Bio-Energy Use and Low Stabilization Scenarios

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This paper explores the potential for bio-energy production, and the implications of different values for the attainability of low stabilization targets. The impact of scenarios of future land use, yield improvements for bio-energy and available land under different sustainability assumptions (protection of biodiversity, risks of water scarcity and land degradation) are explored. Typical values for sustainable potential of bio-energy production are around 50-150 EJ in 2050 and 200-400 EJ in 2100. Higher bio-energy potential requires a development path with high agricultural yields, dietary patterns with low meat consumption, a low population and/or accepting high conversion rates of natural areas. Scenario analysis using four different models shows that low stabilization levels may be achieved with a bio-energy potential of around 200 EJ p.a. In such scenarios, bio-energy is in most models mainly used outside the transport sector.

1. INTRODUCTION

Research has shown that extensive use of bio-energy could be a crucial factor in achieving stabilization at low atmospheric greenhouse gas concentration levels (Fisher et al., 2007; Rose et al., 2008; van Vuuren et al., 2007). First, bio-energy may play a key role in reducing emissions from the transport sector. Compared to other sectors, emission reductions in this sector are difficult to achieve and alternatives to biofuels hinge partly on major cost reductions of new technologies such as fuel cells. At the same time, the effectiveness of biofuels in reducing emissions is a topic of debate. Second, bio-energy may be used as feedstock to produce electric power, heat and hydrogen. Compared to other

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options for emissions reduction, bio-energy is often competitive (i.e. economical at relatively low carbon prices) and requires few system changes to current fossil-fuel based technologies. This contrasts with the use of intermittent energy sources such as wind power (Hoogwijk et al., 2007). A special point of interest is that scenarios aiming for very low concentration targets may require "net negative emissions" from the energy sector (reached when the human-induced uptake of CO_2 is larger than the emission from energy use and land use change) (van Vuuren et al., 2007; van Vuuren et al., 2006). One of the few technologies that results in net negative emissions is the combination of bio-energy and carbon capture and storage (Azar et al., 2006).

The large-scale use of bio-energy is, however, controversial (Dornburg et al., 2008; van Vuuren et al., 2008). The literature reports possible detrimental impacts on world food production, biodiversity and water availability, while greenhouse gas emissions associated with bio-energy production may also cause bio-energy to be ineffective in reducing greenhouse gas emissions. Partly related to these controversies, a very wide range of bio-energy production potentials has been reported in the literature. Bio-energy studies generally report a global production potential of around 200/300 EJ p.a. from 2050 onwards – but with a wide range of outcomes in the range of 50-1,000 EJ p.a. (Berndes et al., 2003; Dornburg et al., 2008).

The scenarios reported in this special issue by the different models rely heavily on bio-energy use. In this article, we will review the assumptions and results in different models on bio-energy use[1]. We also discuss the implications of different levels of bio-energy use. This is done using two complementary approaches.

First, we used the integrated assessment model IMAGE to explore how the bio-energy potential depends on different types of assumptions. The IMAGE model – which includes a geographically explicit land use model - has been used extensively in the past to calculate bio-energy potentials and has been shown to provide outcomes that are fully consistent with the literature (de Vries et al., 2007; Hoogwijk et al., 2005). The use of IMAGE-based bio-energy potentials as a reference allows us to assess systematically the bio-energy potential as a function of uncertainties in land availability, crop yields, the use of natural areas, restrictions based on sustainability considerations, and availability of residues. In the second part of the work, we look into the demand for bio-energy in low-stabilization scenarios by comparing the results of four different energy or integrated assessment models (MERGE, POLES, IMAGE/TIMER and REMIND). As part of a larger model comparison exercise, in each of these

models, scenarios were run that assume no climate policy (baseline) or that aim for a set of ambitious greenhouse gas concentration targets (ranging from 550 to 400 ppm CO_2eq as long-run stabilization targets) (Edenhofer et al., 2010, this issue). These scenarios were run with a different global bio-energy potentials: low (100 EJ p.a.), medium (200 EJ p.a.) or high (400 EJ p.a.) (the individual model assumptions and scenarios are described in individual papers as referenced further in this article). Based on the outcomes of these two parts, we give a description of the developments of the different potentials for bio-energy production, and their associated scenarios.

The article is structured as follows. First, we discuss previous estimates of bio-energy potential in the literature and then Section 3 describes the methodologies used to calculate bio-energy potentials and to compare different model results. In Section 4, we discuss the results of the analysis of bio-energy potentials using the IMAGE model and Section 5 compares the different models. In Section 6, we describe the storylines of the scenarios with low, medium and high bio-energy use and draw some conclusions in Section 7.

2. OVERVIEW OF PREVIOUS ESTIMATES OF BIO-ENERGY SUPPLY AND DEMAND

Different estimates of future bio-energy use have been published. These studies can be classified as either focusing on the potential supply of bio-energy, or accounting for both bio-energy supply and demand. In the section below, we briefly discuss the estimates of bio-energy potential reported in the literature as an input for the range that is explored in the rest of the paper.

2.1 Bio-energy Supply

There are three main categories of bio-energy supply: traditional bio-energy, agricultural and forest residues and bio-energy from dedicated energy crops.

At the moment, around 45 EJ p.a. of traditional bio-energy is used world-wide, in the form of dung, fuel wood and charcoal (IEA, 2006). Most projections expect this form of bio-energy use to stabilize around the present production rate and to subsequently decline, driven by rising income levels and urbanization; a process that has been identified as part of "modernization processes" (van Ruijven et al., 2008). Given the decline in use of this form of bio-energy and the fact that it is not a significant substitute to fossil fuel use, traditional bio-energy is not explored further in this article.

A second category of bio-energy is the use of agricultural and forestry residues. Here, the use of forest wood in particular has been identified as a potentially major source of biomass for energy, with the highest estimates reaching more than 100 EJ in the year 2050 - although very low estimates are also reported (Berndes et al., 2003). Agricultural residues represent a somewhat

smaller source, although again estimates vary over a wide range. One issue that determines the availability of residues concerns their current use: some forms of residues are already used for other purposes (such as soil management) – and different perspectives exist on the question of whether these applications can be replaced. Studies have shown that a central estimate for total residues is around 80-100 EJ p.a. by the end of century. As the IMAGE model does not explicitly deal with residues, estimates here are based on exogenous assumptions.

Dedicated bio-energy crops are an important source of bio-energy. The potential is strongly dependent on land use projections and yield improvements (Hoogwijk et al., 2005; Smeets et al., 2007) and estimates vary over a very wide range, i.e. zero to more than 1,000 EJ p.a. Recent overviews of land use projections for food production have shown that these projections range from a considerable increase (especially for feed production) to a decline in global land use (driven by yield increases; little dietary change, and a low population scenario) (van Vuuren et al., 2008). Crop yield projections play a crucial role. The yields in some developing country regions, which are low compared to potential yield (the so-called yield gap), provide a particularly large opportunity for improvement. Scenarios differ with respect to the extent of use of this opportunity. Bio-energy crop yields could also be improved. So far such yield improvements have focused on food and feed crops, but it is expected that considerable progress can still be made in increasing yields for bio-energy crops. The conversion of crops into usable forms of energy is also expected to improve and the development of cellulosic ethanol in particular could lead to much higher yields of fuel per hectare.

Key factors in the debate on the desirability of bio-energy involve 1) the question whether bio-energy, and especially transport fuels, provide a net positive contribution to greenhouse gas emission reduction – or even energy use (Crutzen et al., 2007; Smeets et al., 2009); 2) the consequences of large scale bio-energy production on land-use, and as a result for food production and biodiversity; 3) consequences for other environmental issues such as water scarcity (Berndes, 2008; de Fraiture et al., 2008; Moldon, 2007) and 4) the effect on land degradation. Regarding the latter, proponents of bio-energy often point to the opportunity to use degraded areas for bio-energy production which would 1) not lead to competition with crop production; 2) not lead to biodiversity loss and 3) could help improve soil quality (Read et al., 2002; Sathaye et al., 1995). However, one may also argue that severely degraded areas should be excluded from potential estimates, as reclamation of degraded soils into land suitable for production or into natural vegetation might be difficult.

