Woody biomass energy potential in 2050

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HIGHLIGHTS

- We examine woody biomass energy potential by partial equilibrium model of forest and agriculture sectors.
- It is possible to satisfy 18% (or 14% if primary forests are excluded) of the world's primary energy consumption in 2050 by woody biomass.
- To achieve this would require an extensive subsidy/tax policy and would lead to substantial higher woody biomass prices compared to their current level.

ARTICLE INFO

Article history:
Received 13 March 2013
Received in revised form 14 October 2013
Accepted 12 November 2013

Keywords:
Woody biomass
Energy
Partial equilibrium
Land use

ABSTRACT

From a biophysical perspective, woody biomass resources are large enough to cover a substantial share of the world's primary energy consumption in 2050. However, these resources have alternative uses and their accessibility is limited, which tends to decrease their competitiveness with respect to other forms of energy. Hence, the key question of woody biomass use for energy is not the amount of resources, but rather their price. In this study we consider the question from the perspective of energy wood supply curves, which display the available amount of woody biomass for large-scale energy production at various hypothetical energy wood prices. These curves are estimated by the Global Biosphere Management Model (GLOBIOM), which is a global partial equilibrium model of forest and agricultural sectors. The global energy wood supply is estimated to be 0–23 Gm3/year (0–165 EJ/year) when energy wood prices vary in a range of 0–30$/GJ (0–216$/m3). If we add household fuelwood to energy wood, then woody biomass could satisfy 2–18% of world primary energy consumption in 2050. If primary forests are excluded from wood supply then the potential decreases up to 25%.

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1. Introduction

Woody biomass is an important source of energy and is currently the most important source of renewable energy in the world. In 2010 global use of woody biomass for energy was about 3.8 Gm3/year (30 EJ/year), which consisted of 1.9 Gm3/year (16 EJ/year) for household fuelwood and 1.9 Gm3/year (14 EJ/year) for large-scale industrial use. 1,2,3 During the same period, world primary energy consumption was 541 EJ/year and world renewable primary energy consumption was 71 EJ/year (IEA, 2013). Hence, in 2010 woody biomass formed roughly 9% of world primary energy consumption and 65% of world renewable primary energy consumption. Despite the widespread use of woody biomass for energy, current consumption is still substantially below the existing resource potential (Openshaw, 2011). Moreover, there is plenty of surplus land that could be converted into energy crop plantations (e.g., Haberl et al., 2010; Beringer et al., 2011). The estimates of available woody biomass resources in 2050 vary in the 100–400 EJ/year range if some borderline results are excluded (Berndes et al., 2003; van Vuuren et al., 2010; IPCC, 2011;
Woody biomass energy potential depends not only on the available woody biomass resources but also on the competition between alternative uses of those resources and competition between alternative sources of energy (Radetzki, 1997; Sedjo, 1997; Berndes et al., 2003). These effects can be separated by using the concept of supply and demand curves. The energy wood supply curve defines the amount of woody biomass available for large-scale energy production at various hypothetical energy wood prices, that is, it summarizes all the relevant information from the biomass sector needed to model large-scale energy wood use. The energy wood demand curve defines the desired amount of woody biomass for large-scale energy production at various hypothetical energy wood prices; in other words, it summarizes all the relevant information from the energy sector needed to model large-scale energy wood use. Note that the term "energy wood" refers to large-scale woody biomass use for energy. Hence, energy wood does not include small-scale woody biomass use for energy (household fuelwood), which is modeled separately. Household fuelwood is not directly connected to large-scale energy wood markets because it often comes from different sources than large-scale energy wood and because its utilization is based on technologies that are incompatible with other forms of energy (May-Tobin, 2011).

The advantage of studying energy wood supply separately from demand is that it provides a consistent way of analyzing woody biomass energy potential without the need for explicitly modeling what happens in the energy sector. The energy wood supply curve defines woody biomass energy potential for an arbitrary range of energy wood prices rather than for some scenario-specific prices and/or quantities. As energy wood demand includes large uncertainties associated with different technology alternatives and mitigation policy options (e.g., IEA, 2010; IPCC, 2011; GEA, 2012), it makes sense to study a large range of possible outcomes. The energy wood supply curve can be used directly for energy policy analysis by connecting it with different energy wood demand scenarios or it can be used as an input to the energy sector model instead of linking the energy and biomass supply models by complicated iterative procedures (Tavoni et al., 2007).

Large unused woody biomass resources and an increasing need for climate change mitigation has awoken policymakers’ interest in woody biomass energy potential and has given rise to a large number of studies on this topic. The majority of these studies focus on regional potentials (e.g., Asikainen et al., 2008; de Wit and Faaij, 2010; Moiseyev et al., 2011; Verkerk et al., 2011; Daigneault et al., 2012; Ince et al., 2012; Lauri et al., 2012). The global studies are not based on explicit economic analysis (Parikka, 2003; Smeets and Faaij, 2007a, 2007b; Anttila et al., 2009); they lack a detailed description of woody biomass supply from forests (Berndes et al., 2003; Reilly and Paltsev, 2008; Hoogwijk et al., 2009; van Vuuren et al., 2009, 2010; Haberl et al., 2010; Beringer et al., 2011; Popp et al., 2011); or they lack a detailed description of woody biomass supply from energy crop plantations (Raunikar et al., 2010; Favero and Mendelsohn, 2013). Hence, the existing literature misses an economic analysis of global woody biomass energy potential, which would include a detailed description of woody biomass supply from forests as well as from energy crop plantations in a consistent framework with the agricultural sector.

