Can Bioenergy Assessments Deliver?

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ABSTRACT

The role of biomass as a primary energy resource is highly debated. Next generation biofuels are suggested to be associated with low specific greenhouse gas emissions. But land consumption, demand for scarce water, competition with food production and harmful indirect land-use effects put a question mark over the beneficial effects of bioenergy deployment. In this paper, we investigate the current state of bioenergy assessments and scrutinize the topics and perspectives explored in the Special Report on Renewable Energy Sources and Climate Change. We suggest that an appropriate assessment requires a comprehensive literature review, the explicit exposition of disparate viewpoints, and exploration of policy-relevant content based on plausible "storylines". We illustrate these storylines with the IPCC's emission scenarios and point out routes to improve assessment making on the future role of bioenergy.

Keywords: Bioenergy, Assessment, Tradeoffs, Sustainability, Scenarios

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1. INTRODUCTION

Bioenergy plays a crucial role in the global transition from fossil fuels to renewable energy, and possibly also for climate change mitigation. With intensive use of traditional biomass, primary energy from plant resources currently exceeds that of other renewable options, including wind energy. The benefits and impacts of bioenergy depend on what feedstocks are used for what purpose and how and where they are produced. In particular, greenhouse gas (GHG) emissions from bioenergy use are widely varying, uncertain and the subject of intensive debates (e.g., Malca and Freire 2010; Plevin et al. 2010; Creutzig et al. 2012). One part of the scientific literature indicates that high direct and indirect land-use emissions compromise the benefits of the current use of many biofuels (e.g., Crutzen et al. 2008; Hertel et al. 2009; Popp et al. 2011a). Another part of the literature highlights the potential of large-scale bioenergy deployment to mitigate climate change and to even produce negative GHG emissions in combination with carbon capture and storage technologies (e.g., Edenhofer et al. 2010). In addition to the climate conundrum, large-scale deployment of bioenergy is influenced by energy security concerns, is subject to industry interests, and impacts food security, biodiversity, water scarcity, soil quality and subsistence farming (e.g., Fargione et al. 2010).

The complexity of this system produces a high level of uncertainty about future outcomes. Policy makers therefore have a need for comprehensive analysis to help inform their decisions about energy, climate change and associated risks. Taking climate change mitigation as a

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framework for analysis, two questions emerge: What is the global warming impact and mitigation potential of bioenergy deployment in various scenarios? And: how sustainable is bioenergy deployment in these scenarios? Only a comprehensive and balanced assessment, integrating analyses from diverse research communities, can provide at least tentative answers to these questions and identify the main sources of uncertainty. Such an assessment is crucial to inform political decisions that intend to influence the future portfolio of mitigation options. The IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation (SRREN) aims to provide such an assessment for renewable energies in general (IPCC 2011a), and bioenergy in particular (Chum et al. 2011). Here we critically evaluate this assessment based on the understanding that the mitigation perspective needs to be accompanied by other perspectives to avoid a one-dimensional analysis. Section 2 outlines the tasks of an assessment. Section 3 reviews the insights from the SRREN on bioenergy. Section 4 scrutinizes the representation of bioenergy in the different SRREN chapters based on the assessment requirements. Section 5 suggests possible routes towards improved assessment making.

2. HOW TO CARRY OUT ASSESSMENTS

Assessments are emerging as a distinct literature category in academia (Keller 2010). Prominent examples include the assessment reports of the IPCC (2007), the upcoming Global Energy Assessment and Global Environmental Outlook, the Millenium Ecosystem Assessment (MA, 2005), and more specific reports such as the Assessment Report of the Urban Climate Change Research Network (Rosenzweig et al. 2011), and many assessments in other areas of science. Unlike scientific publications, assessment reports are requested by a legal body and subject to specific criteria and procedures, like the review process, to ensure high quality. Assessment preparation can take up to five years including scoping, author selection and several iterations of writing and reviewing.

The IPCC reports are special in that they result from an official UN process, signed off by all 194 national governments that are members of the IPCC. The focus of the current literature on assessment making has primarily been on the underlying model of scientific policy advice (e.g., Pielke 2007; Beck 2010), on specific aspects of assessment making, such as the treatment and communication of uncertainty (e.g.,van der Sluijs et al. 2008; Mastrandrea et al. 2011) or on the assessment process (e.g., Agrawala 1998; Farrell and Jäger 2006)—focusing on the impact of assessments (Cash et al. 2002; Mitchell et al. 2006; Keller 2010). We are, however, not aware of any framework that specifies criteria for evaluating the content of a particular assessment. For evaluation of an IPCC report, such as the SRREN, the procedures of the IPCC itself will thus provide us with a point of departure.

The IPCC states that "the best possible scientific and technical advice should be included so that the IPCC Reports represent the latest scientific, technical and socio-economic findings and are as comprehensive as possible"; and in preparing an IPCC report, "Lead Authors should clearly identify disparate views for which there is significant scientific or technical support" (IPCC 2011b, p. 6). Also: "It is important that reports describe different (possibly controversial) scientific, technical, and socio-economic views on a subject, particularly if they are relevant to the policy debate" (IPCC 2011b, p. 7).

Hence, an IPCC assessment needs to meet three tasks: 1) provide a comprehensive review of the relevant literature; 2) identify and possibly reconcile disparate views; and 3) present the scientific content in a manner relevant to policy makers, drawing on the outcomes of the first two tasks. Let us elucidate each task in turn.

First, the review character of an assessment is different from most review articles in disciplinary journals. A review article usually summarizes the results of a particular scientific community on a specific topic, e.g. land modelers on biomass resource potential. An assessment, in contrast, has the mandate to bring different epistemic communities together, communities that work on the same topic but contribute different methods, perspectives, languages, and assumptions.[1] As a consequence, an assessment needs to be comprehensive both in topics covered and in participation of epistemic communities.

