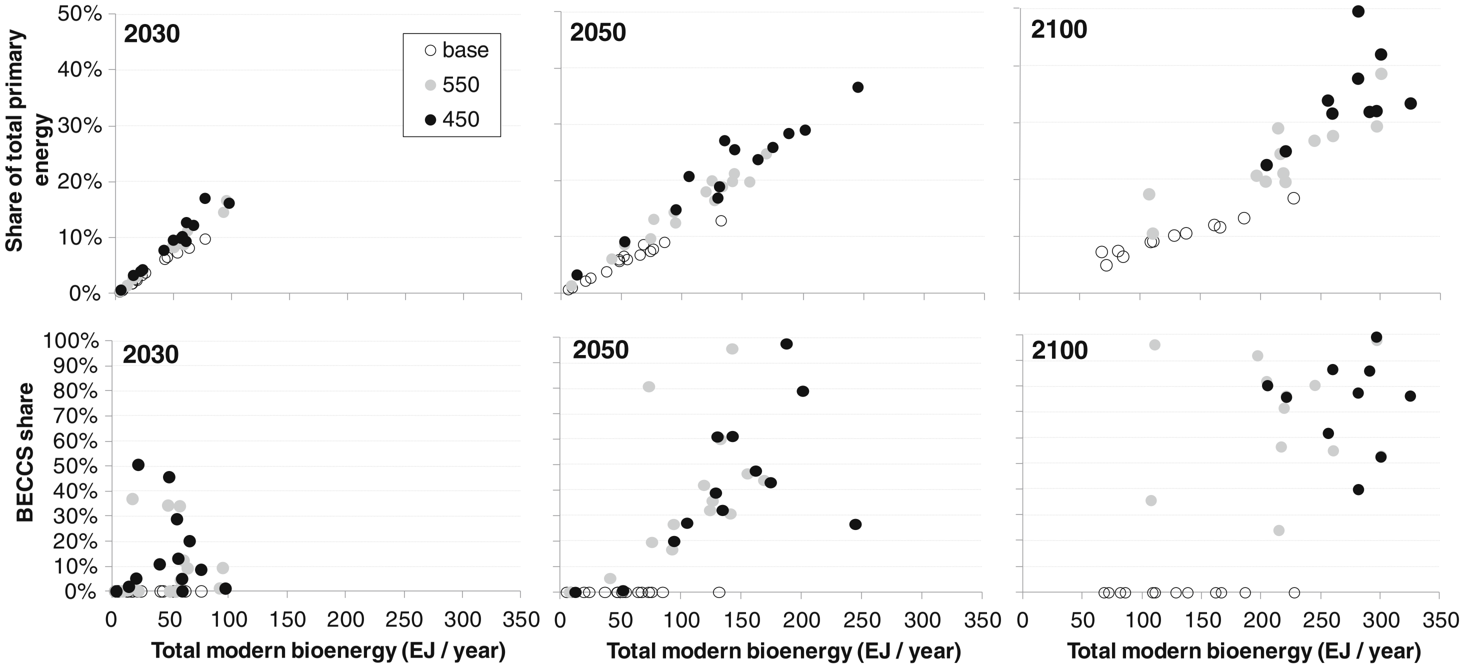

Fig. 1 Annual global modern biomass primary energy and BECCS share of modern bioenergy in baseline, 550 ppm, and 450 ppm scenarios in 2030, 2050, and 2100

hitting the target in 2100. Biomass supply is modeled according to each model's default methodology or is globally constrained to an annual supply of 100 EJ per year of modern bioenergy. The latter was designed to simulate potential constraints placed on modern bioenergy use due to public concerns regarding the net environmental, economic, and social implications of additional bioenergy. The annual constraint level of 100 EJ per year is somewhat arbitrary, but is binding on most models and low relative to technical potential.[1] The constraint on CCS applies to both fossil fuel and bioenergy technologies and represents potential constraints due to technical feasibility issues and public apprehension regarding an unproven technology and geologic storage. The considered scenarios are a parsimonious set chosen to elucidate differences in model preferences for bioenergy—first, without climate policy, and then, in response to increasingly stringent climate targets, and with potential constraints on bioenergy use and emissions capture.

3 Results

We characterize the importance of bioenergy to future energy transformation and climate change management by first assessing projected energy system dependence on bioenergy—overall, by enduse, and by region. We then, using a variety of metrics, evaluate the value of bioenergy to climate change management. Note that results are shown for models that reported the relevant information. Therefore, some models are represented in all figures, and some models are not. To simplify the figures, letter labels are used for the models (see Table 1).