The objective of this paper is to estimate the global woody biomass energy potential in 2050 using the Global Biosphere Management Model (GLOBIOM) (Havlík et al., 2011; Schneider et al., 2011). Our analysis differs from previous studies in four ways. First, it explicitly models the competition between alternative uses and sources of woody biomass through the market mechanism. Second, it includes a detailed spatially explicit description of woody biomass supply from forest and plantations. Third, it separates energy wood supply and demand from each other. Fourth, the land-use competition between food, wood and energy production is modeled explicitly. The focus of the paper is on global level results. However, some regional level implications will also be highlighted.

This paper is organized as follows: Section 2 describes the model and data. Section 3 presents the results of the model (i.e., estimates on energy wood supply curves). In Section 4 we compare the estimates to some other studies. Finally, Section 5 summarizes the results and discusses some of the policy implications of energy wood supply curves.

2. Methods and data

2.1. Model

The Global Biosphere Management Model (GLOBIOM) is a global partial equilibrium model of the forest and agricultural sectors, where economic optimization is based on the spatial equilibrium modeling approach (Takayama and Judge, 1971). The supply of biomass is modeled at 200 km x 200 km resolution, while the demand and trade of biomass operates at regional level. The world is divided into 30 regions that can produce, consume, and trade agriculture and forest sector final products in perfectly competitive markets. Besides final products, the model has several primary and by-products, which are utilized as inputs in final products production activities. The model includes six land cover types: cropland, grassland, other natural vegetation land, managed forests, unmanaged forests, and plantations. The term “managed forests” refers to forest area that is harvested, while “unmanaged forests” refers to forest area that is not harvested. Depending on the relative profitability of primary, by-, and final products production activities, the model can switch from one land cover type to another. Biomass use for large-scale energy production is usually based on the POLES or MESSAGE energy sector models (Havlík et al., 2011; Reisinger et al., 2013), but this option was not used in the present study. Mean annual increments and growing stocks for GLOBIOM are obtained from the Global Forest Model (G4M), which is a spatially explicit process-based forest management model (Kindermann et al., 2006, 2008). Plantations yield is based on own calculations, as described in Havlík et al. (2011). The initial period of the model is the year 2000, and operation is in 10-year time steps. More information about the model and related publications can be found in web page (www.globiom.org).

GLOBIOM is based on recursive optimization so that the solving times of the model can be kept within reasonable limits. In the recursive optimization model decisions are based only on the costs and benefits of the current period, which sets some limitations on the forest dynamics modeling compared to intertemporal optimization models (Sjölie et al., 2011). To handle forest dynamics in the recursive framework, it is assumed that all managed forests are normal forests, which allows the model to ignore the forest age-class dynamics and other intertemporal aspects of forest owners’ decision making. Normal forests have a uniform distribution of

\[ \text{Woody biomass energy potential depends not only on the available woody biomass resources but also on the competition between alternative uses of those resources and competition between alternative sources of energy.} \]

\[ \text{First, it explicitly models the competition between alternative uses and sources of woody biomass through the market mechanism.} \]

\[ \text{Second, it includes a detailed spatially explicit description of woody biomass supply from forest and plantations.} \]

\[ \text{Third, it separates energy wood supply and demand from each other.} \]

\[ \text{Fourth, the land-use competition between food, wood and energy production is modeled explicitly.} \]

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age-classes, which implies that mean annual increments and growing stocks remain constant over time and that forest owners can maintain constant sustainable harvested volumes over time (Reed, 1985).

Deforestation is driven in GLOBIOM by agricultural land use expansion. Afforestation is not modeled explicitly, but it is included implicitly in the deforestation. Hence, deforestation should be interpreted as net deforestation rather than gross deforestation. Deforested biomass is excluded from the available woody biomass resources; this implies that woody biomass demand influences deforestation only indirectly through land-use competition between agriculture and forestry. There are several reasons why deforested biomass often remains unused (Smeets and Faaij, 2007a). First, deforestation happens mainly in tropical areas where the deforested biomass is largely from non-commercial species. Second, burning the deforested biomass on the spot facilitates the land-use change from forest to agriculture. Third, there is often no infrastructure for harvesting and transporting the deforested biomass away from remote areas.

2.2. Available woody biomass resources from forests

The available woody biomass resources in forests depend on forest areas, increments, and biomass expansion factors. As increments measure only stemwood growth, biomass expansion factors are needed to estimate the amount of branches and stumps. Fig. 1 illustrates the available woody biomass resources from forests in the model.

The location of forest areas is based on global land-cover data (GLC, 2000). To be consistent with forest inventory data, total forest area is calibrated to match FAO forest area data (FAOSTAT, 2013). Total forest area is divided into disturbed and undisturbed (= primary) forests. The share of primary forests in total forests is downscaled by G4M based on human activity impact on the forest areas (Kindermann et al., 2008). This approach gives 1771 Mha of primary forests, which is 43% of total forest area (Table 1). The downscaled primary forest area is somewhat higher than the 36% of total forest area given in FAO statistics (FRA, 2010).

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Initial forest areas in the model (Mha)( ^{a} ).</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Total</td>
</tr>
<tr>
<td>World</td>
<td>4085</td>
</tr>
<tr>
<td>EU27</td>
<td>152</td>
</tr>
<tr>
<td>Russia</td>
<td>862</td>
</tr>
<tr>
<td>Africa</td>
<td>718</td>
</tr>
<tr>
<td>Asia</td>
<td>743</td>
</tr>
<tr>
<td>North-America</td>
<td>611</td>
</tr>
<tr>
<td>South-America</td>
<td>999</td>
</tr>
</tbody>
</table>

\( ^{a} \) The EU27 includes European Union, Russia includes Russia and rest of Europe, Africa includes Africa and Middle-East, Asia includes Asia and Oceania, North-America includes Canada and USA, South-America includes Central and South-America.