Second, by bringing together different communities, an assessment allows for the identification of disparate views and perspectives and scrutiny of the reasons for divergence. In particular, an exploration of the whole solution space (e.g., identifying costs, benefits and risks of mitigation options) becomes challenging when the fact-value separability cannot be taken for granted as a precondition for the distinction between means and ends. The separation between facts and values collapses when indirect consequences of means have the potential to undermine the achievement of the societal ends that the means are intended to address (Dewey 1988). The relevant example here is where extensive use of bioenergy (the means) to achieve climate change mitigation (the end) causes unforeseen consequences (e.g. increased risk of famines) (Edenhofer and Seyboth forthcoming). Ideally, a communication effort between scientific communities helps to track down different assumptions and worldviews, to make value judgments transparent, and to explain the observed divergence in results and types of analysis. If this is achieved, it is much easier to reconcile divergent results, and also identify possible co-benefits and trade-offs between societal goals and thus detect and possibly avoid unintended consequences and promote co-benefits. On this basis, assessments can often identify research gaps and opportunities for collaboration, and can produce a closed loop by communicating these findings to the scientific community.

Third, an IPCC assessment is supposed to be policy-relevant without being policy-prescriptive. When results of different epistemic communities mismatch or when the different types of analysis are difficult to reconcile, the communication of the respective sets of assumptions and worldviews and their corresponding results become paramount. An assessment can then inherit the role of an "honest broker", communicating the divergent scientific conclusions to policymakers in an accessible way (Pielke 2007). The use of "storylines" in assessments breaks down complexity and constitutes a useful tool for communication to policy makers, but also to peers and the interested public (Kriegler et al. 2010, Arnell et al. 2011). We understand a storyline to be a narrative (e.g., a rapidly globalizing and consumption-oriented world with efficient markets). Scenarios correspond to a storyline by specifying a particular set of assumptions (e.g., population and economic growth; energy poverty; increasing energy demand; technological development; lifestyle changes, such as a global increase in meat consumption). Given a specific scenario, models can then produce pathways, which provide numeric outcomes and impacts (e.g., bioenergy deployment). Comparison between scenario assumptions will then help to explain the discrepancy between different outcomes and the corresponding impacts. Varying perspectives of epistemic communities can translate into different storylines and corresponding scenarios, but also to different emphasis on dimensions within one storyline. Comparing different storylines with varying emphasis allows

1. According to Haas, an epistemic community is "a network of professionals with recognised expertise and competence in a particular domain and an authoritative claim to policy relevant knowledge within that domain or issue-area" (Haas 1992, p. 3).

the identification and possibly quantification of risks, trade-offs and co-benefits. Feeding these results back into the sphere of public debate might result in substantial revisions of societal goals and the respective policy instruments.

3. STATE OF BIOENERGY ASSESSMENT

Before evaluating the SRREN bioenergy assessment, we need to summarize its main findings. We roughly follow the SRREN and discuss five key dimensions of the bioenergy assessment: 1) costs; 2) life-cycle emissions; 3) resource potential and deployment; 4) socioeconomic and environmental impacts; and 5) governance (sections 3.1–3.5). For this, we mostly rely on SRREN Chapter 2 ("Bioenergy": Chum et al. 2011), Chapter 9 ("Renewable Energy in the Context of Sustainable Development": Sathaye et al. 2011), Chapter 10 ("Mitigation Potential and Costs": Fischedick et al. 2011), and Chapter 11 ("Policy, Financing and Implementation": Mitchell et al. 2011).

3.1. Costs of bioenergy

The SRREN cost analysis is based on levelized cost of energy (LCOE) calculations. LCOE is calculated as the per-unit price at which energy must be generated from a specific source over its lifetime to break even. As a result, levelized costs of energy enable an apple-to-apple comparison of different sources of energy with widely diverging cost structure. Figure 1 displays levelized costs of bioenergy for various feedstocks and purposes. Ethanol and biopower production show cost reductions due to technological learning comparable to those of other renewable energy technologies. But estimated feedstock cost supply curves also point out that increased production leads to higher marginal costs, e.g. because of lower quality land (Chum et al. 2011).

Crucially, the SRREN finds that levelized costs of bioenergy are already competitive with fossil fuels for some feedstocks, purposes and countries. For example, ethanol from sugarcane outperforms gasoline in the Brazilian transport market. In Europe, biomass heating applications in the building sector, often designed as cogeneration facilities, are cost competitive and increase rapidly. The large amount of traditional biomass, still dominating overall biomass use, is mostly grown locally, and is often not part of formal markets.

3.2. Life-cycle emissions

As bioenergy use is partially motivated by climate change, the carbon balance of feedstocks and production pathways is of particular interest and is frequently instrumentalized for policy goals (Creutzig & Kammen 2009). The SRREN breaks down life-cycle emissions according to the different life-cycle methods. Relying on attributional life-cycle analysis (LCA)—accounting for the direct emissions of the supply-use-disposal chain, the SRREN reveals that biomass used for electricity and heat always has lower CO_2 life-cycle emissions than fossil fuels (SRREN Fig. 2.10). For transportation, the relative performance of biofuels compared with gasoline and diesel depends on the particular feedstock and production context. Possibly more relevant, however, are the consequential marginal GHG emissions of bioenergy use, including e.g. the indirect land-use emissions from deforestation. SRREN Figure 2.13 summarizes emissions from land-use change, differentiating between models and world regions. The figure and the accompanying text demonstrate unambiguously that land-use emissions are potentially