3.1 Dependence on bioenergy

In Fig. 1, we find substantial variation across models in *baseline* deployment of modern bioenergy. All models project an increasing role for modern bioenergy over time, generally with increases in both the level and share of primary energy. In 2030, we observe bioenergy of 5–75 EJ. By 2050, deployment is 5–130 EJ, and by 2100, 70–230 EJ (see the SM for model specific results). In 2030, bioenergy's share of baseline global primary energy is less than 10 % in all models, with the share less than 5 % in most models. However, by 2050, some models have reached over 10 %, and by 2100, some are over 15 %. Assumed increasing demand for liquid fuels late in the century, and scarcity of alternatives, such as oil and coal to liquids, are contributing to the high baseline bioenergy levels by 2100.

The climate targets create a strong incentive for increased bioenergy deployment and reliance in all models (Fig. 1). Increases, especially those further in the future, are dominated by BECCS use when modelled. Increases in bioenergy without CCS are strongest in the near-term (e.g., 2030) when CCS is assumed to not be commercially available or BECCS is less cost-effective. The timing of BECCS deployment is discussed later. Energy system dependence on bioenergy increases substantially compared to the baseline as bioenergy levels increase and the overall energy system shrinks. For the 550 ppm policy, bioenergy becomes 1–17 % of global primary energy by 2030 (2–15 % from the 100-year horizon models), and 1–25 % (9–25 %) by 2050, and 10–39 % (10–39 %) by 2100.[2] For the 450 ppm policy, bioenergy's share of the energy system is even larger, reaching 1–

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[1] Technical potential has been estimated at around 300 and 500 EJ/year in 2020 and 2050 respectively (Chum et al. 2011). The 100 EJ/year constraint is applied globally and does not apply to traditional uses of bioenergy (e.g., rural heating and cooking). This level is consistent with the lower end of past scenario results and analysis of the consequences of sustainability criteria on biomass supply.

[2] Three of the fifteen models included in this study have 2050 time horizons (models D, L, and U).

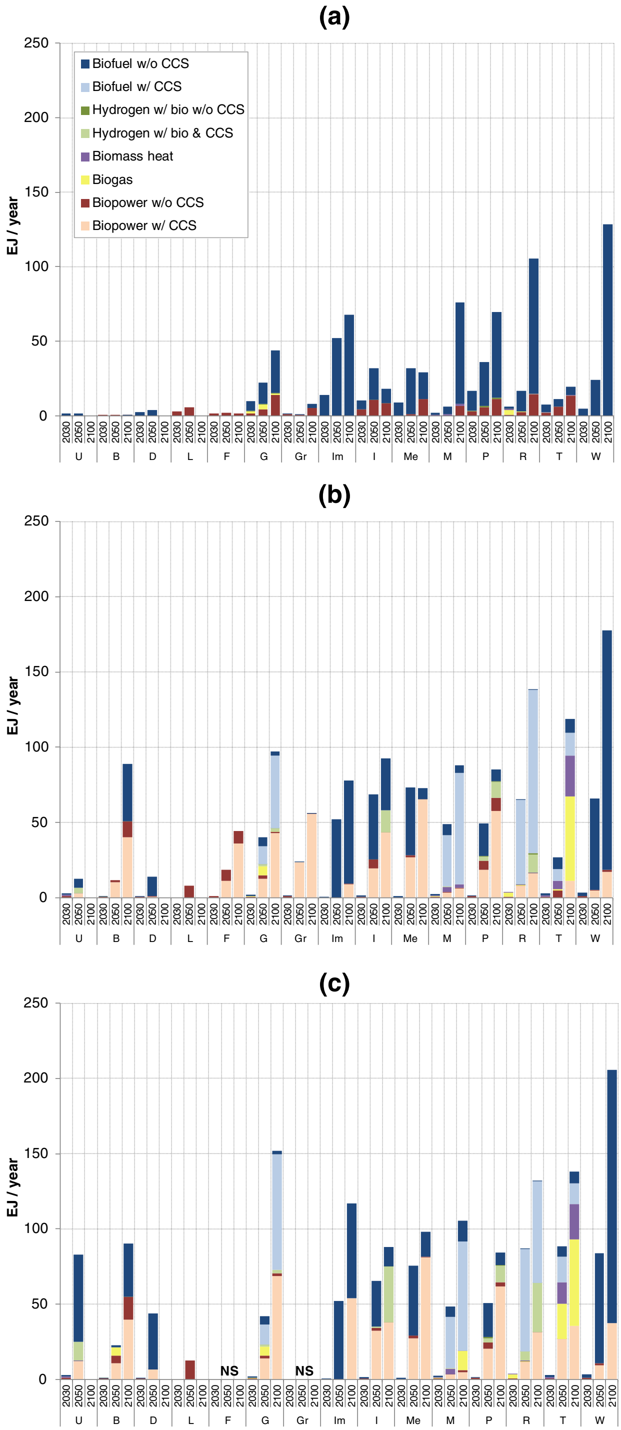

Fig. 2 Global secondary bioenergy in 2030, 2050, and 2100 for baseline (**a**) 550 ppm (**b**) and 450 ppm (**c**) scenarios. Note: NS indicates no scenario reported