Overall, according to different studies, the potential for bio-energy may be in the order of 0-150 EJ p.a. for residues and it varies from zero to several hundreds of EJ p.a. for bio-energy crops, with a central number around 100-200 EJ in 2050. The latter, for instance, include the studies by Van Vuuren et al. (2009b) and Beringer and Lucht (2008).
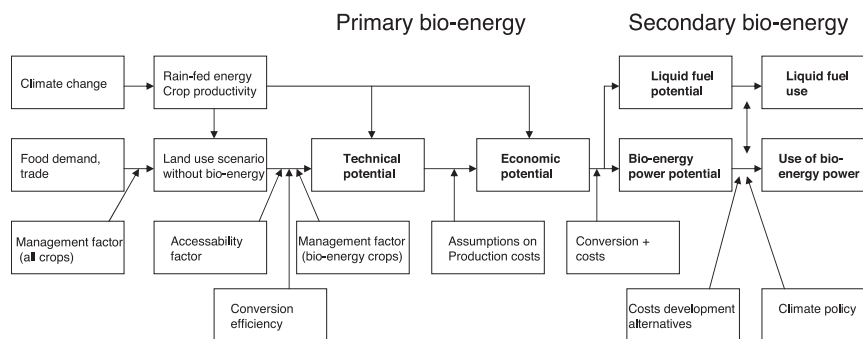
2.2 Bio-Energy Demand

Future bio-energy production is obviously also determined by expected demand. Some studies combine estimates of bio-energy supply with a description of bio-energy demand. These studies show that massive use of bio-energy might occur in transport, as feedstock for power, heat and hydrogen generation, and in order to produce materials. In each case, the demand depends strongly on the competition with alternative climate-neutral options, particularly the hydrogen fuel cell and electric car for the transport sector and carbon-capture and storage and other renewables in the power sector. Recently, a summary was made of selected scenarios that reported bio-energy use. This found that in most energy scenarios bio-energy use in the year 2100 is projected to be in the order of 200-300 EJ, with a minimum of 150 EJ in a conservative reference scenario without any climate policy. and a maximum above 400 EJ in a biomass-intensive scenario with active climate policy (Dornburg et al., 2008). Another overview made for the IPCC came to similar conclusions (Rose et al., 2008).

3. EXPERIMENTAL METHODS

3.1 Procedure to Explore Bio-Energy Potentials Using the IMAGE Model

The integrated assessment model IMAGE 2 and the global energy model TIMER have been used earlier to estimate the technical and economic potential of bio-energy (de Vries et al., 2007; Hoogwijk et al., 2005; van Vuuren et al., 2009b). An overview of the method is provided in Figure 1. The first step is assessing which areas can be used for production of biomass for energy given their physical-geographical characteristics and other land requirements. To this

Figure 1. Method for Assessing Bio-energy Potential

The Bio-energy Potential presented in Figure 3-8 is the Technical potential as shown here in the middle of the Figure. Source: Van Vuuren et al. (2009b).

end, the IMAGE model is used to describe land-use in the absence of biomass production, considering projected future driving forces like food demand, crop yields and climate change. In earlier work the area available for biomass production was constrained to 1) abandoned agricultural land and 2) natural grassland systems (such as savannah, scrubland, tundra and grasslands), thereby excluding land used for food production, forests, nature reserves and urban areas. Additionally, an accessibility factor representing other constraints such as biodiversity protection and alternative land use further reduces the fraction of land of each land cover type that can be used for biomass production. Finally, areas with a very low potential yield (part of tundra and desert ecosystems) are excluded. The resulting available areas, together with the potential yields of the bioenergy crops maize, sugar cane and woody biomass, determine the biophysical potential. Next, the technical potential is calculated by taking into account that actual yields are lower than potential yields.
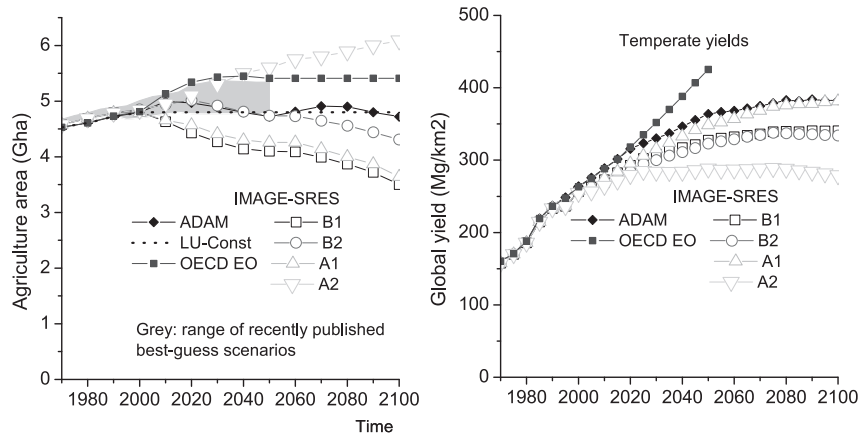
Here, we explore several of the uncertainties in the assessment of the technical bio-energy potential and identify which assumptions coincide with low, medium and high availability of bio-energy. On the basis of the literature discussion in section 2 we define medium values for global bio-energy use as lying around 200-300 EJ p.a.; low values around 100 EJ p.a.; while high values are in the order of 400 EJ p.a.. In our calculations, we focus solely on woody bio-energy crops. We do so for two reasons. First, many studies expect woody or grass-type biomass (miscanthus, switch grass) to become the most dominant source of bio-energy in the long-term, either for direct use in power plants or for production of cellulosic ethanol (van Vuuren et al., 2008). The generic crop type "woody bio-energy" in IMAGE is representative of such biomass types (in contrast to so-called "first generation crops" like sugar cane, palm oil etc. that have very specific growth patterns). Secondly, the focus on woody bio-energy crops greatly simplifies the analysis.

The factors examined in our analysis are described in the following paragraphs.

3.1.1 Scenarios for Land Use for Agriculture Production (Excluding Bio-energy)

Land use projections for agriculture production critically determine the potential for bio-energy. Such land use projections depend mostly on assumptions on population growth, dietary preferences and consumption levels and yield assumptions. As shown in Figure 2, a set of recent land use projections developed using the IMAGE model represent the different outcomes in the literature reasonably well. In the Figure, the grey area represents the land use outcomes of recently published "best-guess scenarios" (see also Van Vuuren et al., 2008), while a wider range exists for scenarios that deliberately explore alternative land use developments.

Figure 2. Different Developments for Agriculture Land Use

Total agricultural area and global yields for temperate cereals for the ADAM scenario (van Vuuren et al., 2009a); LU-const = constant 2000 land use; OECD-EO (Bakkes et al., 2008); IMAGE-SRES (van Vuuren et al., 2007). Grey-area depicts the range of recently published "best-guess" scenarios (van Vuuren et al., 2008).

   The ADAM baseline scenario (which is used as a baseline scenario by all models discussed in this Special Issue; see Edenhofer et al., this Issue) has land use based on medium assumptions/dynamics as usual – and lies within the range of similar scenarios that have recently been published (Rose et al., 2008). It is based on the UN medium population scenario, a medium/rapid economic growth path and the Adapting Mosaic land use scenario developed together with the agro-economic IMPACT model for the Millennium Ecosystem Assessment (Alcamo et al., 2005).

   In order to explore the influence of land use on bio-energy potential, we have included several alternative scenarios. The first is the reference scenario of the OECD Environmental Outlook, another "medium" scenario but with land use assumptions based on the agro-economic model LEITAP, originally calibrated to FAO's projections (Bakkes et al., 2008). A second set is formed by the IMAGE 2.3 SRES scenarios that aim to explore the ranges of possible outcomes for land use. The scenarios are updates of the original SRES scenarios, using the full range of scenarios of the Millennium Ecosystem Assessment. The scenarios differ in expectations for population, income, yield increase and dietary patterns as indicated below.

• The B1 scenario depicts a world with high economic growth oriented at sustainable development and is based on a low population scenario, relatively rapid yield improvement and a rather meat-extensive diet relative to the income development.

- The A1 scenario, in contrast, depicts a high growth world with low population, relatively rapid yield improvement and a much more meat-intensive diet.
- The A2 scenario describes a politically fragmented world, with high population growth, low income growth, and relatively slow technology development. As a consequence, agricultural land use in this scenario is relatively high.
- The B2 scenario, finally, is based on medium assumptions for most parameters.