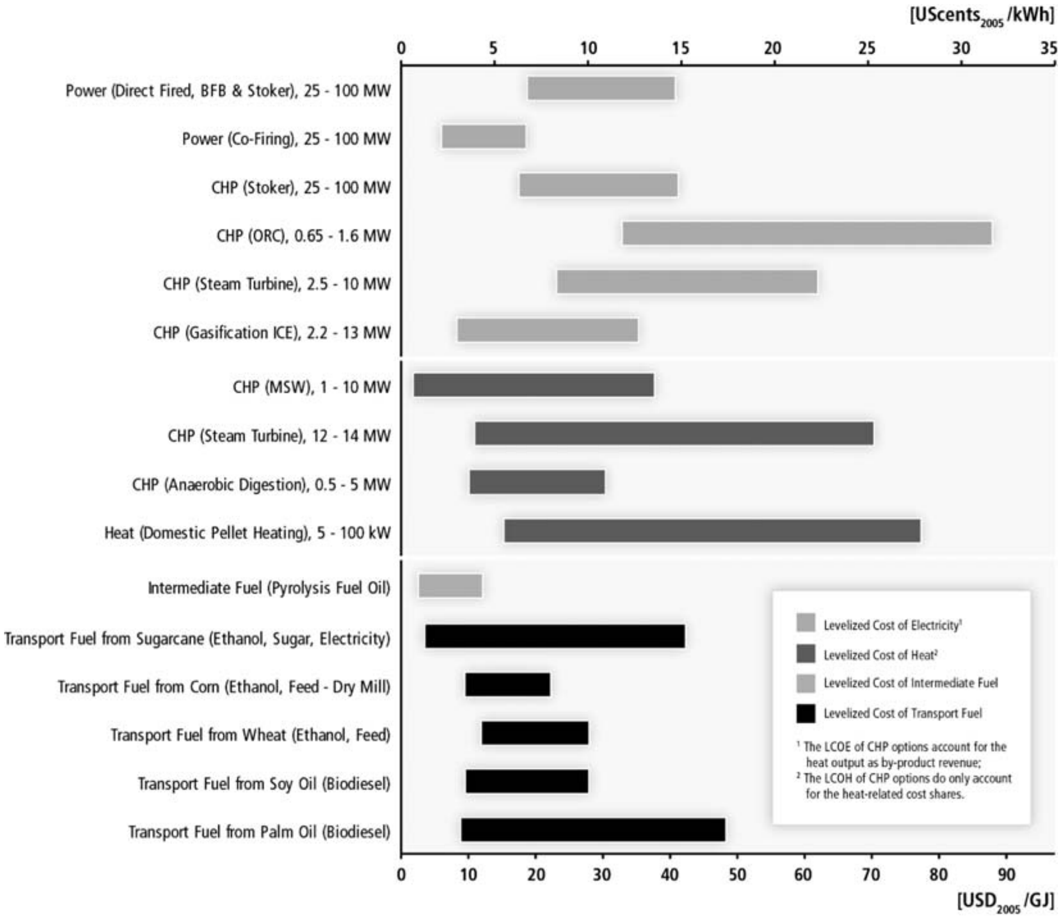

FIGURE 1

Levelized cost of energy service from commercially available bioenergy systems at a 7% discount rate and with feedstock cost ranges differing between technologies (from Chum et al. 2011). For biofuels, the range of levelized costs represents production in a wide range of countries whereas levelized costs of electricity and heat are given only for major user markets of the technologies for which data were available. The underlying cost and performance assumptions used in the calculations are summarized in SRREN Annex III.

higher than the direct emissions of conventional fuels. A key challenge is that emissions occur up-front, contributing immediately to climate change, whereas potential carbon savings occur in the future, after paying back the initial carbon debt (Fargione et al. 2008). The SRREN concludes that increased bioenergy deployment needs to be supplemented with better protection of tropical forests and other carbon-rich ecosystems.

3.3. Resource Potential and Deployment

According to the literature review in the SRREN, the global technical potential for bioenergy, considering also demand for other land-use, ranges from less than 50 EJ to more than 1000 EJ in 2050 (Fig. 2a; Dornburg et al. 2010; Haberl et al. 2010). In some of the studies,

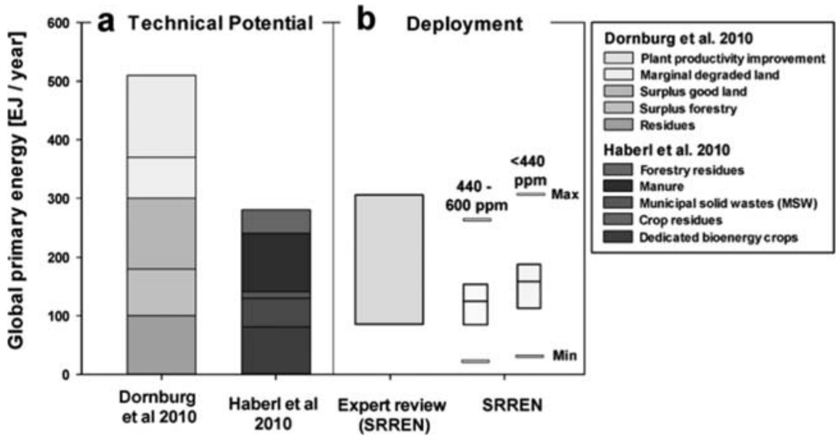

FIGURE 2

a) Bioenergy technical potential in 2050 listed according to categories. b) Expert judgment on deployment in 2050 from SRREN Chapter 2 and deployment scenarios from SRREN Chapter 10. Source: adapted from (Creutzig et al. 2012).

the theoretical potential is even considered to exceed 1500 EJ by 2050 (e.g., Smeets et al. 2007). Contrast this with current energy demand of around 500 EJ and expected energy demand of between 500 and 1000 EJ in 2050 (Fischedick et al. 2011). The huge uncertainty is rooted in the following factors, among others: soil degradation; water scarcity; yield growth; production potential of degraded land; nature protection; and climate change feedback.

Based on this review of the available literature, the authors conclude that realistic deployment levels of biomass for energy could reach a range of 100 to 300 EJ/yr around 2050 (Fig. 2b). But: "the inherent complexity of biomass resources makes the assessment of their combined technical potential controversial and difficult to characterize" (Chum et al. 2011). Based on cost projections, including the opportunity cost of land, future biomass supply curves can be derived, implicitly determining the market potential (SRREN Figure 2.5). Different assumptions on economic and energy demand growth, the cost and availability of competing low-carbon technologies as well as different mitigation scenarios add complexity to potential estimates. Taking these into account, integrated assessment models (IAMs, see Box 1) obtain ranges of potential deployment of bioenergy comparable to the SRREN Chapter 2 expert judgment. In these models, deployment is estimated to be higher when mitigation targets are more ambitious (Fig. 2b).