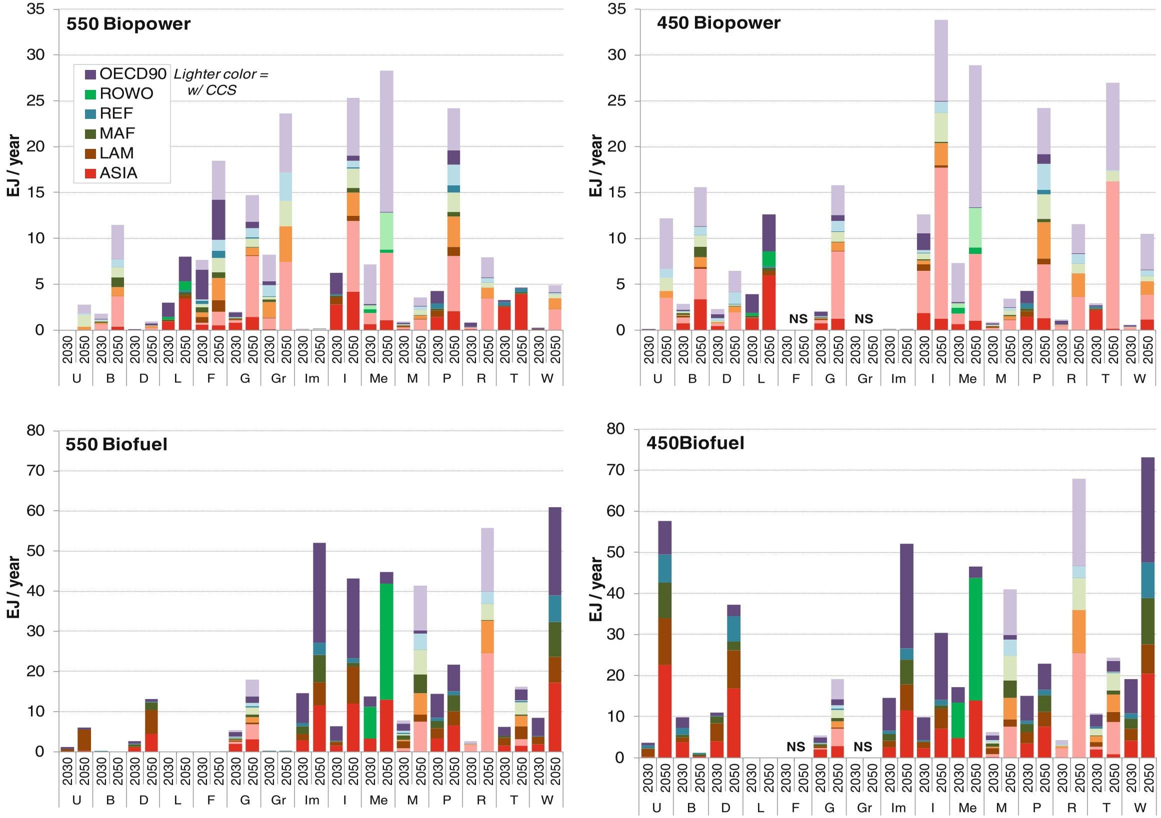

Fig. 3 Regional secondary biopower (*top*) and biofuel (*bottom*) in 2030 and 2050 for 550 (*left*) and 450 (*right*) ppm scenarios. Notes: ROWO is only used by the models L and Me. For the L model, ROWO is defined as countries not included in the other regions. For the Me model, ROWO is defined as an aggregation of LAM, MAF, and REF. Light (*dark*) shading is used for technologies with (*without*) CCS. NS indicates no scenario reported

17 % (3–17 %) by 2030, 3–37 % (9–37 %) by 2050, and 23–50 % (23–50 %) by 2100. By 2100, most of the models depend heavily on bioenergy for energy supply, and it is largely with BECCS.

The implied bioenergy growth from today can be substantial, and represents a challenge for pursuing expanded bioenergy pathways. Bioenergy average annual growth rates for 2005–2050 increase from 0 to 6 % (0–6 %) per year in baseline scenarios to 1–9 % (1–9 %) in 550 scenarios, and to 4–10 % (4–9 %) in 450 scenarios (see SM).

The share and growth rate ranges are broad, and generalizations are elusive, as there are no simple explanations for low or high results. For instance, we cannot conclude that more bioenergy would be deployed with more feedstock or bioenergy conversion options (such as additional BECCS options). Results are being determined by combinations of assumptions regarding biomass feedstock supplies, bioenergy options and costs, other technology options and costs, integrated systems modeling, and baselines (e.g., energy system size, emissions levels and composition). Elucidating and assessing these modeling elements requires a dedicated effort beyond the scope of this analysis, but one that should be a priority for future research.