The variation in agricultural land use across these scenarios is from a 15% decline compared to 2000 land use in the B1 case up to a 15% increase in the A2 case. As a last case, we also included a constant land use scenario. Figure 2 also illustrates the impact of yields on land use by showing the yields for temperature cereals included in all scenarios. The figure illustrates the high yield increases in A1 and the low yield increase in A2 (ranging from a 50% to 10% improvement across the century). Both the ADAM baseline and the baseline of the OECD Environmental Outlook have relatively high improvement rates for temperate cereals but this is partly compensated for by other crops and/or assumptions on consumption patterns (resulting for instance in a relatively large agriculture area in the OECD scenario).

3.1.2 Yields for Bio-energy Crops

A second crucial factor is the yield assumption for bio-energy per se. In IMAGE, the potential yield of different crops is calculated per grid cell, for a 0.5º x 0.5º grid based on an agro-ecological zones approach. Yields of crops and pasture are computed, estimating the areas needed for their production as determined by climate and soil quality (Alcamo et al., 1998). In the calculations, the potential yield is multiplied by a management factor (MF) to arrive at actual yields. The MF represents the ability of farmers (through agricultural knowledge, infrastructure, investments etc.) to achieve the potential yields. For the historic period, the MF is estimated by calibrating calculated yields against FAO data on actual yields – and in general, the MF is lower than 1, especially in developing countries. For the future, it is assumed that yields increase, for both food crops and energy crops. The influence of food crop assumptions occurs via the land use scenarios discussed in the previous section. For energy crops, we use the data from Hoogwijk et al. (2004), and assume yields to increase in the base scenario to a management factor of 1.25 in 2075 globally. This corresponds for the grid cells with the highest global yields of 13 to around 30 ton dry matter per hectare per year in the 2000-2050 period (label "base"). In the uncertainty analysis, we have explored 1) constant year 2000 yield (label "2000 yield"; management factor of 0.3-0.7); 2) a maximum yield of 23 ton dry matter per hectare for the cells with highest yields (label MF-1; management factor of 1) and 3) a maximum yield of 35 ton dry matter per hectare (label MF-1.5; management factor of 1.5 in 2100).

3.1.3 The Use of Natural Grassland and Forest Area

Bio-energy can be produced on different types of land. One possibility is the use of abandoned agricultural land (Campbell et al., 2008; Hoogwijk, 2004). The availability of abandoned agricultural land strongly depends on land use assumptions. In most scenarios, some abandoned agricultural land is assumed to become available, as agricultural land in some regions (e.g. Western Europe) is likely to contract. For this study, we assume that all abandoned agricultural areas can be used for bio-energy production. In our default estimates of bio-energy potentials, we have also assumed that 50% of the natural grasslands (tundra, grasslands, savannah, shrub land) can be used. Forests however cannot be used (label "base") both because of biodiversity considerations and because deforestation is likely to result in a very unfavourable balance for net greenhouse gas reductions from bio-energy use. For uncertainty analysis, we have explored a wide range: varying the availability of natural grassland from 0-100% (label "GR0" and "GR100") and of forest area from 0-30% (label "FO0" and "FO30").

3.1.4 Restrictions on Land Use Based on Sustainability Considerations

As mentioned in the introduction, concerns have been expressed over the impact of bio-energy use on water scarcity, land degradation and biodiversity. In order to explore the impact of these factors, we excluded areas with severe water scarcity, severe land degradation and areas that might become bio-reserves in the future within our sensitivity analysis.

- The GLASOD database (Oldeman et al., 1990) was used to explore the potential reduction of the bio-energy potential through *land degradation*. The GLASOD database classifies the global land area with respect to soil degradation. It is based on information available in the late 1980s, uses a high level of aggregation and does not provide information on the possible development of land degradation in the future. It does, however, provide a first insight into the interaction of bio-energy potential and land degradation. In our analysis, we exclude severely degraded areas as production would not be very likely in these areas. However, it has been argued that medium degraded areas would be very attractive for bio-energy production as careful bio-energy cultivation on such sites would allow for land restoration and avoid competition with food production. Earlier we explored the potential on such sites (van Vuuren et al., 2009b), but have not explored this further here.
- For *water scarcity*, we used an estimate of water scarce areas as calculated by the WaterGap model (Döll et al., 2003) for the same scenario that underlies the bio-energy potential (OECD, 2008). Each grid-cell is assigned a water scarcity category based on the total actual water withdrawal as a proportion of the maximum available runoff minus environmental water requirements.
- Finally, for development of future *bio-reserve areas* we used a scenario that was developed for UNEP's 4th Global Environmental Outlook (UNEP, 2007).

This describes in a geographically explicit way an ambitious expansion of world-wide bio-reserve area from 12% to 25% of total land. This scenario should be regarded as a rather high estimate of future expansion of bio-reserve areas and can therefore give an indication of the availability of bio-energy after safeguarding a considerable part of the world's biodiversity. In the default calculations existing bio-reserve area is already excluded.

3.1.5 Residues

The availability of agricultural residues for bio-energy production has been estimated to range from hardly any available material to over 100 EJ p.a. Berndes et al. (2003) reviewed a wide range of studies, including studies on bio-energy (including residues) potentials and bio-energy use. They found that a typical range for residue use/availability in 2020-2030 might be 20-80 EJ p.a. (average 50 EJ p.a.), for 2050 it is 30-100 EJ (average 65 EJ), and for 2100 it is 30-150 EJ (average around 80-100 EJ). Much lower estimates have also been published, such as Nonhebel (2007), who states that of the 12 EJ p.a. of agricultural residues, most cannot be regarded as available, since it is used as livestock feed. In our default calculations we have therefore widened the range somewhat compared to the typical ranges derived from Berndes et al. to 0-50 EJ p.a., 0-100 EJ p.a. and 10-120 EJ p.a.

3.1.6 Integrated Estimates

In order to explore the interaction across the factors described above, we have grouped them in two main categories:

1. The efficiency of land use, including yields for bio-energy crops and, indirectly via the land use scenarios, the yields for food and feed production. The land use scenarios also include other factors such as population assumptions and dietary changes, but it has been shown that yield assumptions are a crucial factor.
2. The impact of bio-energy use. This includes the use of natural grassland and forest, criteria with respect to water scarcity, soil degradation and biodiversity, and the availability of residues.

For these two groups, the settings explored in the sensitivity analysis for the individual factors described in the previous paragraphs were combined. These combinations are summarised in Table 1.

3.2. Scenarios of Bio-Energy Use

We compare the demand for bio-energy in the different low greenhouse gas concentration scenarios produced by the four energy/integrated assessment models described in this special issue: the optimal growth models MERGE

Table 1. Settings in the Integrated Analysis of Bio-Energy Potentials

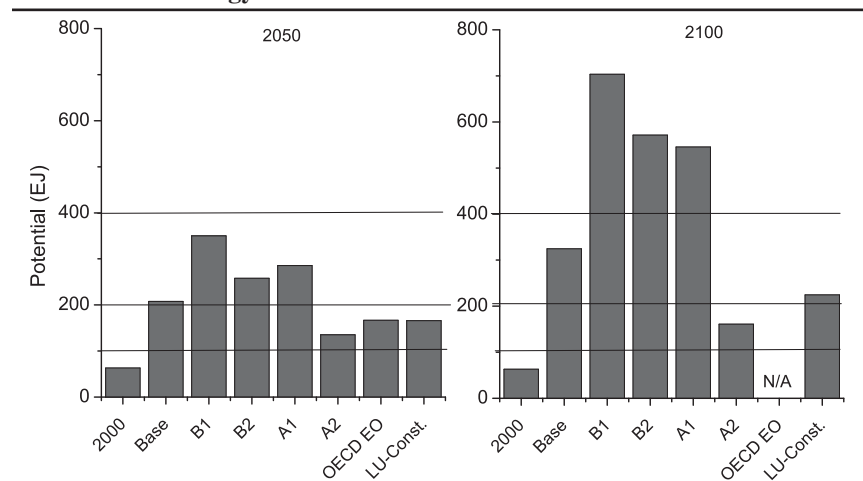| Land use scenario and bio-energy yields		Acceptance of bio-energy impacts	
A1_MF1.5	A1 land use scenario and bio-energy yields following Hoogwijk (2004)	GR100_FO20	Accessibility factor for natural grassland 100% and forests 20%
A1_MFbase	A1 land use scenario and bio-energy yields according to the ADAM scenario (MF^a = 1.25)	GR100_FO0	Accessibility factor for natural grassland 100% and forests 0%
ADAM_MFbase	ADAM land use scenario and bio-energy yields according to the ADAM scenario (MF = 1.25)	GR50_FO0	Accessibility factor for natural grassland 50% and forests 0%
ADAM_MF1	ADAM land use scenario and bio-energy yields limited to MF = 1.0	GR50_FO0*	Accessibility factor for natural grassland 50% and forests 0%; exclusion of areas with potential for severe soil degradation, severe water scarcity or high biodiversity value
A2_MF1	A2 land use scenario and bio-energy yields limited to MF = 1.0	GR0_FO0	Accessibility factor for natural grassland 0% and forests 0%
A2_MF2000	A2 land use scenario and constant bio-energy yields	GR0_FO0*	Accessibility factor for natural grassland 0% and forests 0%; exclusion of areas with potential for severe soil degradation, severe water scarcity or high biodiversity value
		GR0_FO0**	Accessibility factor for natural grassland 0% and forests 0%; exclusion of areas with potential for mild soil degradation, mild water scarcity or high biodiversity value