3.4. Socioeconomic and environmental impacts

In addition to the GHG performance of bioenergy options (see section 3.2), other socioeconomic and environmental impacts are also analyzed in the SRREN (Chum et al. 2011; Sathaye et al. 2011).

First, the increased demand for agricultural inputs such as land and water influences food commodity prices and thus food security. The SRREN points out possibly relevant but uncertain contributions of increased biofuels production to the food price increase in the mid-2000s. This implies an overall adverse effect on food security in developing countries (World Bank 2009).

Second, increased biomass production may imply increased income for farmers and agro-business. But using productive and degraded lands for bioenergy purposes might compromise the needs of local populations for subsistence farming. This is particularly important for vulnerable communities and female farmers who may have less secure land rights (FAO 2008).

Third, natural ecosystems can be destroyed to make space for bioenergy plantations, leading to biodiversity loss. For example, the rising demand for biofuels has contributed to extensive deforestation in parts of Southeast Asia; palm oil plantations support significantly fewer species than the forest they replaced (Fitzherbert et al. 2008). Biodiversity loss may also occur through indirect land use change (see section 3.2). In some cases bioenergy expansion can lead to increased biodiversity, e.g., through the establishment of perennial herbaceous plants or short-rotation woody crops in agricultural landscapes (Semere and Slater 2007).

Fourth, the impact on water resources varies greatly across feedstocks, cultivation systems and conversion technologies. While biofuels derived from irrigated crops are water intensive, use of agricultural or forestry residues or rain-fed feedstock production does not require water extraction from lakes, rivers or aquifers. But the latter might reduce downstream water availability by redirecting precipitation to crop evapotranspiration. Aquatic ecosystems might negatively be affected by leaching as well as by emissions of nutrients and pesticides. In contrast, ligno-cellulosic feedstock might decrease water demand. Water impacts can be reduced through integration in agricultural landscapes as vegetation filters to capture nutrients in passing water (Börjesson and Berndes 2006).

Fifth, the soil impacts of feedstock production (e.g., soil carbon oxidation, changed rates of soil erosion, and nutrient leaching) depend heavily on agronomic techniques and the feedstock under consideration. Similarly, the risk of soil degradation associated with using residues from agriculture or forestry heavily depends on management, yield, soil type and location. While wheat, rapeseed and corn require significant tillage (FAO 2008), crops that provide continuous cover might have a positive effect on soil outside the growing season of annual crops by reducing erosion (Berndes 2008).

The SRREN concludes that "few universal conclusions . . . can currently be drawn, given the multitude of rapidly evolving bioenergy sources, the complexities of physical, chemical and biological conversion processes, the multiple energy products, and the variability in environmental conditions" (Chum et al. 2011, p. 258).

3.5. Governance

Global, regional, national and local policies shape agricultural practices and affect bioenergy resource potential, GHG performance of bioenergy deployment and other socioeconomic and environmental dimensions. Depending on the combination of specific policy priorities, such as climate change mitigation, trade, energy security, food security or rural development, the overall policy impact can be decisive or negligible, conflicting or complementary, sustainable or unsustainable. The policy chapter of SRREN concludes that biofuel mandates and blending requirements are key drivers in the development of most modern biofuel industries (Mitchell et al. 2011). The example of Brazil is given where a combination of tax incentives, blending mandates, regulation and infrastructure investments, starting in the 1970s, produced a high share of biofuels in the overall fuel mix. More recent biofuel mandates in the U.S. and the EU, and high subsidies for corn ethanol, induced a surge in biofuel demand and deployment but were non-discriminative with respect to life-cycle GHG emissions, resulting in mostly low-cost biofuel deployment with relatively high GHG emissions. In response, the updated low-carbon fuel standard (California), renewable fuel standard (U.S.) and fuel quality directive (EU) introduce rules that discriminate based on GHG emissions (Creutzig et al. 2011). Similarly, sustainability criteria and certification schemes for bioenergy sources aim to limit harmful impacts of bioenergy deployment. The policy review in chapter 11 is organized by end-use sectors (electricity, heating, and transport). All sectors are increasingly reliant on bioenergy. As a result, the discussion of policies relevant to bioenergy deployment is fragmented over chapter 11.

4. EVALUATING THE BIOENERGY ASSESSMENT

In this section, we evaluate the bioenergy assessment of the SRREN, notably its chapters 2 ("Bioenergy") and 10 ("Mitigation Potential and Costs"). In particular, we verify whether the bioenergy assessment conforms to the assessment criteria developed in section 2 of this article:

- Is the assessment comprehensive in topics and communities?
- Are diverging assumptions made transparent? Is reconciliation attempted?
- Is there a consistent set of policy-relevant storylines?

Box 1. The role and purpose of Integrated Assessment Models

Integrated Assessment Models (IAMs) are key to the SRREN and previous Assessment Reports of the IPCC. IAMs are tools for exploring long-term and global transition pathways under various opportunities and constraints. IAM teams develop their models into different directions and aim to improve the level of detail (e.g. energy conversion technologies, etc.) and to integrate more systems (e.g. the land-use system). In addition to research of individual teams, the international community undertakes model comparison exercises. These consist of undertaking model runs with common assumptions of the policy targets and other constraints, possibly also harmonizing the assumptions on population, GDP, and other drivers. The community compares the scenario results of different transition pathways. The modelers" attention shifted to strong emission reduction in recent years, resulting in increased deployment of bioenergy in models. To systematically understand unintended side effects of land-use change, some IAMs are coupled to global land-use models.