Please cite this article as: Lauri, P., et al., Woody biomass energy potential in 2050. Energy Policy (2013), http://dx.doi.org/10.1016/j.enpol.2013.11.033
roundwood is stemwood that is suitable for industrial roundwood (sawlogs, pulpslogs and other industrial roundwood). Harvest losses and non-commercial roundwood are stemwood that is unsuitable for industrial roundwood, but can be used for energy wood or household fuelwood. The difference between harvest losses and non-commercial roundwood is that the former has unwanted stemwood sizes, while the latter has unwanted tree species. The amount of harvest losses is based on G4M model estimates and is about 20% of the increment. The share of non-commercial species is based on FRA (2010) data on commercial and non-commercial growing stocks. In tropical zones the diversity of tree species is high, and only 20–50% of the growing stock can be utilized for industrial roundwood. Most tropical tree species have no commercial use because their properties are unknown and/or because the production process require homogenous raw material (e.g., chemical pulp production). In boreal and temperate zones, forests are more homogenous and the share of non-commercial species is practically zero. At the global level the share of non-commercial species is about 40% of the growing stock.

In addition to stemwood, available woody biomass resources also include branches and stumps, which can be used for energy wood or household fuelwood. The biomass expansion factor for branches and stumps is estimated by assuming that total tree biomass consists of 60% stemwood, 25% branches and stumps, and 15% foliage and roots. There are large variations in the biomass fractions of different tree species and tree ages (IPCC, 2006; Petersson et al., 2012). However, GLOBIOM currently does not differentiate explicitly the different tree species and therefore we use average fractions. The average fractions are based on coniferous and non-coniferous species with a stand age of 60 years from boreal and temperate forests (Lehtonen et al., 2004; IPCC, 2006; Petersson et al., 2012). The fraction of stemwood is usually lower than 60% and the fraction of branches and stumps is higher than 25% for tropical non-coniferous trees (IPCC, 2006; FAO, 2007). However, if tropical forests are managed more intensively or even transformed into plantations, the fraction of stemwood will increase. Hence, we also apply the above values for tropical forests, as suggested by Anttila et al. (2009).

Logging residues consist of harvest losses, branches and stumps. Logging residues are by-products of roundwood harvesting, that is, they are allowed to be harvested on harvested volumes of roundwood. The fraction of logging residues that can be removed from forests depends on technical and environmental constraints such as industrial roundwood harvesting methods, tree species, soil type, etc. (Hakkila, 2004; EEA, 2007; Mantau et al., 2010). As this type of data is not available at the global level, the share of logging residues that can be recovered is commonly approximated by using recovery ratios. Recovery ratios define the fraction of logging residues that can be realistically harvested. The estimates of recovery ratios vary in the range of 0.25–0.75 (Gan and Smith, 2006; Smeets and Faaij, 2007a; Titus et al., 2009; Offermann et al., 2011). Most studies use a recovery ratio of 0.5, which is also used in this study.

---

### Table 2

<table>
<thead>
<tr>
<th>Region</th>
<th>Mean annual increment</th>
<th>Harvest losses</th>
<th>Roundwood (non-commercial)</th>
<th>Roundwood (commercial)</th>
<th>Branches and stumps</th>
</tr>
</thead>
<tbody>
<tr>
<td>World</td>
<td>6.1</td>
<td>1.2</td>
<td>2.0</td>
<td>2.9</td>
<td>2.5</td>
</tr>
<tr>
<td>EU27</td>
<td>5.2</td>
<td>0.9</td>
<td>0</td>
<td>4.4</td>
<td>2.2</td>
</tr>
<tr>
<td>Russia</td>
<td>3.6</td>
<td>0.8</td>
<td>0</td>
<td>2.8</td>
<td>1.5</td>
</tr>
<tr>
<td>Africa</td>
<td>6.9</td>
<td>1.4</td>
<td>4.3</td>
<td>1.2</td>
<td>2.9</td>
</tr>
<tr>
<td>Asia</td>
<td>6.7</td>
<td>1.4</td>
<td>1.8</td>
<td>3.5</td>
<td>2.9</td>
</tr>
<tr>
<td>North America</td>
<td>5.2</td>
<td>1.0</td>
<td>0</td>
<td>4.2</td>
<td>2.1</td>
</tr>
<tr>
<td>South America</td>
<td>8.0</td>
<td>1.4</td>
<td>4.0</td>
<td>2.6</td>
<td>3.3</td>
</tr>
</tbody>
</table>

### Table 3

<table>
<thead>
<tr>
<th>Region</th>
<th>Total</th>
<th>Cropland</th>
<th>Grassland</th>
<th>Other natural vegetation</th>
</tr>
</thead>
<tbody>
<tr>
<td>World</td>
<td>1088</td>
<td>448</td>
<td>189</td>
<td>451</td>
</tr>
<tr>
<td>EU27</td>
<td>80</td>
<td>49</td>
<td>20</td>
<td>11</td>
</tr>
<tr>
<td>Russia</td>
<td>197</td>
<td>48</td>
<td>26</td>
<td>123</td>
</tr>
<tr>
<td>Africa</td>
<td>106</td>
<td>38</td>
<td>21</td>
<td>47</td>
</tr>
<tr>
<td>Asia</td>
<td>312</td>
<td>172</td>
<td>16</td>
<td>124</td>
</tr>
<tr>
<td>North America</td>
<td>189</td>
<td>68</td>
<td>9</td>
<td>113</td>
</tr>
<tr>
<td>South America</td>
<td>204</td>
<td>73</td>
<td>98</td>
<td>33</td>
</tr>
</tbody>
</table>