a. MF = Management Factor

(Magné et al., 2010, this Issue) and REMIND (Leimbach et al., 2010, this issue) and the energy system models POLES (Kitous et al., 2010, this Issue) and IMAGE-TIMER (van Vuuren et al., 2010, this Issue).[2] IMAGE-TIMER has the most detail concerning land-use representation and its evolution, followed by POLES, which

2. Often abbreviated as TIMER in the following when speaking of the energy system modeling and as IMAGE when dealing with the biomass potential elaboration

Table 2. Overview of the Models Included in the Analysis

Model	Description
REMIND	REMIND considers the ligno-cellulosic biomass type to calculate the potential. The model follows Hoogwijk (2004) scenarios for the biomass potential projections, and the maximum potential is reached by 2030. Costs of supply increase with increasing demand but there is no explicit trade-off with other land-use and the maximum potential is limited.
MERGE	MERGE implicitly includes many biomass types into the potential. These are wood, forest residues, short rotation crops (SRC), agricultural and wastes residues and oil and sugar crops. The potential is assumed to apply to arable land and pastoral / marginal land. The biomass potential is projected with a linear trend and the maximum technical potential is available by 2100.
POLES	POLES represents explicitly different biomass types: forest residues, short-rotation crops and oil and sugar crops. In the model, biomass types are assigned to specific areas and yields are directly linked to the biomass types. Land areas available to produce bio-energy are forests for residues and grasslands for short rotation crops. In the beginning of the simulation, the oil and sugar crops potential is assigned to arable land. This potential progressively decreases over time due to the competition with food supply needs with a rapidly increasing population.
IMAGE-TIMER	See Section 3.1 In TIMER, the bio-energy potential is translated to cost-supply curves. Bio-energy then competes with other energy sources on a cost basis.

Figure 3. Impact of Different Land Use Scenarios on Woody Bio-Energy Potential

The 2000 column indicates potential under 2000 assumptions; all other cases show the impact of changing only the land use scenario assumptions while keeping all other factors the same (see Section 3). Base (= ADAM baseline (van Vuuren et al., 2009a)); B1, B2, A1, A2 = IMAGE 2.3 elaborations of the SRES scenarios (van Vuuren et al., 2007); OECD-EO = OECD Environmental Outlook (Bakkes et al., 2008); LU-const assumes constant 2000 land use patterns.

has a simplified biomass module. The two other models do not have explicit land-use representation and use exogenous hypotheses based on literature to elaborate biomass potential scenarios (mainly FAO and IEA databases and output from other models such as IMAGE). A description of the approach taken by the models to model bio-energy use is given in Table 2.

In each of the low greenhouse gas concentration scenarios developed by the models, biomass has been found to be a key energy source. All models have been run using sensitivity analyses on the biomass resource in which the total available amount of biomass is set to 100 EJ p.a., 200 EJ p.a. and 400 EJ p.a. as a maximum (referred to hereinafter as 100EJ, 200EJ and 400EJ).

4. RESULTS OF THE ANALYSIS OF BIO-ENERGY POTENTIAL

4.1 The Influence of Individual Factors on the Potential for Bio-Energy
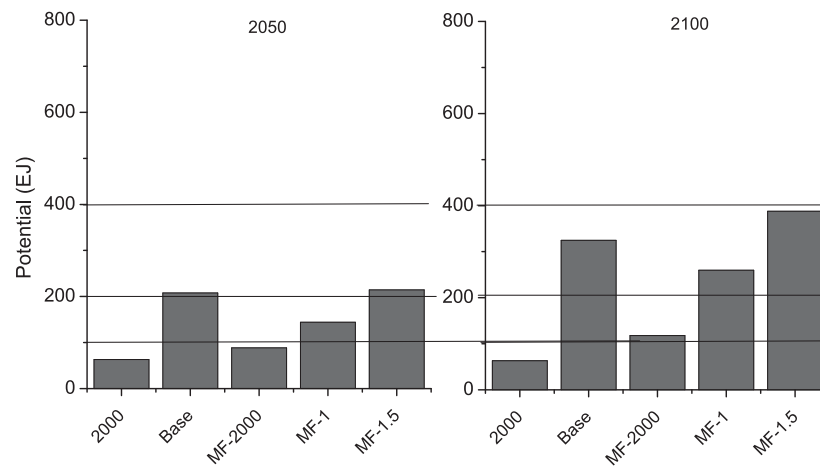
4.1.1 Scenarios for Land Use for Agriculture Production
(Excluding Bio-Energy)

The impact of land use on the bio-energy potential is considerable, as shown in Figure 3 (see Section 3 for a description of the land use scenarios; other factors follow the base assumptions also described in Section 3). In 2050, the bio-energy potential differs from less than 150 EJ (in the A2 scenario) up to 350 EJ for the B1 scenario. The differences are even larger in 2100, being 150 EJ and 700 EJ respectively. The difference between the A2 and B1 scenarios, representing the total range, is mainly caused by a high area of abandoned agricultural land and a higher availability of natural grassland in the B1 scenario, in contrast to a massive expansion of agricultural land in the A2 scenario. The OECD and ADAM scenarios result in values around 150-200 EJ in 2050, while the ADAM scenario shows a potential of 300 EJ in 2100 (the OECD scenario does not look further than 2050). A scenario that assumes constant land use from 2000 onwards results in a lower potential of slightly more than 200 EJ in 2100; Although land use in ADAM is also nearly constant, the shift in agricultural production across different regions results locally in large areas of abandoned agricultural land, accounted for in the bio-energy potentials.
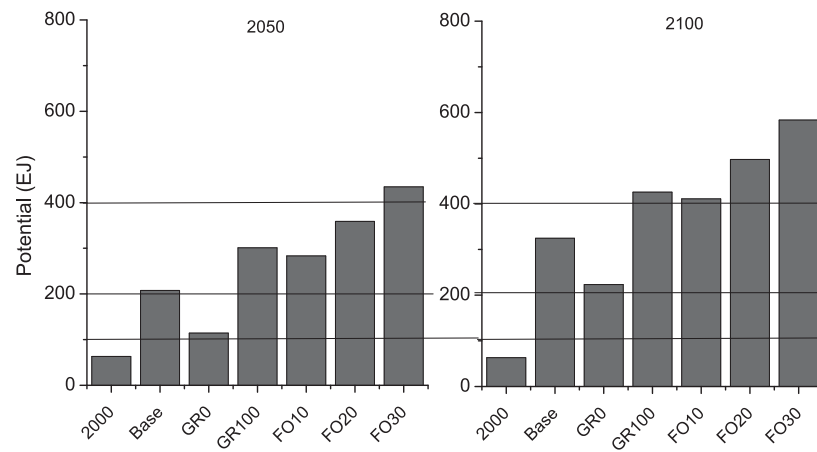
4.1.2 Yields for Bio-Energy Crops

As shown in Figure 4, the impact of assumptions on yield is somewhat smaller than that of the land use scenarios. The calculated bio-energy potential varies from between 80 EJ in 2050 and 100 EJ in 2100 when there is no yield improvement at all to slightly above 200 EJ in 2050 and 400 EJ in 2100.