4.1. Comprehensiveness

Chapter 2 of SRREN collects insights on bioenergy deployment from various disciplines and communities. Agro-economic and biophysical models of land use and availability provide the backbone for potential deployment estimates. These models also consider water availability and food security as constrains to different degrees. Studies from the life-cycle community are cited to estimate the GHG emissions of bioenergy. Techno-economic studies deliver cost estimates of various bioenergy feedstocks and pathways. Analysis of policy instruments contributes to evaluating the governance of bioenergy. The results of these contributions are summarized in section 3 of this paper.

Social scientists, analyzing inter alia discourses, political economy, and local communities, also contribute to the huge literature on bioenergy in ways that go beyond what is captured in the SRREN. For example, human geographers and anthropologists often observe local communities and the de facto implementation of bioenergy policies and programs. A common observation is that the intended outcomes of bioenergy initiatives diverge from their real impacts (Borras et al. 2010). For example, research in India finds that despite a "pro-poor" discourse about the oilseed shrub *Jatropha curcas*, efforts to promote the crop have favored resource-rich farmers and likely contributed to a widening of the wealth gap (Ariza-Montobbio et al. 2010). Similarly, in Brazil the spread of sugar cane for bioenergy has been linked to increased social exclusion (Hall et al. 2009). Further case studies that examine the interactions between bioenergy deployment and subsistence farming reveal circumstances that have produced better or worse outcomes for local people (McCarthy 2010). Biofuel policies have also been identified as a major driver of the recent increase in both the number and size of large-scale land acquisitions (Franco et al. 2010; Vermeulen and Cotula 2010), a trend with significant implications for social relations and smallholder farmers (Toulmin et al. 2011). The SRREN makes scarce reference to these studies. The use of marginal land for subsistence farming is noted as a constraint in 2.2.2.1 and 2.2.4.3, pointing out that subsistence farming may considerably, or even totally, limit the potential of marginal land for bioenergy deployment. But the social science literature on local politics is not cited or used to identify successful programs.

Another gap is that governance of bioenergy deployment is discussed in a fragmented way (see section 3.5). A comprehensive review of bioenergy policies, their impact on GHG emissions, deforestation, biodiversity, water and food competition is missing. As noted in 3.2, uncertainties of life-cycle emissions can be very high, constraining the reliability of policies that rely on quantitative estimates. This fundamental problem of policy making is not discussed in the SRREN.

4.2. Reconciliation and clarification of assumptions

The key dimensions of assessment of the future role of bioenergy are, as identified above, costs, GHG emissions, resource potential and deployment, socio-economic and environmental impacts and governance. The SRREN makes clear that projections in any of these dimensions are highly uncertain and contingent. SRREN Chapter 2 brings together research results from different types of analysis—some of which are difficult to reconcile. Based on this review of partially disparate views and the underlying methods and assumptions, several key trade-offs arise with respect to the future role of bioenergy. In SRREN chapter 10, the IAMs explore more than 150 scenarios, some of which vary bioenergy deployment constraints exogenously. Table 1 specifies these different trade-offs, and summarizes how the different chapters treat them.

A major gap of the SRREN bioenergy assessment was identified as the missing reconciliation between the LCA and the IAM community, representing disparate perspectives on bioenergy-associated GHG emissions (Creutzig et al. 2012). IAMs assume first-best worlds where so-called market failures, such as land-use emissions from bioenergy deployment, are addressed by appropriate policy instruments. A key result of IAMs is that low-carbon bioenergy can substitute fossil fuels, emerging as the key renewable energy source in 2050 and beyond (Fischedick et al. 2011). LCA researchers observe life-cycle emissions of biofuels that can be comparable to gasoline, and are highly uncertain (Plevin et al. 2010). High deployment levels

TABLE 1
Bioenergy trade-off characterization in SRREN

Possible trade-offs	**Insights from bioenergy experts (Chapter 2, SRREN)**	**Insights from integrated models (Chapter 10, SRREN)**
Deployment and affordability	Higher deployment implies higher marginal land and production costs (Fig. 2.5); but higher deployment also implies economies of scale and technological learning, decreasing unit prices (Fig. 2.21)	Global bioenergy cost-supply curves are given for different land use scenarios based on SRES assumptions (Fig. 10.23). Marginal costs of biomass production increase with increasing deployment level (Fig. 10.23) but over time they decline due to land productivity improvements, learning of conversion technologies, and capital-labor substitution (10.4.4, Table 10.10). Despite being considered in some IAMs, neither assumptions nor insights from IAMs on costs are reported.
Deployment and water availability	Possible competition between bioenergy deployment and water security. Impact on water resources varies greatly across feedstocks, cultivation systems (e.g. irrigated or rain-fed) and conversion technologies (2.2.4.2, 2.5.5.1).	Briefly mentioned in 10.6.2.3: "RE can have impacts on waters, land use, soil, ecosystems and biodiversity." Neither assumptions nor insights from IAMs on water availability are reported, mainly due to a lack of literature (van Vuuren et al. 2009).
Deployment and food security	Cited studies generally agree on a discernable contribution to food price increases by bioenergy deployment expansion, but not on the size of this contribution. This implies an overall adverse effect on food security in developing countries—particularly for high oil price development (2.5.7.4).	Only one study (de Vries et al. 2007) addresses this trade-off (10.4.4). For a food-first policy, it finds declining technical potential as a "direct consequence of more people, [. . .] hence more land demand for food production". The assumptions made for the bioenergy supply curves (Fig. 10.23: production on abandoned and rest lands only) also imply an underlying food-first-policy. No explicit information about food-security assumptions in IAMs is given. The "relationship between bioenergy production, crop production and deforestation" is identified as a knowledge gap in 10.2.4.
Deployment and climate mitigation	GHG performance of bioenergy is estimated by LCA analyses showing substantial but hugely varying life-cycle emissions for different types of bioenergy. In some cases land-use emissions are potentially higher than the direct emissions of conventional fuels (2.5.2, 2.5.3).	For stricter mitigation targets, more bioenergy is deployed. Neither the assumptions in nor the insights from IAMs concerning co-emissions are reported. 10.2.2.4 says: "Some studies have indicated that it is the combination of bioenergy with CCS that makes low stabilization goals substantially easier through negative emissions"
Deployment and soil quality	Soil impacts of bioenergy feedstock production (e.g., soil carbon oxidation, changed rates of soil erosion, nutrient leaching) depend on agronomic techniques and feedstock. Under certain conditions, bioenergy crops can enhance carbon sequestration in soils. Residue removal could negatively impact soil carbon and fertility (2.2.4.1, 2.5.5.3).	Briefly mentioned in 10.6.2.3: "RE can have impacts on waters, land use, soil, ecosystems and biodiversity." Neither assumptions nor insights from IAMs on water availability are reported, mainly due to a lack of literature (van Vuuren et al. 2009).
Deployment and subsistence farming	Using degraded lands for bioenergy purposes might compromise the needs of local populations for subsistence farming (2.2, 2.5.7.5).	Not mentioned.