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2.3. Available woody biomass resources from plantations

Available woody biomass resources from plantations depend on plantation areas and plantations yields. Plantations are dedicated energy crop plantations, that is, they produce only energy wood. Industrial roundwood and household fuelwood plantations are included in forests because they are often closer to natural forests than energy crop plantations in terms of their rotation times and increments.

Plantation area expansion depends on the land-use change constraints and economic trade-offs between alternative land-use options. Land-use change constraints define which land areas are allowed to be changed to plantations and how much of these areas can be changed within each period and region (so-called inertia conditions). Land-use inertia conditions limit the maximum feasible plantation expansion to 5% of available areas for each period.

Permitted land-cover types for plantations expansion include cropland, grassland, and other natural vegetation areas, and they exclude forest areas (Table 3). However, plantation expansion indirectly affects forest areas through relocation of cropland and grassland. Excluding forest areas from plantation expansion can be interpreted as a sustainability criterion, as in van Vuuren et al. (2010) and Beringer et al. (2011). Within each land-cover type the plantation expansion is additionally limited by land suitability criteria based on aridity, temperature, elevation, population, and land-cover data, as described in Havlík et al. (2011).

Plantation expansion to cropland and grassland depends on the economic trade-off between food and wood production. Hence, the competition between alternative uses of land is modeled explicitly instead of using the “food/fiber first principle”, which gives priority to food and fiber production and allows plantation to be expanded only to abandoned agricultural land and wasteland (Smeets and Faaij, 2007b; Hoogwijk et al., 2009; van Vuuren et al., 2009; Beringer et al., 2011; IPCC, 2011).

Plantations yields are based on NPP maps and own calculations, as described in Havlík et al. (2011) (Table 4). Woody biomass supply from plantations is not separated to stemwood and other tree parts because energy crop plantations usually utilize total tree biomass and do not produce any logging residues. Moreover, the fraction of stemwood from the total tree biomass in plantations is 80–90% (FAO, 2007), which makes the share of other tree parts relatively small importance.

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2.4. Woody biomass production costs

Woody biomass production costs consist of harvest and transport costs. Harvest costs are modeled by using spatially explicit constant unit costs. Transport costs are not spatially explicit but are modeled by using regional level constant elasticity transport cost functions, which approximate the short run availability of woody biomass in each region.9 Transport costs functions are shifted over time in response to the changes in the harvested volumes such that in the long run only average transport costs matters. There are several institutional factors like building forest roads and transport capacity limitations that make woody biomass supply less elastic in the short run than in the long run (Binkley and Dykstra, 1987).

Harvest costs include planting, logging, and chipping in the case of logging residues. Harvest costs for forests are based on the G4M model and they vary in the range of 10–40$/m³ depending on the region and the steepness of terrain. Harvest costs for plantations are based on own calculations, as described in Havlík et al. (2011), and they vary over a range of 5–30$/m³ depending on the region and the steepness of terrain.

Transport costs include costs of accessing and moving woody biomass from forests or plantations to domestic production units like sawmills, pulp mills and energy plants. Transport costs are based on recursive regional level constant elasticity cost functions, which are parameterized by previous period harvested volumes and average transport costs from forest to mills. Average transport costs are assumed to be 5–15$, depending on the region, based on Hakola (2004), Hamelinck et al. (2005) and regional adjustment. The elasticity of the transport cost function is assumed to be 0.1–0.5 based on the country/regional level estimates of the price elasticity of industrial roundwood supply (Buongiorno et al., 2003). In the case of plantations, the elasticity is assumed to be 1 because plantations are usually located close to production units and therefore have lower transport costs than forests.

2.5. Woody biomass demand for material products and household fuelwood

The forest sector has seven final products (chemical pulp, mechanical pulp, sawnwood, plywood, fiberboard, other industrial roundwood, and household fuelwood). Final product demands are modeled by using regional level constant elasticity demand functions, which are parameterized by consumption quantities from FAO (2013), price data from Buongiorno et al. (2003), price and income elasticities from Buongiorno et al. (2003), and population and GDP growth data from the POLES energy sector model (Havlík et al., 2011).

The demand function for household fuelwood is assumed to be independent of energy wood and primary energy prices. The reason for this simplification is that in low income countries household fuelwood is often used for cooking and cannot be replaced by fossil fuels, which would require investments in new stoves (Arnold et al., 2010; IARC, 2010; May-Tobin, 2011). Hence, fossil fuels are not substitutes for household fuelwood in developing countries where most household fuelwood consumption occurs. Moreover, household fuelwood is often woody biomass that is not used for energy wood for technical or economic reasons, that is, unrecovered logging residues. Hence, household fuelwood does not have a direct connection to fossil fuels or large-scale energy wood markets.

2.6. Forest industry technologies and recycled wood

Forest industry final products (chemical pulp, mechanical pulp, sawnwood, plywood and fiberboard) are produced by Leontief production technologies. Input-output coefficients for Leontief technologies are based on the engineering literature (e.g., FAO, 2010). By-products of these technologies (bark, black liquor, sawdust, sawchips) can be used for energy production or as raw material for pulp and fiberboard (Fig. 2).