We also find that CCS availability does not necessarily lead to more bioenergy in the next few decades, but could result in increased bioenergy use over the century. Comparing the default and no CCS (NoCCS) 550 ppm scenario results, we find that almost all models use less bioenergy globally in the first half of century and more in the second half of the century, with more bioenergy cumulatively over the entire century (see SM). The changes in annual bioenergy primary energy resulting from the availability of CCS range from very modest to significant, with changes of 30-60 %. Whether CCS leads to an increase in annual bioenergy mid-century or later is a function of model specific costs and cost-effective overshoot. Only a few models submitted NoCCS 450 ppm results. For all those that did, CCS decreases near-term bioenergy, while increasing long-term bioenergy. Overall, BECCS reduces the need for near-term mitigation by offering the possibility of rapid and significant mitigation later in the century. This reduces costs but may have climate implications as discussed below.

The remainder of this sub-section focuses on the projected sources of modern bioenergy, and their destination within the energy system. We evaluate where biomass supplies are coming from, the types of feedstocks being supplied, and where bioenergy is being used across sectors and regions.

In general, the models project increasing production of modern biomass primary energy from non-OECD countries, with 50-85 % of global bioenergy coming from non-OECD countries in 2050 (see SM).[3] Within non-OECD countries, most models project increased bioenergy supply from non-OECD Asia to 2050. Beyond 2050, to 2100, there is less agreement—with some models projecting an increasing share from non-OECD Asia, while others suggesting a declining share, and increasing roles for other non-OECD regions, such as Latin America and Africa.

Second generation dedicated lignocellulosic feedstocks, including energy crops and woody biomass for some models, are a key bioenergy feedstock for all the models that reported feedstock detail (SM). Dedicated lignocellulosic feedstock use increases over time, while first generation energy crops play only a small role.[4] The use of residues (agricultural, forestry, and municipal solid

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[3] Across the models, we find significant variation in 2005, the implications of which is a topic for further analysis.

[4] Five of the models did not model first generation feedstocks (see SM). Some, such as sugar cane for ethanol, have more appealing yield, cost, and GHG performance. However, we did not have decomposed results necessary for assessing the role of individual feedstocks.