Figure 4. Impact of Different Yield Assumptions on Woody Bio-Energy Potential

The 2000 column indicates potential under 2000 assumptions; all other columns show impact of changing only yield assumptions while keeping all other factors at base scenario assumptions (see Section 3). Base (= ADAM baseline (van Vuuren et al., 2009a)); MF-2000 represent constant 2000 management factors. MF-1 and MF-1.5 increase the management factor linearly to 1 and 1.5 in 2100.

Figure 5. Impact of Using Natural Areas on Woody Bio-Energy Potential

The 2000 column indicates potential under 2000 assumptions; all other columns show the impact of changing only assumptions on using natural areas while keeping all other factors at base scenario assumptions (see Section 3). Base (= ADAM baseline, includes 50% use of natural grasslands (van Vuuren et al., 2009a)); GR0 and GR100 explore impacts of using 0 and 100% of natural grasslands. FO10, FO20 and-FO30 explore impacts of using 10, 20 and 30% of natural forests.

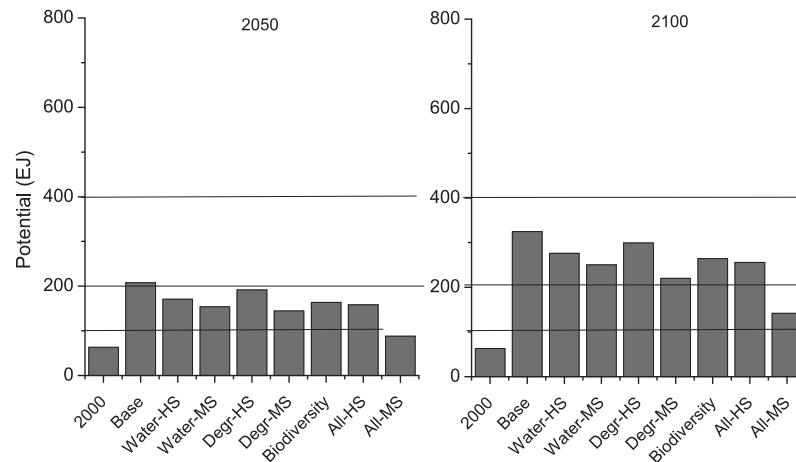*4.1.3 The Use of Natural Grassland and Forest Area*

The results for bio-energy potential also depend on the type of land included in the analysis (Figure 5). Obviously, the question of whether land use for food production should be replaced by energy production is most controversial; in our analysis therefore, land for agricultural production is excluded. The use of abandoned agricultural land is the least controversial as its current biodiversity value is in most cases rather low. The inclusion of other land types however, is a trade-off between bio-energy production and potential use of the same land for biodiversity protection and/or other ecological services. Including areas currently still natural, for potential bio-energy production represents a different choice. According to EU policies, for instance, use of grasslands for bio-energy production is not acceptable for "high-biodiversity" grasslands, but acceptable for grasslands that are not highly diverse.

In the default calculations we assumed that 50% of natural grasslands (savannah, grasslands, shrub land, wooded tundra) can be used (and no forest area). Both grassland and forest area use substantially influence potential. For grassland, the range in the sensitivity analysis (GR0 and GR100) is about 100 EJ p.a. either side of the base case. The impact of forest conversion assumptions is even larger, given the relative area of productive land within these two different biomes. Allowing a 30% loss of forest area (FO30) can increase potential to 500-600 EJ p.a. by 2100. However, conversion of forest area causes a considerable loss of carbon due to deforestation. We do not know how much time is needed to compensate for this by avoided fossil fuel emissions through bio-energy production.
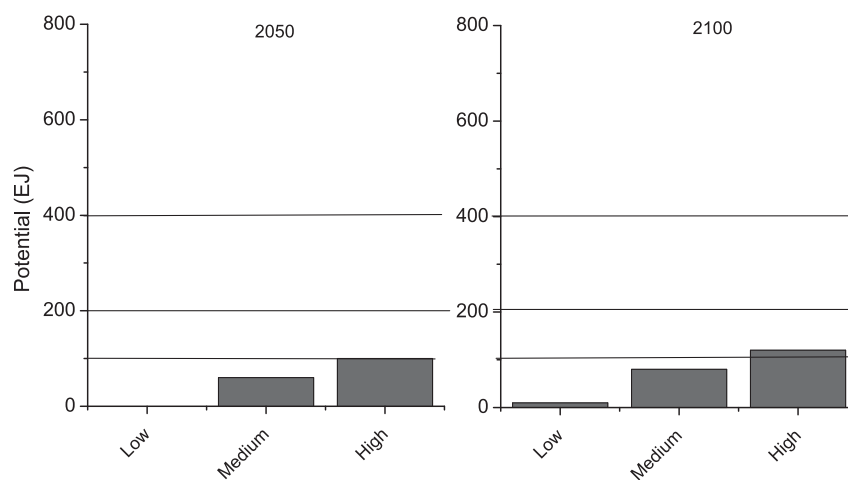
4.1.4 Sustainability Criteria

The potential for bio-energy might also be constrained by additional criteria such as water scarcity, soil degradation and biodiversity considerations. Figure 6 shows that removing areas characterised by high or medium water scarcity (stress) from the included area reduces the potential by 20% and 25%, respectively (in 2100 the potential is reduced from 325 EJ to 250 EJ). Removing areas characterised by high and medium soil degradation has a similar result (10% reduction for high and 30% for medium degradation). However, one might also see the 20% of the potential attributable to medium degraded soils as a prime target for bio-energy production as no competition with food production will occur in those areas and careful cultivation of bio-energy crops might even help restore soils. Figure 6 also shows that removing those areas that were classified as interesting for biodiversity protection in the GEO-3 Sustainability First scenario reduces potential by 20%. Altogether this means that removing areas characterised by high water stress, high soil degradation or as interesting for biodiversity protection reduces bio-energy potential by 25% (from 325 EJ down to 250 EJ in 2100). If much stricter criteria are used and bio-energy cannot be

Figure 6. The Impact of Considerations With Respect to Water Scarcity, Soil Degradation and Biodiversity Protection on Woody Bio-Energy Potential
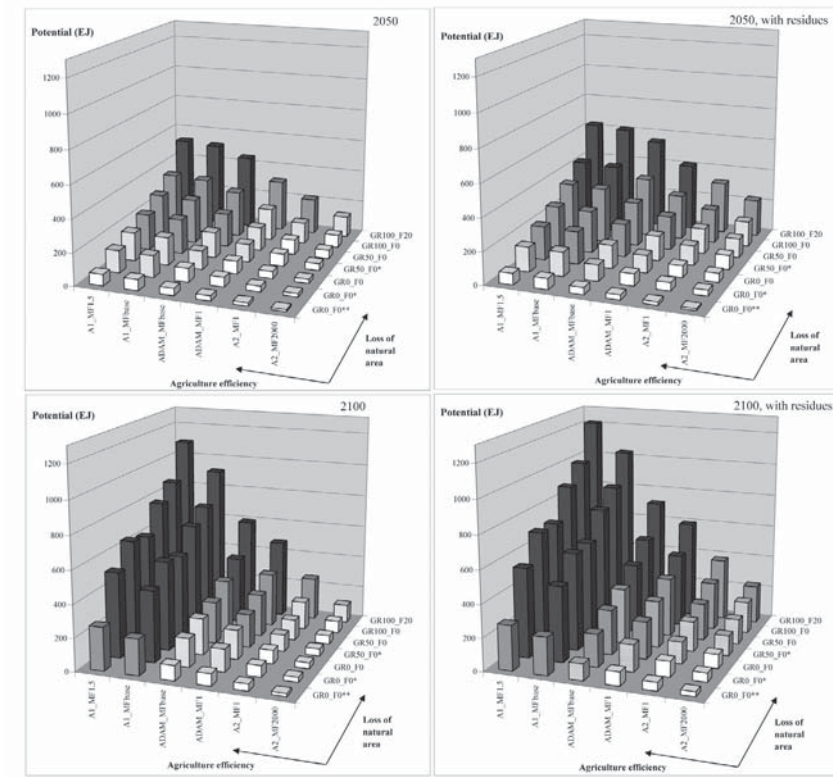

The 2000 column indicates potential under 2000 assumptions; all other columns show the impact of including restriction with respect to sustainability issues (see Section 3). Base (= ADAM baseline (van Vuuren et al., 2009a)); Water HS and Water MS show impact of excluding areas suffering from high and medium water scarcity respectively. Degr HS and Degr MS show impact of excluding areas suffering from high and medium soil degradation based on the GLASOD database, respectively. Biodiversity shows impact of excluding nature reserves according to UNEP Sustainability First scenario. All HS and All MS put restrictions of water scarcity and soil degradation both at respectively high and medium values.