Initial production capacities for forest industry final products are based on production quantities from FAOSTAT (2013). After the base year the capacities evolve according to investment dynamics, which depend on depreciation rate and investment costs. The investment pay-back time is assumed to be 10 years, which is the time step of the model. The annual depreciation rate is assumed to be 0.03, which approximates to 30 average capital operating times. Capital operating times and investment costs are based on the engineering literature (e.g., Diesen, 1998).

Some forest industry final products (sawnwood, plywood, and fiberboard) can be recovered as recycled wood after their final consumption. Recycled wood can be used for energy production or raw material for fiberboard. Recycled wood recovery varies between 20% and 50% of the final product consumption depending on the country (Mantau et al., 2010). Hence, it is assumed that the maximum available amount of recycled wood is 50% of sawnwood, plywood, and fiberboard consumption.

2.7. Scenarios

We examine two different scenarios: baseline and environment scenarios. In the baseline scenario all forest areas are allowed to be used for harvesting (i.e., we do not exclude protected or primary forests from the available forest areas). The environment scenario assumes that primary forests are set aside for protection (i.e., primary forests cannot be harvested or deforested). For each scenario we solve energy wood supply curves using GLOBIOM and analyze their implications for the forest and energy sectors. Energy wood supply curves display the amount of woody biomass available for large-scale energy production at various hypothetical energy wood prices.

Energy wood supply curves are generated as follows. In the base year (2000) energy wood demand is based on IEA data regarding solid biomass use for energy. After the base year, energy wood demand is replaced by hypothetical energy wood prices, which increase (or decrease) linearly such that they reach the desired hypothetical prices: 0–30 $/GJ in 2050. Prices higher than 30 $/GJ were not considered because they seemed to be irrelevant from perspective of energy wood demand projections (e.g., GEA, 2012).10

10 From the analytical viewpoint the energy wood supply curve y1−S(p1) is derived from the following type of static profit maximization problem for each period: Maxp1y1+p2(y2)y2+p3(y3)y3−C(y1+y2+y3). s.t. y1+y2+y3≤S(y1,y2,y3), where p1=energy wood price, y1=energy wood quantity, y3=fuelwood quantity, y1=material products quantity, p2(y2)=demand function for fuelwood, p3(y3)=demand function for material products, (c(y1+y2+y3)=cost function and
Energy wood prices are mill gate prices at which the energy sector buys woody biomass. Woody biomass volume is measured in terms of fresh wood, mass in terms of oven dry wood, and energy content in terms of primary energy. This method allows quantities and prices to be easily converted from volume units to energy units, as described in Footnote 3.

To simplify the discussion on the implications of the model we aggregate woody biomass to six product categories: pulplogs, sawlogs, energy crops, logging residues, forest industry by-products, and fuelwood. Pulplogs include pulplogs and other industrial roundwood. Forest industry by-products include bark, black liquor, sawdust, sawchips, and recycled wood. Moreover, the 30 regions of the model are aggregated to the six large regions already used in the section on data description.

3. Results

3.1. Baseline scenario volumes

Global woody biomass use for energy wood increases in 2050 from 0 to 23 Gm³/year when hypothetical energy wood prices increase from 0 to 30$/GJ (216$/m³) (Fig. 3). With low energy wood prices 0–5$/GJ (36$/m³) the most important source of energy wood is forest industry by-products because they are the most easily accessible source of energy wood. When energy wood prices exceed 5$/GJ (36$/m³) logging residues, non-commercial roundwood and plantations replace forest industry by-products as the most important source of energy wood. When energy wood prices exceed 10$/GJ (72$/m³) the use of industrial roundwood for energy starts to increase.

Global woody biomass use for material products vary in a range of 3.1–3.3 Gm³/year when hypothetical energy wood prices increases from 0 to 30$/GJ (Fig. 3). Energy wood prices affect woody biomass use for material products through by-product and competition effects. The by-product effect increases woody biomass use for material products when energy wood prices are higher because the use of forest industry by-products for energy increases (Moiseyev et al., 2011). The competition effect decreases woody biomass use for material products when energy wood prices are higher because material products compete for the same woody biomass resources as energy wood (Lauri et al., 2012). At the global level, the by-product effect dominates when prices are lower, but the competition effect becomes stronger when energy wood prices exceed 10$/GJ, that is, when industrial roundwood use for energy starts to increase.

Global woody biomass use for fuelwood decreases in 2050 from 2.0 to 1.8 Gm³/year when hypothetical energy wood prices increase from 0 to 30$/GJ (Fig. 3). Energy wood prices affect woody biomass use for fuelwood only through the competition effect because forest industry by-products are not used for fuelwood. The overall effect of energy wood prices on woody biomass use for fuelwood and material products is negative, but relatively small, because by-product and competition effects tend to cancel each other out. At the regional level energy wood prices have

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Please cite this article as: Lauri, P., et al., Woody biomass energy potential in 2050. Energy Policy (2013), http://dx.doi.org/10.1016/j.enpol.2013.11.033
a greater impact on woody biomass use for material products, because these effects do not necessary cancel each other out (see next chapter).

3.2. Baseline scenario areas

In 2050 the forest area varies in the range of 3829–3848 Mha and plantation area in the range of 0–315 Mha at different energy wood prices (Fig. 4). The plantation area stays relatively low compared to the forest area and the suitable plantation area. The reason for the former is higher increments of plantations compared to forests while the reason for the latter is land-use change constraints and land-use competition, which limit plantations expansion.