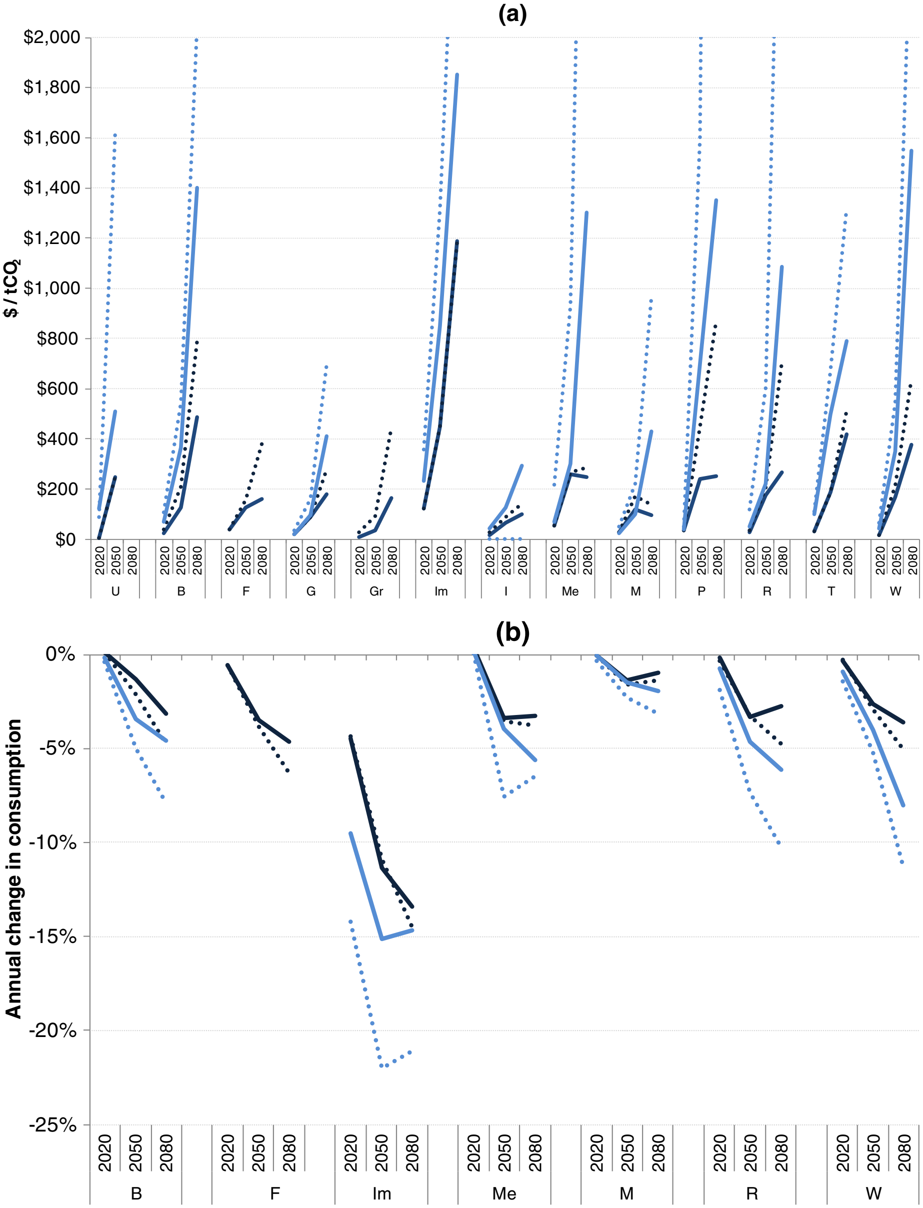

Fig. 4 Annual marginal mitigation cost (**a**) and world consumption loses relative to baseline (**b**) with default and constrained biomass supply. Notes: Results from 550 and 450 ppm scenarios indicated by *dark blue* and *light blue* respectively. *Solid* and *dotted* lines correspond to default and constrained biomass supply respectively. Figure (**a**) y-axis truncated at \$2000/tCO$_2$. Models D and L did not exceed 100 EJ/year and are therefore not included. Model U did not in the 550 scenario only. Models Gr and Im only slightly exceeded 100 EJ/year in the 550 scenario. Model Im reports substantially larger consumption losses than the other models. Some portion of this difference is due to the model's consideration of market imperfections, inertia, short-run adjustment constraints and imperfect expectations

waste) is significant, but varies substantially across models. Generally, residue use increases over time, but its bioenergy share decreases.

Biomass can be deployed to various parts of the energy system. In the baseline, modern bioenergy is primarily biofuels, with volumes increasing over time (Fig. 2a).[5] Biopower is the second most prominent use, with biogas a distant third. Beyond these generalizations, there is no shared vision for baseline bioenergy deployment levels. Model variations in the bioenergy mix are, among other things, due to differences in the options modeled (Table 1).

Deployment shifts substantially in response to the climate policy (Fig. 2b and c), with significant increases in bioenergy use, primarily biopower. BECCS assumes a prominent role in the 550 ppm policy results, which increases with the 450 ppm policy and over time. Specifically, in the 450 policy, for models with BECCS, BECCS represents approximately 70 to 100 % of biopower, 70 to 100 % of biofuels, and 85 to 100 % of hydrogen production by 2050, with similarly high shares in 2100. Whether BECCS expansion is greatest in electricity, liquids, or hydrogen depends on the BECCS options modeled, as well as the other power and transportation decarbonization technologies available. As noted, only a few models consider biofuel or bio-hydrogen with CCS technologies. These technologies could be valuable to the transportation sector where there are fewer decarbonization options. Differences in life cycle emissions may also play a role, with CCS in the refinery sector reducing only biorefinery emissions and not tailpipe ethanol combustion emissions. CCS emissions capture rates also vary across technologies and models. However, from the models with BECCS available for all three uses, we do not find a clear preference. For example, in models M and R, biofuels with CCS is the dominate BECCS strategy, while in models G and P, biofuels with CCS is barely used.

From the NoCCS scenarios, we find that having CCS can lead to a different allocation of biomass across end-uses. Logically, the allocation is towards the end-uses with CCS. Thus, some models allocate towards biopower, while others allocate towards a combination of enduses. When biogas is modeled, having CCS tends to reduce biogas.

Bioenergy is projected to contribute to the decarbonization of the power sector in most regions (Fig. 3). The largest regional levels are projected for OECD and Asian countries. Overall, most future biopower is projected to be in non-OECD countries (Asian and other non-OECD), primarily with CCS when the technology is modeled. From 2030 to 2050, some models exhibit a dramatic increase in biopower, with biopower representing anywhere from a small to sizable share of regional electricity systems. For instance, in 550 ppm scenarios, biopower represents 0–15 % of electricity in Asia, 0–33 % in Latin America, 0–13 % in Middle East and Africa, 0–31 % in the OECD, and 0–21 % in Reforming Economies (Former Soviet Union and Central and Southeastern Europe). With the tighter climate target, there are regional increases and decreases in biopower levels with increased dependence on biopower in some key regions—with biopower 0-27 % of electricity in Asia, 0–23 % in Latin America, 0–19 % in Middle East and Africa, 0–31 % in the OECD, and 0–21 % in Reforming Economies. In the 450 ppm scenario, biopower is produced almost entirely with CCS, even in 2030.