(continued)

TABLE 1
Bioenergy trade-off characterization in SRREN *(continued)*

Possible trade-offs	Insights from bioenergy experts (Chapter 2, SRREN)	Insights from integrated models (Chapter 10, SRREN)
Deployment and biodiversity	The impact of bio-crop production on biodiversity depends on crop choice, agricultural management and previous land use. Biodiversity loss may also occur indirectly. Under certain conditions, however, the effect might be positive (2.2.4.4, 2.5.5.2).	Briefly mentioned in 10.6.2.3: "RE can have impacts on waters, land use, soil, ecosystems and biodiversity"; and in 10.3.1.4: "As the available land for bioenergy is limited and competition with nature conservation issues as well as food and materials production is crucial, the sectoral use for the available bioenergy significantly depends on scenario assumptions and underlying priorities".

could lead to co-emissions from land use change (e.g., Fargione et al. 2008; Melillo et al. 2009; Popp et al. 2011a). and agricultural intensification (e.g., Wise et al. 2009; Popp et al. 2011b). Creutzig et al. (2012) conclude that plausible scenarios of future bioenergy deployment correlated with high bioenergy-induced GHG emissions are systematically underrepresented in the literature and in SRREN, specifically.

Another relevant gap is the absence of trade-off specification between deployment and subsistence farming and informal markets. This seems to be related to the absence of experts on this topic. Most studies on subsistence farming emphasize the local variability of effects. The question then is under which conditions what kinds of bioenergy deployment can benefit subsistence farmers. This kind of question needs to be given greater attention, and possibly be comprehensively answered, in future bioenergy assessments.

While SRREN identifies disparate views on the future role of bioenergy and provides detailed analyses from different communities, the reconciliation of insights sometimes remains incomplete. A systematic summary, similar to table 1, linking the treatment of trade-offs in Chapter 2 and 10 is not provided by SRREN. In some of the cases this is due to a lack of literature. But, more crucially, interdisciplinary communication across SRREN chapters and their respective communities is missing (for early efforts of tentative integration see (e.g., van Vuuren et al. 2009; Wise et al. 2009)). The SRREN provides little indication of how research could help to assess the salience of the respective trade-offs, e.g. through improved consequential LCA and through integrated assessment of climate, energy, economy and land use.

4.3. Consistent storylines

In this subsection, we evaluate storylines of Chapter 2 and Chapter 10 of SRREN, and their interaction.

Special Representative Emission Scenarios

Chum et al. develop four storylines aiming to clarify possible futures in a high-dimensional output space. For this they map their expert judgment on future bioenergy deployment on the four Special Representative Emission Scenarios (SRES), developed by the IPCC in 2000, relying on Hoogwijk et al. (2005). These scenarios represent storylines on globalization/regionalization and more environmentally sensitive versus more materially oriented world (IPCC 2000) and form the common scenario basis for the assessment of climate change and its mitigation for the climate modeling and integrated assessment communities in preparation of