A comparison of managed forest areas to total forest area indicates the intensity of forests resource use in the model because there is no variation in forest management, (i.e., all managed forests are normal forests). In 2050 the global managed forest area varies in the range of 818–1939 Mha at different energy wood prices, which is 21–50% of total forest area (Fig. 4). One way to put these proportions into perspective is to compare them to disturbed forest area, which was 64% of total forest area in 2010 (FRA, 2010). An alternative way to measure the intensity of forest resource use is to consider the amount of unmanaged forest area as in Kraxner et al. (2013). From this viewpoint there will be a significant loss of unmanaged forests when energy wood prices increase 10$/GJ, that is, when industrial roundwood use for energy starts to increase.

The effect of energy wood prices and plantations expansion on the forest area is small (Fig. 5). There are several reasons for this. First, we apply a sustainability constraint, which does not allow a direct land-use change from forest to plantations. Second, forest area becomes more valuable when it is used more extensively. The indirect land-use effect of plantation expansion on forest area increases deforestation with lower energy prices. However, higher forest land prices override this effect with higher energy wood prices such that deforestation starts to decrease when energy wood prices exceed 10$/GJ. Third, plantation expansion on agricultural land is partially compensated for by conversion of other natural vegetation land and forest land to agricultural land.

3.3. Regional implications of baseline scenario

There are large differences between regions in energy wood supply and woody biomass use for material products and fuelwood (Fig. 6). Africa, Asia and South America dominate the global energy wood supply with 80% of total supply potential. Woody biomass use for material products is concentrated in the EU27, Asia, and North America, while woody biomass use for fuelwood in Asia and Africa.

In the EU27 forest industry by-products and logging residues make up most of the energy wood supply, especially when prices are in the range of 0–10$/GJ (Fig. 6). Hence, the by-product effect should be high in woody biomass use for material products. However, as there is full use of woody biomass resources and large amounts of pulplogs are used for energy wood, the competition effect is also high and dominates the by-product effect. Hence, higher energy wood prices crowd out woody biomass use for fuelwood and material products. When energy wood prices exceed 10$/GJ all available forest industry by-products and logging residues are in full use and it is only possible to increase energy wood supply by plantations and industrial roundwood.

In North America and Russia, the situation is much the same as in the EU27. However, because woody biomass resources are not in full use, the competition effect is lower and energy wood prices crowing in woody biomass use for fuelwood and material products at the lower end of the supply curve. It is also noteworthy that in
these regions a significant part of energy wood consists of industrial roundwood. In Africa, Asia and South America non-commercial roundwood, logging residues and plantations cover majority of energy wood supply (Fig. 6). The highest share of plantations is in Asia, because the suitable area for plantations is highest there (Table 3). The highest share of non-commercial roundwood is in Africa, because the share of non-commercial roundwood is highest there (Table 2). Because forest industry by-products form only a small part of energy wood supply in these regions, the by-product effect is small and higher energy wood prices crowd out woody biomass use for fuelwood and material products.

At regional level the EU27 is the only region where all forest area is managed already at price 20$/GJ (Fig. 7). The proportion of managed forest is lowest in Russia, where the share of managed forest is only 10–20% of total forest area. The amount of unmanaged forest decreases most in the tropical zone, indicating that environmental consequences are most severe there.

3.4. Environment scenario

Setting primary forests aside for protection decreases the available forest area by 43%: from 4085 Mha to 2314 Mha. The global energy wood supply decreases by 0–25% compared to the baseline scenario depending on the hypothetical energy wood price (Fig. 8). The effect is smaller for low levels of supply, where the available forest area matters less. The effect is highest in South America (0–46%) where almost half of the world’s primary forests are located.

Excluding primary forest has a relatively larger effect on the intensity of forest resource use than on the energy wood supply. At the global level, the cumulative loss of unmanaged forests between 2000 and 2050 decreases from 1587 Mha to 921 Mha at a price of 30$/GJ (Fig. 9). At the regional level, unmanaged forest is saved the most in South America, where the loss decreases from 562 to 148 Mha at a price of 30$/GJ. At low energy wood prices (0–10$/GJ), protecting primary forests is not much of a factor, as there is no need to harvest them anyway. On the other hand, with high prices (10–30$/GJ), large amounts of unmanaged forest can be saved without sacrificing too much energy wood supply potential. In particular, at a price of 30$/GJ, giving up 25% of the energy wood supply decreases unmanaged forest loss by 42%.

4. Discussion

In this section we compare our estimates to a number of other studies on energy wood potential and discuss the differences between the models. In the comparison we apply the terms theoretical, technical, and market potential, which are commonly used in the literature (IPCC, 2011; Offermann et al., 2011). Theoretical potential refers to woody biomass supply that is limited only by biophysical constraints. Technical potential is theoretical potential, where alternative uses of woody biomass resources (food, fuelwood, and material products) are subtracted. Market potential is the part of technical potential that can be produced at an economically profitable level.

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Fig. 7. Regional managed and unmanaged forest areas in 2050 for baseline scenario at different energy wood prices.

Fig. 8. Energy wood supply in 2050 for baseline and environment scenarios at energy wood prices of 10 and 30$/GJ.