Bioenergy is also projected to contribute to the decarbonization of liquid fuels in most regions (Fig. 3). The largest biofuel levels are in the OECD and Asia, yet the OECD is a larger fraction of the total than it was for biopower. CCS is less prominent in biofuels, which is a function of it not being modeled in many models. When modeled, biorefineries with CCS are projected throughout the non-OECD regions, with notable levels in Latin America, Middle East and Africa, and Reforming Economies. By 2050, biofuels represent 0–38 % of total liquid fuel use in Asia, 0–71 % in Latin America, 0–34 % in Middle East and Africa, 0–37 % in the OECD, and 0–70 % in

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[5] Biomass conversion losses vary by conversion process. Thus, in Fig. 2, a unit of biofuel energy does not imply the same amount of biomass feedstock as a unit of biopower.

Reforming Economies. With the tighter climate target, dependence of biofuels grows to where it could be the majority liquid fuel in all regions by 2050: 1–51 % in Asia, 0–70 % in Latin America, 2–52 % in Middle East and Africa, 0–47 % in the OECD, and 3–71 % in Reforming Economies.

As noted, it is difficult to generalize on the ranges. For some of the models, under the tighter climate policy, dependence on bioenergy spreads to other regions, as well as earlier in time. The broad ranges however reflect differences in relative generation and transportation technology assumptions and market conditions. For instance, regional ranges are also broad for natural gas electricity shares (e.g., 2–31 % in Asia and 4–67 % in the OECD in 2050 for the 550 ppm scenario). Low 2050 regional bioenergy dependence can be consistent with low global bioenergy, a different regional allocation of bioenergy, allocation of biomass to an alternative bioenergy use, limited bioenergy use in the first half of the century, and/or more or less bioenergy technologies.

3.2 The value of bioenergy

We assess the value of bioenergy deployment in the climate policy scenarios by analyzing the implications of constraining bioenergy, i.e., by comparing the default scenario with the constrained biomass supply and no CCS scenarios. We use a variety of metrics to examine alternative dimensions of "value"—some conventional measures of economic value and others proxies for value. Specifically, we explore the policy cost implications of bioenergy mitigation, and then the energy system and GHG emissions implications. For the former, we consider the effects on the marginal cost of mitigation and losses in global economic consumption. For the later, we analyze energy consumption, energy system substitution for bioenergy, and effects on GHG emissions trajectories.

The marginal costs of mitigation in 2020, 2050, and 2080 are shown for the 450 and 550 ppm scenarios in Fig. 4a. Results for this and subsequent figures are shown for models that submitted both the default and constrained biomass scenarios and for which the bioenergy constraint binds (i.e., over 100 EJ per year used in Fig. 1). For models where the bioenergy constraint is non-binding, projected costs, energy systems, and emissions are unaffected. The marginal costs of controlling GHGs are substantially higher for the 450 policy, despite the ability to overshoot, and the difference between the 450 and 550 policy marginal costs grows over time. However, there can be a slowing, leveling off, or even a decline in the latter half of the century. For some, this is because they have reached the climate target prior to 2100 and can be less aggressive with mitigation.

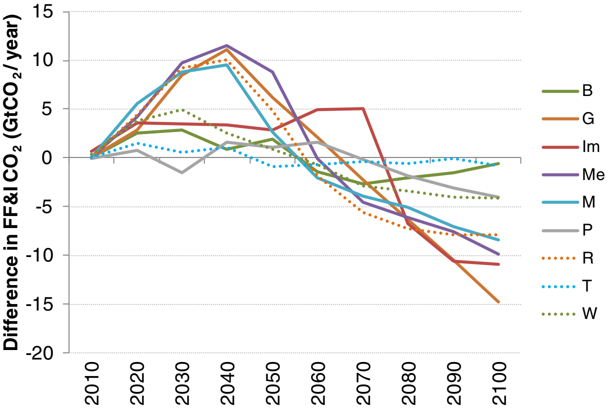

Fig. 5 Additional reductions in global fossil fuel and industrial CO_2 emissions with constrained versus default biomass supply for 450 ppm scenarios. Note: only models with 2100 horizons shown

Of most interest to this paper are the differences between the solid and dotted lines. The dotted lines are the marginal costs when annual use of modern biomass is constrained. Constraining biomass supply increases the marginal cost significantly in most models for both the 550 and 450 policies, with the impact increasing over the century when default bioenergy deployment is largest (recall Fig. 1). The effect is greatest for the 450 policy when the dependence on bioenergy is strongest, especially for models with BECCS (Lemoine et al. 2012). For instance, in the 550 policy, marginal costs increase by up to 170 % in 2020 and 2050, and in the 450 policy, by up to 210 % and 220 % in 2020 and 2050 respectively. The constraint on biomass is forcing models into more expensive mitigation technologies. Marginal costs are increasing over time in most results.