Figure 7. Bio-Energy Potential from Residues

Values based on literature assessment (Berndes et al., 2003).

**Figure 8. Combinations of Different Factors Determining
Bio-Energy Potential**

Upper panels 2050; without (left) and with (right) residues included; lower panels 2100; without (left) and with (right) residues included. Black bars are above 400 EJ p.a., dark grey bars indicate potential from 200-400 EJ p.a., light grey 100-200 EJ p.a. and white bars below 100 EJ p.a.. Names of different assumptions indicated in Table 1.

grown in areas with medium water stress and medium soil degradation a total of 60% of the potential is removed (from 325 EJ p.a. down to 140 EJ p.a.).

4.1.5 Residues

The availability of residues for bio-energy production is mostly independent of other factors already considered. Although values for this potential are typically less than for bio-energy crops, they are still substantial, as shown in Figure 7.

4.2 Bio-Energy Potential Resulting from Combinations of Factors

In Figure 8 the results for combinations of the different factors are shown. In 2050, most combinations of factors result in a bio-energy potential below 200 EJ. Only a few combinations result in a bio-energy potential above 400 EJ, all having a substantial impact on biodiversity. If bio-energy production is constrained to abandoned agricultural land, 50% of the natural grass land area and no forest land, and land use follows the A1 scenario, the maximum potential for bio-energy crops and residues in 2050 is just above 300 EJ. However, if yields develop along a median path, potential is around 200 EJ p.a. In such a situation, bio-energy potential can only rise above 200 EJ p.a. (including residues) if some forest is converted to energy crops. Strict criteria with respect to biodiversity loss (limited use of natural areas; expansion of bio reserves and excluding areas with severe water scarcity or soil degradation) lead in all cases to a potential below 100 EJ in 2050.

In 2100, the bio-energy potential is considerably larger than in 2050, through improvements in yields and the expected slow down in population growth or even population decline; as a result, the number of combinations that could generate more than 400 EJ p.a. bio-energy increase significantly. In fact, the bio-energy potential exceeds 400 EJ p.a. for most combinations based on the A1 scenario. Under the median ADAM scenario, potential would be around 200-400 EJ p.a. in most cases. Strict sustainability criteria however, are likely to limit bio-energy potential below 200 EJ in 2100.

5. RESULTS ON BIO-ENERGY USE IN DIFFERENT MODELS AND SCENARIOS

All the models used to develop low stabilization scenarios make assumptions on bio-energy supply. Below we discuss the assumptions made in the different models, and their main results:

5.1 Bio-Energy Potential in Different Energy Models

In their calculations on low emission scenarios, the four integrated assessment models REMIND, POLES, MERGE and TIMER have made assumptions on the bio-energy supply consistent with maximum values of 100, 200 and 400 EJ p.a. Table 3 shows the evolution of the biomass potential in the different scenarios for the four models.

As shown in the previous section, such potentials can be consistent with different trends in land use and agricultural yields. The underlying data in the energy models have not been harmonised and they differ over time and with respect to regional assumptions (see the individual papers for a description of these assumptions). The distribution of bio-energy potentials across different regions is important: along with climate change mitigation, an important argument for

Table 3.   Global Biomass Potential Over Time in Four Models

	2005	**2030**	**2050**	**2100**
400 EJ sensitivity case				
POLES	218	270	318	400
MERGE	104	178	238	398
REMIND	68	400	400	400
IMAGE	135	178	253	448
200 EJ sensitivity case				
POLES	161	172	185	198
MERGE	94	120	141	203
REMIND	68	200	200	200
IMAGE	130	158	203	286
100 EJ sensitivity case				
POLES	109	99	100	100
MERGE	89	91	92	106
REMIND	68	100	100	100
IMAGE	135	164	184	194

Note that the IMAGE/TIMER model constrained bio-energy potential from dedicated bio-energy crops to the reported numbers; but left potential from residues unchanged).

developing bio-energy is security of energy supply. In Figure 9, for each model the potential in key world regions is shown. In general, the regional assumptions in the different models follow a similar pattern. However, some differences are that MERGE shows a higher potential for bio-energy in India than the other models, while REMIND seems very optimistic in Russia. POLES is more optimistic than the other models in Canada, Australia and New Zealand, while TIMER indicates the highest potential for bio-energy in the USA and China, and a much lower potential than the other models in India.

In Europe, all models estimate similar levels of bio-energy potential. These results can also be compared to individual model studies. For instance Hall (Hall et al., 1993) reports a 12.1 EJ p.a. biomass potential while Fisher (Fisher and Schrattenholzer, 2001) reports 17.6 EJ p.a. potential in a medium scenario. Other studies show much lower potentials for Europe such as de Noord (2004) with less than 5 EJ p.a. which is close to the low biomass potential estimation by the ADAM models.

Figure 9. Regional Biomass Potentials for Different Models in Three Scenarios for Key World Regions
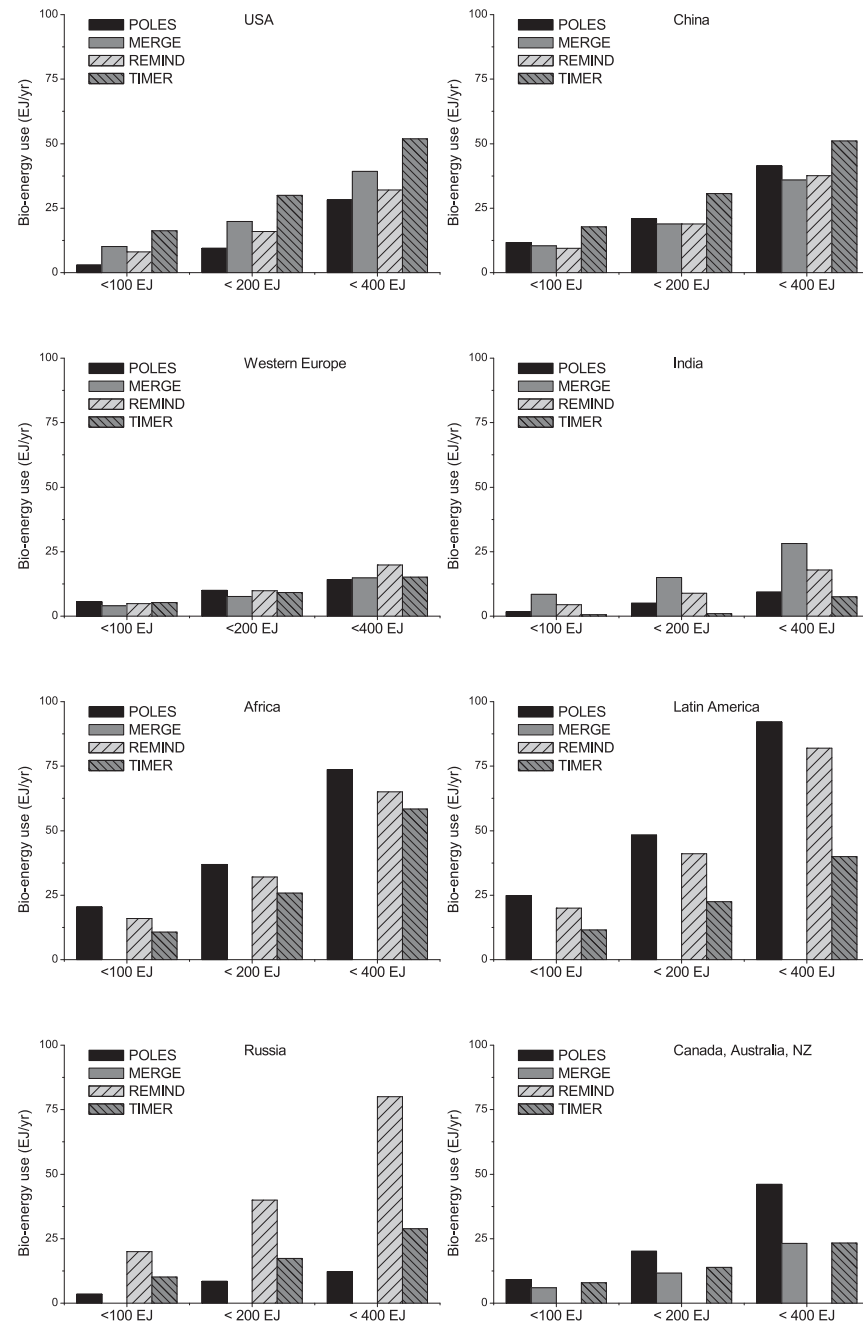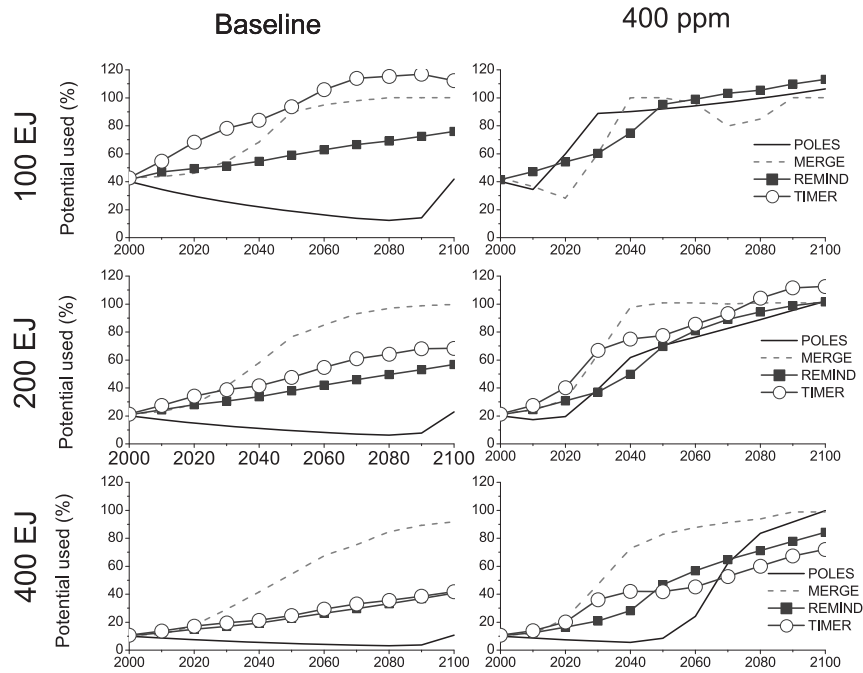
Figure 10. Biomass Potential Use Across Models and for Different Potentials, in the Baseline and 400ppm Scenarios