Fig. 9. Cumulative loss of unmanaged forests 2000–2050 for baseline and environment scenarios at energy wood prices 10 and 30$/GJ.
Most studies consider only technical potentials (i.e., they do not include any economic analysis). The estimates of energy wood technical potential in 2050 typically vary in the range of 100–400 EJ/year if we exclude some borderline results (Berndes et al., 2003; van Vuuren et al., 2010; IPCC, 2011; Offermann et al., 2011). Models that consider the market potential of energy wood can be divided into two classes. One line of studies based on forest sector models implies typically lower potentials than our own because the studies ignore energy crop plantations (Smeets and Faaij, 2007a; Raunikar et al., 2010; Favero and Mendelsohn, 2013). Moreover, there are large differences in biomass yields between the process-based and empirical forest management models, which partly explains the different results. In process-based forest management models increments are based on NPP maps, which tends to imply higher increment values than forest inventory data. For example, the global average gross annual increment in FAO (1998) is 3.4 m³/ha/year, which is much lower than the global average mean annual increment of 6.1 m³/ha/year in our model. The reason for the difference is that forest inventory studies measure the growth of existing forests while NPP maps the growth potential (Openshaw, 2011). For example, forest inventory data tends to imply low increments for tropical forest due to their mature age-class structure while NPP maps imply high increments for them due to high growth potential. The choice between NPP maps and forest inventory data greatly depends on the modeling approach. If the model does not include age-class dynamics, then using NPP maps makes sense because they define the increment independently of the age-class distribution.

Another line of studies based on agriculture sector land-use models implies usually higher market potential than ours because their estimates about available land areas for energy crop plantations are more optimistic (Hoogwijk et al., 2009; van Vuuren et al., 2009; Popp et al., 2011). Moreover, there are large differences in production costs, which partly explains the different results (Richards and Stokes, 2004). Typically land-use models imply more elastic woody biomass supply than forest sector models, because they do not consider short run inelasticity of woody biomass supply. The supply of woody biomass from plantations is probably more elastic than from forests, because the majority of feasible plantation area is cropland and grassland, which is typically located close to settlements and thus easily accessible. However, plantation expansion includes other factors like water availability (van Vuuren et al., 2009; Beringer et al., 2011; Popp et al., 2011) and vulnerability of monoculture to natural disturbances (Evans, 2009), which could potentially decrease the elasticity of woody biomass supply from plantations.

The theoretical potential of our model can be derived by integrating the data from Tables 1 to 4 (Table 5a). Note that theoretical potential is independent of time period because increments and yields stay constant over time. Technical potential is obtained by removing deforestation, material products, fuelwood, and food production from the theoretical potential and adding recycled wood to it (Table 5b). Deforestation from 2000 to 2050 is about 250 Mha (Fig. 5) and woody biomass use for material products and fuelwood about 5 Gm³ (Fig. 1). In the technical sense food production does not reduce suitable plantation areas in the model because cropland and grassland areas used for plantations can be replaced by converting other natural vegetation land and forest land into cropland and grassland. Available recycled wood is estimated from the consumption of sawnwood and panels (about 1 Gm³/year in 2050) by using a recovery ratio of 0.5.

The different potentials and main assumptions of the models are summarized in Tables 5 and 6. According to our estimates the theoretical potential of energy wood in 2050 is 49.7 Gm³/year (358 EJ/year), technical potential 43.5 Gm³/year (306 EJ/year), and market potential 0–23 Gm³/year (0–165 EJ/year). Hence, market potential is 0–46% of theoretical potential and 0–53% of technical potential. If primary forests are set aside for protection, then the potentials decrease by about 25%. Smeets and Faaij (2007a) estimate that the market potential of energy wood in 2050 is 0–6.2 Gm³/year (0–72 EJ/year), which accounts for 0–56% of their technical potential of 11 Gm³/year (128 EJ/year). Hoogwijk et al. (2009) estimate that market potential of energy wood in 2050 will be 15–439 EJ/year, which is 5–65% of their technical potential of 302–675 EJ/year.

### Table 5a. Theoretical potential of energy wood in baseline scenario.

<table>
<thead>
<tr>
<th>Category</th>
<th>Technical potential</th>
<th>Market potential</th>
</tr>
</thead>
<tbody>
<tr>
<td>Industrial roundwood</td>
<td>11.8 Gm³/year</td>
<td>675 EJ/year</td>
</tr>
<tr>
<td>Non-commercial roundwood</td>
<td>7.7 Gm³/year</td>
<td>606 EJ/year</td>
</tr>
<tr>
<td>Logging residues</td>
<td>2.3 Gm³/year</td>
<td>122 EJ/year</td>
</tr>
<tr>
<td>Branches and stumps</td>
<td>4.8 Gm³/year</td>
<td>38 EJ/year</td>
</tr>
<tr>
<td>Plantations</td>
<td>22.1 Gm³/year</td>
<td>132 EJ/year</td>
</tr>
<tr>
<td>Material products and fuelwood</td>
<td>5.0 Gm³/year</td>
<td>27 EJ/year</td>
</tr>
<tr>
<td>Total</td>
<td>49.7 Gm³/year</td>
<td>675 EJ/year</td>
</tr>
</tbody>
</table>

### Table 5b. Technical potential of energy wood in baseline scenario.

<table>
<thead>
<tr>
<th>Category</th>
<th>Technical potential</th>
</tr>
</thead>
<tbody>
<tr>
<td>Industrial roundwood</td>
<td>11.1 Gm³/year</td>
</tr>
<tr>
<td>Non-commercial roundwood</td>
<td>7.7 Gm³/year</td>
</tr>
<tr>
<td>Logging residues</td>
<td>2.3 Gm³/year</td>
</tr>
<tr>
<td>Branches and stumps</td>
<td>4.8 Gm³/year</td>
</tr>
<tr>
<td>Plantations</td>
<td>22.1 Gm³/year</td>
</tr>
<tr>
<td>Material products and fuelwood</td>
<td>0.5 Gm³/year</td>
</tr>
<tr>
<td>Recycled wood</td>
<td>0.5 Gm³/year</td>
</tr>
<tr>
<td>Total</td>
<td>43.5 Gm³/year</td>
</tr>
</tbody>
</table>
Table 6
Comparison of the results with other studies.