Marginal costs are useful estimates of the most expensive technologies deployed over time in each model. However, consumption losses are a more useful measure of overall costs to the economy. We are only able to provide consumption loss estimates from a subset of models (Fig. 4b). However, from these, we see sizable relative increases in consumption losses when bioenergy is constrained. For the 550 policy, consumption losses increase by as much as 60 % and 75 % in 2050 and 2080 respectively. For the 450 policy, consumption losses increase by as much as 90 % and 75 % respectively. Thus the constraint on biomass is forcing more resources to be directed towards mitigation, away from other productive uses, which drives up prices and drives down consumption. In summary, from Fig. 4, we can surmise that the value of bioenergy is extremely high for many models.

Is BECCS essential for achieving low climate targets? The NoCCS 450 scenarios give us some indication. However, they are not a direct evaluation as these scenarios exclude fossil fuel CCS options as well. Overall, we find that we cannot draw a strong conclusion. Of the ten models that used greater than 100 EJ per year in the 450 scenario and had 2100 horizons, four were able to identify solutions without CCS (models G, P, R, and T), while five reported solution infeasibility, and one reported infeasibility due to an extremely high carbon price. BECCS plays a prominent role in the default 450 scenario for all four models with feasible NoCCS solutions, yet BECCS does not appear to be essential in these models. Furthermore, as shown in Fig. 4a, two of the models (G and T) are fairly insensitive to the constraint on bioenergy use. A direct model inter-comparison study of this issue would be useful: one that establishes a variety of criteria for BECCS to be considered essential (e.g., scenario infeasibility without BECCS when all other technologies are available; or a finding that BECCS is required when other technologies are unavailable and/or mitigation action is delayed).

To understand the cost implications of constraining bioenergy, we investigate how each model substitutes for bioenergy. Knowing what trades-off with bioenergy helps us to understand why constraining bioenergy is more or less costly across models. Models can substitute for bioenergy by changing energy demand and/or utilizing alternative supply technologies. Mitigation costs transmit through to the cost of energy and thereby affect energy demand. Specifically, mitigation results in reductions in final energy demand, and constraining biomass supply leads to additional demand reductions in all models. For example, with the 450 policy, final energy reductions increased from 13–44 % to 19–56 % in 2050 with biomass constrained, and from 23–54 % to 25–70 % in 2100 (SM).

The models are also substituting energy supply technologies in response to the constraint on biomass. Through 2050, many models keep fossil fuels without CCS around longer (coal, gas, and oil), as well as replace bioenergy mitigation with fossil fuels with CCS. Comparing cumulative changes in primary energy when bioenergy is constrained (vs. default) for the 550 policy, we find that, by 2100, the models most dependent on bioenergy with default biomass supply are forced to capture most fossil fuel emissions, as well as push into their other more expensive technologies (SM). For many it is high-cost renewables. Note that, in addition to bioenergy reductions, we also see reductions in gas, oil, and coal. This is due to a variety of factors, in particular, the fact that BECCS is constrained and can no longer accommodate as much continued use of fossil fuels.

We find that constraining biomass supply not only affects the cost of stabilization, but also the cost-effective emissions trajectory. For the 450 policy, with biomass supply constrained, seven of the models must reduce fossil fuel and industry CO_2 emissions significantly more quickly in the near-term, and subsequently less in the latter half of the century (Fig. 5). Constraining biomass supply constrains the opportunity for negative emissions, and forces an increase in near-term emissions reductions. Specifically, these seven models reduce an additional 75–345 $GtCO_2$ of fossil fuel and industry (FF&I) CO_2 through 2060, and 70–255 $GtCO_2$ less from 2060 to 2100. The result is a fundamentally different emissions trajectory that is flatter and that may have different global temperature implications (e.g., Blanford et al. 2013). The models using significant bioenergy (especially BECCS) in their default 450 scenario exhibit the most dramatic change in their FF&I CO_2 emissions pathway. This result is similar to the insight of Azar et al. (2010) and Lemoine et al. (2012) who suggested that BECCS could cost-effectively accommodate higher near-term fossil fuel emissions. The other two models shown in Fig. 5 exhibit similar, but more modest, effects (P and T). The more muted differences from these models are, in part, due to model implementation of the climate targets (emissions budgets vs. radiative forcing targets) and model optimization algorithm (myopic vs. intertemporal). The magnitude of the difference in models is also affected by the mitigation options beyond those associated with FF&I CO_2 (e.g., see Popp et al. 2013, on land use emissions and mitigation).

An important additional perspective to consider with respect to bioenergy deployment is land-use related GHG emissions. Land conversion caused by bioenergy demand is a prominent public concern, as is intensification of agricultural land-use. Both have the potential to release additional GHG emissions into the atmosphere. A few models in this study reported land-use CO_2 and N_2O emissions (n = 6 and 3 respectively). Comparing default and constrained bioenergy land-use emissions, we find that most models cost-effectively trade-off lower land carbon stocks and higher N_2O emissions for the long-run climate change management benefits of bioenergy (SM). The nature of the emissions-for-bioenergy trade-off varies across models, e.g., reduced forest carbon mitigation (afforestation and avoided deforestation), displaced natural growth, or reduced N_2O mitigation (see Popp et al. 2013, for a focused discussion of the land-use implications of bioenergy for three of the models). The models are, however, weighing the increased emissions (or reduced mitigation) implications of land adjustments from increasing bioenergy with the long-run mitigation value of bioenergy, and determining that the bioenergy is worthwhile. Other models show essentially no trade-off between bioenergy and land-use CO_2 emissions/mitigation. For some of these models, this is due to land-use not being explicitly modeled. For others, residues are the only feedstock modeled (model Gr), or avoided deforestation levels are modeled as similar in both scenarios (R).