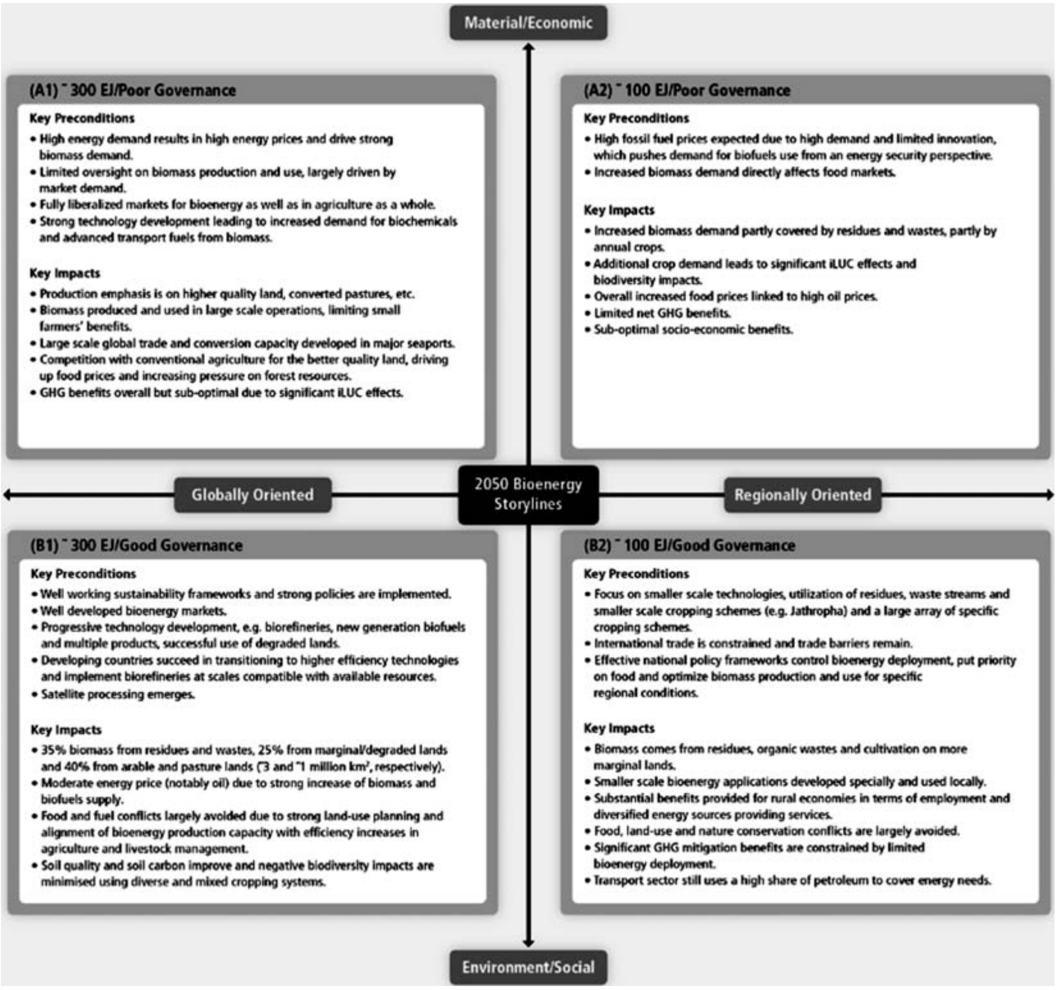

FIGURE 3

Possible futures for 2050 biomass deployment for energy: Four illustrative contrasting sketches describing key preconditions and impacts following world conditions typical of the IPCC SRES storylines (see IPCC 2000; Hoogwijk et al. 2005), taken from Chum et al. (2011), p. 308, Fig. 2.27.

the Third and Fourth Assessment Reports. Each SRES bundles a set of assumptions, representing a storyline. The SRES emphasize fossil fuel availability but hardly discuss bioenergy.

In Figure 3, the four storylines are adapted for bioenergy following Hoogwijk et al. (2005) and organized in a matrix, regional versus global orientation, and material/economic versus environmental/social orientation. The material/economic direction is identified with poor governance, the environmental/social dimension with good governance. In the global orientation, bioenergy deployment approaches a high number of 300EJ in 2050; in the regional orientation, deployment is limited to 100EJ in 2050. The figure is built on the hypothesis that "biomass and its multiple energy products can be developed alongside food, fodder, fiber, and forest products in both sustainable and unsustainable ways". Each storyline is associated with key preconditions and key impacts. In these storylines, Chum et al. attempt to reconcile global drivers of energy demand with the detailed analysis of a particular renewable energy source in a narrative way. This attempt is very challenging, but is nonetheless a crucial exercise. Particularly, parts of their storylines could be criticized (e.g. asking: 1) Could high deployment and poor governance imply net additional GHG emissions? 2) How do these storylines relate to the original SRES?). But the main point is to take these narrative storylines and systematically scrutinize and analyze them, taking all relevant insights on market dynamics, LCOE, resource potential, GHG emissions, water scarcity, food security, policy options and the associated trade-offs discussed in Section 4.2 into account, and then verify the plausibility of storylines or adapt them to consistent results of these analysis efforts in a more structured and possibly quantitative way. IAMs are understood to be the right tool to systematically analyze tradeoffs and different storylines. The next section will thus present how storylines are used in the SRREN analysis of bioenergy deployment levels as derived from IAMs.

Modeling storylines (Chapter 10 of SRREN)

For energy and climate change, IAMs provide a suitable infrastructure for scenario development. Each scenario, common bundles of assumptions, represents a storyline, reflecting numerous assumptions on input parameters and model design. Specific realization and numeric representations constitute pathways. To some extent, one could call chapter 10 of SRREN the storyline chapter. Two questions arise then: First, does the set of storylines on bioenergy cover the identified dimensions and trade-offs of SRREN Chapter 2? Second, do these storylines map on the SRES storylines, as identified above?

The IAM scenario results assessed in the SRREN cover a wide range of assumptions on economic and energy demand growth, the cost and availability of renewable energies, and competing low-carbon technologies. Only scant information is given on future bioenergy deployment. Most scenarios assume a reduction in traditional biomass, and substantial growth in modern bioenergy sources (SRREN Section 10.2.2.2), not further discriminating between different types of bioenergy. Most models do not cover the land use sector explicitly but rely on an exogenous supply cost function for bioenergy. In fact, in many models future yield improvements, land competition or land exclusion due to food production, forest protection, biodiversity, soil quality, and water scarcity are lumped into this supply cost curve. Global bioenergy cost-supply curves are given for 2050 and four different land use scenarios (SRREN Fig. 10.23) based on the same SRES storylines presented in Chapter 2 (Fig. 3). In contrast to the potential deployment sketches in Chapter 2 also considering “poor governance” cases (A1 and A2) Chapter 10 supply cost curves assume “good governance” for all SRES storylines (A1, A2, B1, B2). This is indicated by the assumption that bioenergy is produced on abandoned and rest land only, which implies underlying food-first or nature protection policies. The maximal potentials given with the supply-curves range from 170 EJ/a (B2) to 420 EJ/a (A1) and are sufficient to cover the deployment levels of 300 EJ/a (A1, B1) and 100 EJ/a (A2, B2) presented in Chapter 2. Section 10.3.1.4 briefly points out that “the available land for bioenergy is limited and competition with nature conservation issues as well as food production is crucial” and as a consequence “the use of bioenergy significantly depends on scenario assumptions and underlying priorities”. However, the SRREN gives no explicit information about land availability and biomass costs assumptions in IAMs.