Reference to the maximum potential as requested for each scenario.

5.2 Bio-Energy Use in the Baseline and Low Stabilization (550 and 400 ppm CO₂eq) Scenarios

5.2.1 Baseline

For each model used in the comparisons of this special issue, the main baseline assumptions (population, income and storyline) were harmonized. Energy sector assumptions were also harmonized as far as possible. As the energy mix is a model output, it differed across the models, in relation to differences in endogenous energy prices, technology assumptions and model preferences (Edenhofer et al., 2010, this issue). Figure 10 shows the implemented bio-energy in the baseline and 400ppm stabilization scenarios under a bio-energy potential of 100, 200 and 400 EJ p.a.

REMIND is the only model to achieve full potential using the 100EJ and 200EJ sensitivities, and almost full potential in the 400EJ case. The other models have a lower biomass contribution as fossil fuels have lower costs than the
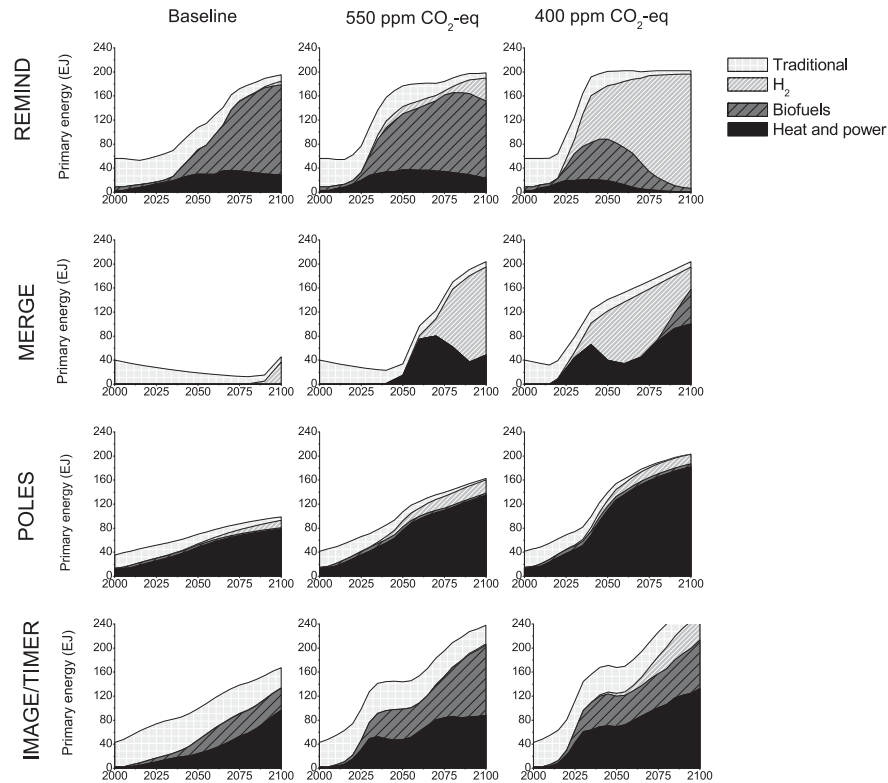
bio-energy alternatives (at a certain level of penetration). In MERGE the use of bio-energy decreases over time until 2090, after which the model makes higher use of biomass in each sensitivity case. Biomass use is very different across the models, but the behavior of each model is similar through the 100EJ, 200EJ and 400EJ sensitivity cases.

5.2.2 Low Stabilization Scenarios

All models have run different stabilization scenarios, including stabilization at 550 ppm CO_2eq (550ppm) and an ambitious climate policy scenario with a long-term stabilization target at a concentration of 400ppm CO_2eq.(400ppm) In the latter scenario, radiative forcing peaks quickly close to three Wm^{-2} and then declines to 2.6 Wm^{-2} by 2100. As explained in Edenhofer et al. (2010, this issue), every model has implemented this target, albeit in different ways (either as a cumulative emission target, or an annual emission gap). The strategies developed in each model to reach the target are very different from one model to another (Edenhofer et al., 2010, this issue). Energy mix is not a robust feature across the models, but depends heavily on the model assumptions about the available technologies, learning rates and resource prices. For emissions reduction, MERGE relies mainly on renewables development, which takes most of the market share, but also on energy efficiency. TIMER uses substantial fossil fuels with carbon capture and storage (CCS) to reach the target. POLES and REMIND have more diversified energy mixes; POLES relies heavily on energy efficiency while REMIND uses more CCS. Obviously, these different strategies also have major consequences for bio-energy use.

In the 400ppm scenario, biomass is a key resource to reach the emission target for all models. In the 200EJ and 100EJ sensitivity cases, all models reach the maximum technical potential – but at different moments in time. In the low stabilization scenarios, bio-energy use is much higher than in the baselines. Among the different models, REMIND focuses most on bio-energy reaching maximum technical potential early (by 2040 in the 100EJ and 200EJ sensitivity cases and by 2090 in the 400EJ case). As a result, the model shows a rapidly increasing bio-energy use during the 2020 to 2040 period. MERGE reaches maximum potential at the very end of the simulation in the 200EJ and 400EJ sensitivity cases. POLES does not reach the technical potential in the 400EJ sensitivity case, but makes significant use of bio-energy from 2050. The model reaches the potential at the very end of the simulation in the 200EJ sensitivity and earlier (2060) in the 100EJ case. TIMER does not reach the maximum in the 400EJ sensitivity, but overshoots it in the 200EJ case. The combination of 100 EJ p.a. bio-energy potential and the stringent mitigation target was not feasible in TIMER.