Overall, these results, to some degree, help reconcile the climate management perspective that bioenergy is valuable with the more narrowly focused indirect land-use and lifecycle analysis emissions discussion estimating reduced net emissions benefits, and potentially increased net emissions, with increased use of bioenergy (e.g., Searchinger et al. 2008; Hertel et al. 2010).The result here represents the bigger picture—the potential long-run climate management value of bioenergy.

Note that not all bioenergy is alike, and the results shown reflect each model's characterization of biomass feedstocks, conversion processes, and resource use. Thus, the long-run value of bioenergy is a function of these elements. In addition, pricing land carbon, which is what is implemented in some models, does not value other benefits (e.g., biodiversity, environmental services), and it is not the same as setting land aside, which implies that the set aside land has infinite value. When pricing land carbon, it may still be cost-effective to displace the carbon, as shown in the results here, and valuing other benefits may act as an additional land conversion disincentive.

There is still much to be explored to fully reconcile the two GHG emissions accounting perspectives—including assessing assumptions on yield responses, residues, land use change, and conversion efficiencies, as well as implications for commodity markets and consumption. In addition, the scenarios here assume that we are able to price, and therefore internalize, all emissions and carbon stock changes. However, land use policy coordination and implementation will be challenging, and is unlikely to be comprehensive, which could have cost and emissions leakage implications (see, for instance, the discussion in Lubowski and Rose 2013).

4 Conclusion

This study takes advantage of a unique opportunity to take a coordinated, consistent, and comprehensive look across 15 models to elucidate and evaluate the potential importance of bioenergy in managing future climate change. In particular, we are interested in how much projected future energy systems rely on bioenergy.

The results suggest that bioenergy could play a substantial and valuable role in the world's energy system and in the management of climate change. Most models project bioenergy as a significant part of the energy transformation, with increasing dependence on bioenergy with tighter climate targets, both in a given year as well as earlier in time, and bioenergy constituting up to 35 % of global primary energy by 2050 and 50 % by 2100. Biomass cost-effectively deploys for various uses—including biopower, biofuels, hydrogen, biogas, and heat, which is markedly different than baseline deployment that is dominated by biofuels. The majority of modern biomass is produced and used in non-OECD countries, with bioenergy up to 35 % of regional electricity and 70 % of regional liquid fuels by 2050. Furthermore, when modeled, most models project a significant role for bioenergy with CCS technologies.

We find little agreement on what bioenergy, when available, displaces in the energy system. However, bioenergy is very valuable, especially with tighter climate targets, with 2050 marginal costs up to three times higher and economic consumption losses potentially doubling when biomass supply is constrained. Constraints on biomass supply also result in reductions in energy consumption and deployment of more expensive energy supply technologies.

BECCS could be very valuable for reaching lower targets (especially during later half of century). BECCS provides temporal mitigation flexibility that reduces near-term mitigation pressure—by up to 345 $GtCO_2$ cumulatively through 2060. However, the additional emissions may have climate benefit implications. Whether BECCS is essential for climate management is not directly evaluated, but the results here give mixed impressions. When biomass supplies are constrained, the models still achieve the climate objective, but some at substantially higher costs. When CCS is unavailable, only four models identify solutions for the 450 policy, but the mitigation costs of two are relatively insensitive to bioenergy availability.

Finally, we show that some models are explicitly finding substantial bioenergy worthwhile even when accounting for emissions increases from land adjustments. This result helps in reconciling the climate management perspective favoring large-scale bioenergy with the less favorable impressions flowing from the indirect land-use and lifecycle analysis emissions debate regarding bioenergy. While not a definitive statement on the net benefits of bioenergy, these findings raise the possibility of net climate benefits in the long-run with full net emissions accounting.

This study helps elucidate the current projected role played by bioenergy across future energy systems. Given the magnitude of projected deployment, concentration of that deployment in non-OECD countries, and large dependence on and value of bioenergy, this study suggests both opportunities and challenges for technologies, implementation, and policy. Finally, while we find significant bioenergy deployment, we also find broad ranges for most results that we cannot explain within the confines of this study. With uncertainties about net environmental and social implications, as well as bioenergy feedstocks, logistics and conversion technologies, additional exploration into the need for and viability of large-scale global bioenergy deployment is merited.

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