Many IAMs do not account for the GHG emissions from (indirect) land-use change and increased land-use intensification; in effect, bioenergy is generally assumed to be carbon-neutral. Exceptions are models like POLES, IMAGE, MiniCAM and MESSAGE incorpo-

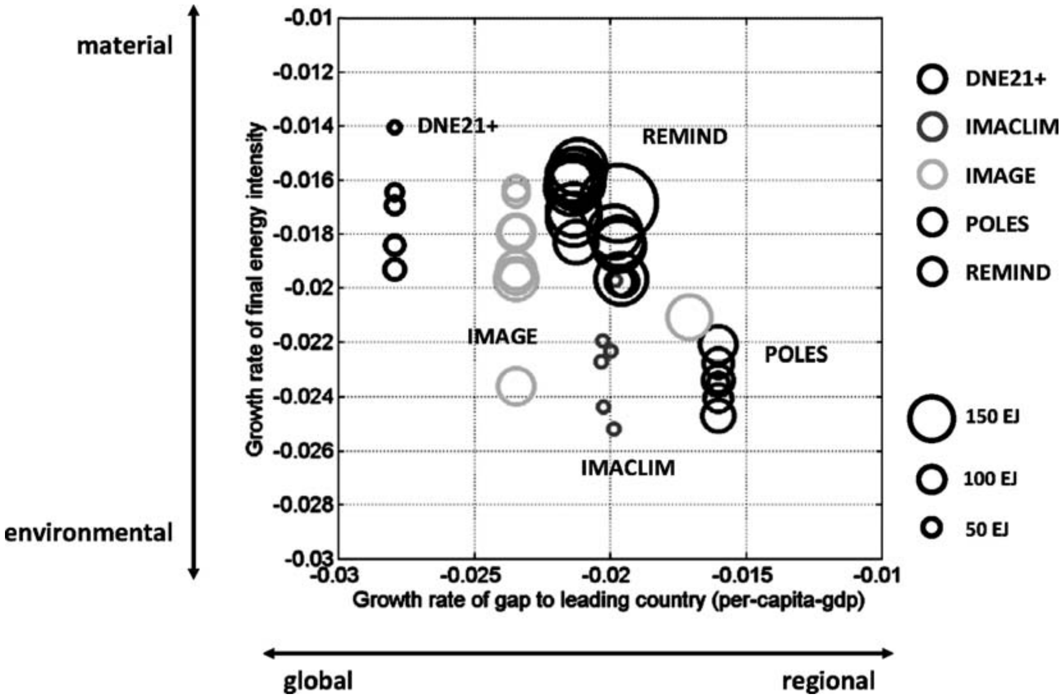

FIGURE 4
Bioenergy deployment levels (indicated by the size of the circles) of IAM scenarios along crude proxies of the SRES dimensions.

rating more detailed land use modules. In conclusion, sustainability issues related to bioenergy supply are poorly reflected in IAMs (Sathaye et al. 2011: Section 9.4).

Hence, the space of possible bioenergy storylines explored with IAMs is very narrow. Neither is the SRES scenario space of Chapter 2 systematically covered.

Harmonization of Storylines

Figure 4 visualizes the insufficient consideration of SRES dimensions in assessment models. It depicts the bioenergy deployment levels of IAMs along the same global-regional and environmental-material dimensions used for the deployment matrix in Fig. 3. For the representation of the material-environmental dimension, we use the growth rate of global final energy intensity. Energy intensity is a short-hand for the final energy use per unit of GDP. High negative growth rates of final energy intensity indicate a rapid improvement of energy efficiency corresponding to an environmentally oriented world (Grübler 2004). To identify whether a scenario represents a globally-oriented or a regionally-oriented world, we use the convergence over time in the levels of per-capita-GDP as an indicator. More precisely we estimate the growth rate of the gap in per-capita-GDP between regions with lower income and the leading region (Barro and Sala-i-Martin 2003). High negative growth rates correspond to fast convergence and represent a "globally oriented" world. The growth rates for both axes are derived for the scenarios from 2020 to 2050 with 10-year intervals using the geometrical mean. Regional values of convergence are weighted with population to obtain a global value. The chosen indicators are the only ones related to these SRES dimensions on which a substantial number of IAMs have reported data. Other indicators would be a better fit to represent SRES dimensions (Hoogwijk et al. 2005).

The graph shows some variety of convergence across models but little or no variety of convergence in scenarios within one model. In contrast to high projections of deployment levels for a globally oriented world in Chapter 2, IAM results in Fig. 4 show no clear sensitivity of deployment levels to any of the two depicted dimensions, not even within the models. Even acknowledging the limited possibilities to represent all relevant dimensions in highly demanding models, Fig. 4 illustrates that IAMs insufficiently operationalize important dimensions of bioenergy supply. Harmonization of assumptions with Chapter 2 is not attempted.

Numerous specifications need to be introduced into IAMs such that a more complete scenario space, representing the trade-offs identified in SRREN Chapter 2, can be systematically explored in an integrated setting. The complexity of existing IAMs suggests that this is a highly ambitious task. Creutzig et al. (2012) suggest that more specialized models with high resolution on bioenergy but coarse grained representation of other energy technologies can complement and soft-couple to the current model world.

5. WAYS FORWARD

We have summarized the state of bioenergy assessment as performed in the IPCC's Special Report on Renewable Energies. Assessments need to comprehensively present literature, reconcile disparate views by making assumptions transparent, and develop coherent storylines around varying sets of assumptions to be policy relevant. The SRREN succeeds in bringing various insights from different communities together—but insufficiently represents results from social sciences. The governance of bioenergy is discussed in a fragmented way. Trade-offs between bioenergy deployment and other essential land-use related dimensions of the bio-socio-sphere are identified and discussed. The key trade-off between emission savings from bioenergy and emission production by induced land-use changed is not represented in the IAMs of the SRREN. Storylines of representative scenarios representing various worldviews are identified but—with the exception of deployment costs—not systematically explored in models. The report remains largely silent on possible tradeoffs and risks related to variations on induced co-emissions, and impacts on human living condition on a global scale but also in regional or local settings. This paper has considered *how* the SRREN performed in relation to the discussed assessment requirements. Understanding *why* it did so, and how its gaps could realistically be filled, would require considering a broader set of issues including the institutional context. The integrated assessment community is currently working on a new class of storylines, the so-called shared socio-economic pathways (see Kriegler et al. 2010; Arnell et al. 2011). We express the hope that this process, together with upcoming assessments, fills the gaps left by the SRREN and leads to further improved exploration of bioenergy futures.

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