Figure 11. Biomass Potential Use Across Models and for Different
Potentials, in the Baseline, 550 and 400ppm CO$_2$eq Scenarios

5.2.3 Different Types of Use

Figure 11 shows how the different models use bio-energy in the energy system for the baseline and both mitigation scenarios. In the baseline, bio-energy is used for electric power generation in POLES and TIMER (less in REMIND), but it is also used to produce biofuels (REMIND and TIMER). Traditional biofuel use decreases rapidly in most models, but remains relatively high in TIMER.

In the stabilization scenarios, bio-energy use is considerably higher than in the baseline, and is mostly utilized in the generation of hydrogen and power generation. In power and hydrogen generation, part of production is combined with carbon capture and storage (CCS).

The use of biomass for biofuel shows different dynamics across the stabilization scenarios and models. In the 400ppm scenario, biofuel use is small (POLES, MERGE) or is less important relative to the baseline (TIMER,

REMIND). For the intermediate target, however, biofuel use plays an important role in TIMER and REMIND. Under stringent mitigation targets, bio-energy can contribute most effectively to greenhouse gas emission reduction in stationary applications in combination with CCS, where it can result in net negative emissions (carbon uptake during the crop growth phase and no emissions during the bio-energy combustion). In the baseline or for less stringent targets, biofuels are an attractive way to use bio-energy potential.

6. STORYLINES FOR WORLDS WITH VARYING BIO-ENERGY POTENTIALS

6.1 Storylines for a World with a Bio-Energy Potential of 400 EJ p.a.

The calculations on bio-energy potentials show that high global bio-energy use, in the order of 400 EJ by 2050, is only feasible if demand for agricultural land for other purposes follows a pathway including high agricultural yields, or if considerable loss of natural areas and biodiversity is accepted. In the longer run (2100), 400 EJ would be feasible under most land use scenarios – although considerable improvements of yields would still be required. In other words, reaching 400 EJ p.a. of bioenergy under sustainability criteria will not be easy. For such a scenario, major dietary changes or a high demand for bio-energy and improved yields in developing countries may also play an important role.

Given these rather optimistic assumptions, this scenario is only likely in a situation in which the world focuses heavily on managing climate change and/or energy security by all available means, including the land-use related options. As a high conversion of forest area into bio-energy area results in both a high loss of biodiversity and most likely little climate benefit, one may conclude that these cases are not consistent with either limiting greenhouse gas emissions, or conserving biodiversity. The high forest conversion rate experiments can thus be ruled out – making this scenario dependent on high yield improvements for both food and bio-energy production by 2050 (and/or dietary changes).

One may speculate on the implications of the yield improvements, as high yields may require extensive use of fertilizers, or use of genetically modified crops. If bio-energy is introduced for climate reasons, the supply needs to be mostly based on crops that have relatively low fertilizer input – such as woody biofuels in order to have an attractive greenhouse gas balance. The environmental impacts of this scenario are potentially high, e.g. in terms of changes in landscapes, and possibly even forest conversion (directly or indirectly.). If loss of forest area is to be avoided, the most effective approach would probably be to restrict expansion into forest areas for all forms of agriculture – as setting criteria for bio-energy alone is not likely to be effective under a scenario with severe land constraints (due to indirect effects).

6.2 Storyline for a World with a Bio-energy Potential of 100 EJ p.a.

Our results show that bio-energy potential could be constrained to just 100 EJ p.a. worldwide. This is in particular the case if one of the following factors is true: 1) high population growth with little yield improvement; 2) little yield change for bio-energy; 3) strict application of criteria with respect to water scarcity and soil degradation; 4) strict criteria with respect to protection of biodiversity. At the same time, availability of residues would need to be low. If more than one of these assumptions is true, the potential could also be considerably less than 100EJ p.a.

A scenario with around just 100 EJ p.a. of bio-energy potential is likely in the case of a politically fragmented world, with little yield improvement and high population growth. Strict biodiversity criteria might also strongly reduce potential however – emphasizing the potential trade-off between protection of biodiversity by avoiding climate change (and thus possibly using large amounts of bio-energy) and protection of biodiversity from the effects of massive bio-energy use.

Under a low supply scenario, yields could progress steadily, in a sustainable way. Agricultural residues could satisfy a large part of the soil fertilizing function. In general, the environmental impacts of energy crops in such a scenario are limited.

6.3 Storylines for a World with a Bio-Energy Potential of 200 p.a.

A potential of 200 EJ p.a. lies, by definition, between the two storylines sketched above. Many combinations of factors exist that could result in a 200 EJ p.a. potential. For a more extensive discussion of this option, exploration of the consistency of these combinations is necessary.

7. CONCLUSIONS

In this paper, we have described the various factors that may influence the potential for bio-energy supply. We have also explored how bio-energy is used in stringent mitigation scenarios according to four integrated assessment models – and explored what limitation in bio-energy supply would mean for these models. The following conclusions can be drawn:

- **Typical values for sustainable potential of bio-energy production in 2050 are around 50-150 EJ, while potential may be in the 200-400 EJ range in 2100.** The potential for bio-energy strongly depends on a set of critical uncertainties, including agricultural yields and dietary patterns, the size of the global population, the acceptability of use of natural areas for bio-energy production and the possibilities of using water-scarce and degraded areas. Depending on these factors, bio-energy supply can vary over a very wide range (0-500 EJ p.a.). Typical values with reasonable land use assumptions and modest sustainability criteria are around 50-150 EJ p.a. In 2100 the range

increase to 0-1200 EJ p.a. This range is consistent with the range reported in literature – but is now related to specific assumptions.

• **Achieving the high part of the range of production, requires a development path following high agricultural yields, dietary patterns with low meat consumption, a low population and/or accepting high conversion rates of natural areas**. In fact, in 2050 potentials above 200 EJ can only be achieved by assuming loss of natural area due to bio-energy growth. In 2100, potentials may be above 400 EJ without much loss of natural area assuming relatively optimistic development paths for agricultural efficiency. Median bio-energy potentials, below 200 EJ p.a. but above 100 EJ p.a., result from many different combinations of factors. Establishing strict sustainability criteria reduces potential to below 200 EJ in 2100 even for a scenario with high agricultural efficiency. In a low growth scenario, minimal biodiversity and sustainability criteria will result in a potential of less than 200 EJ p.a. Fundamental shifts in dietary patterns to low meat consumption could lead to a much lower need for agricultural land and a higher potential for bio-energy (see B1 scenario).

• **Bio-energy potential may be small if agricultural yields develop at a low to medium pace accompanied by strict biodiversity and sustainability criteria.** In all scenarios, strict criteria with respect to loss of natural areas in 2050 reduce potential to below 100 EJ.

• **Bio-energy plays an important role in low mitigation scenarios**. In the baseline scenarios developed using four different integrated assessment models, we see that bio-energy use increases in three out of four models – but does not achieve its full potential. In the strict mitigation scenario, on the other hand, with a potential of 200 EJ p.a. or less, all models reach the point where the full potential is exploited. Thus, if bio-energy potential is not very high, under a strict mitigation scenario the limiting factor on its use will be the size of that potential. Even with the high potential of 400 EJ p.a., the full potential can be utilized.

• **In stringent mitigation scenarios, bio-energy is used mostly in stationary applications such as power generation and hydrogen production where it can be combined with carbon capture and storage.** In the baseline and the less stringent stabilization case of the TIMER and REMIND models, bio-energy is used extensively for transport. In the very stringent scenario, however, bio-energy use in stationary sources becomes more attractive.

• **Despite the potential role of bio-energy use for greenhouse gas reduction, it will be important to monitor its impacts closely, given the potential negative impacts on biodiversity.** Model scenarios show high use of bio-energy under stringent greenhouse gas emission reduction criteria. We have shown however, that bio-energy potential could be severely limited, given certain assumptions. Heavy pressure will probably be exerted to either reduce mitigation aims or to increase the bio-energy potential and the easiest way to increase this potential would be to relax criteria for biodiversity conservation and sustainability. In order to prevent these undesirable consequences, a considerable effort would be needed to increase bio-energy potential in other ways, such as the improvement

of yields. Since land-use is a complex issue, there are clearly other factors influencing the availability of land and yields, such as dietary changes. These might be important in cases in which a clash is foreseen between the demand for biofuels for purposes of climate change mitigation and the demand for sustainability and biodiversity conservation.

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