<table>
<thead>
<tr>
<th>Available forest area in 2000 (Mha)</th>
<th>Baseline scenario</th>
<th>Environment scenario</th>
<th>Smeets and Faaij (2007a)</th>
<th>Hoogwijk et al. (2009)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4085</td>
<td>2314</td>
<td>2800</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Suitable area for plantations (Mha)</td>
<td>1088</td>
<td>1088</td>
<td>–</td>
<td>2900-3600</td>
</tr>
<tr>
<td>Average increment of forests (m³/ha)</td>
<td>6.1</td>
<td>6.1</td>
<td>3.4</td>
<td>–</td>
</tr>
<tr>
<td>Average yield of energy crops (m³/ha)</td>
<td>20.3</td>
<td>20.3</td>
<td>–</td>
<td>20–40¹</td>
</tr>
<tr>
<td>Theoretical potential (EJ/year)</td>
<td>358</td>
<td>271</td>
<td>157</td>
<td>3500</td>
</tr>
<tr>
<td>Technical potential (EJ/year)</td>
<td>306</td>
<td>223</td>
<td>128</td>
<td>302–675</td>
</tr>
<tr>
<td>Market potential (EJ/year)</td>
<td>0–165</td>
<td>0–124</td>
<td>0–72</td>
<td>15–439</td>
</tr>
</tbody>
</table>

¹ Calculated by using density 0.45 t/m² and Fig. 4 in Hoogwijk et al. (2009).

5. Conclusion

This paper provides an economic analysis of global woody biomass energy potential. The analysis is conducted by using a spatially explicit partial equilibrium model, which includes a detailed description of woody biomass supply both from forests and plantations. The subject has been studied extensively in the literature, but previous studies have focused on land-use modeling, ignoring the forest sector or on forest sector modeling, ignoring land-use issues, or they are not based on economic analysis. The advantage of the economic optimization model is that it explicitly considers the competition between alternative uses and sources of woody biomass through the market mechanism. The disadvantage is that it includes complex interactions of supply and demand, which makes the model less transparent compared to non-economic models that consider woody biomass use for energy in terms of different potentials (Smeets and Faaij, 2007a; Anttila et al., 2009).

Woody biomass supply curves not only illustrate the woody biomass energy potential, but they can also be used for mitigation and energy policy analysis by including energy wood demand in the analysis. One way to do this is to use energy wood demand estimates of global energy assessments (Raunikar et al., 2010; Ince et al., 2012). According to the Global Energy Assessment (GEA, 2012), stabilizing global climate change to 2 °C above pre-industrial levels requires 80–140 EJ/year (11.1–19.4 Gm³/year) of biomass use for energy in 2050 depending on the pathway. GEA estimates do not distinguish between woody and non-woody biomass, but if we make a simplifying assumption that all biomass is woody biomass then our estimates imply that energy wood prices should be in range of 13–245$/GJ (94–173$/m³).

Alternatively to global energy assessments we can compare energy wood supply potential directly to projected total primary energy consumption. Our estimates imply that energy wood could satisfy 0–16% of global primary energy consumption in 2050.¹⁴ If we also include household fuelwood in the potential, then woody biomass could satisfy 2–18% of global primary energy consumption in 2050. At the regional level, energy wood (energy wood + fuelwood) could satisfy 5% (6%) of the EU27, 18% (20%) of Africa, 9% (10%) of Asia, 10% (11%) of Russia, 15% (16%) of North America, and 74% (75%) of South America primary energy consumption in 2050. South America has significantly larger energy wood potential with respect to primary energy consumption than other regions. Hence, if energy wood use increases in the future, we can expect South America to start exporting energy wood to Asia, the EU27, and Russia, which have lower energy wood potential with respect to primary energy consumption.

Africa, Asia, and South America cover 80% of world’s energy wood supply potential. Hence, if energy wood use increases significantly in the future, we can expect the focus of the forest sector to move from the traditionally strong boreal zone to the temperate and tropical zones in the future. In Africa, Asia, and South America most energy wood consists of woody biomass that does not compete directly with material wood (i.e., logging residues and energy crop plantations). Hence, the competition between energy wood and material wood is low, and an increasing production of energy wood would not have significant impact on woody biomass use for material products. In the EU27, Russia, and North America the opposite is true because industrial roundwood and forest industry by-products form an important source of energy wood. In these regions the competition between energy wood and material wood is stronger, and a significant decrease in woody biomass use for material products was observed as the production of energy wood increases.

Increasing the energy wood supply would imply more intensive use of the world’s forests. According to our calculations, this would mean that up to 50% of the world’s forests would be converted to intensively managed forests. Such a high share is not implausible at the global level given that 64% of the world’s forests are currently disturbed by human actions (FRA, 2010). At the regional level the highest pressure would be in the EU27 where all forests would be in full use when energy wood prices exceed 15$/GJ. It is worth noting that the amount of unmanaged forests starts to decrease more strongly at the global level when energy wood prices exceed 10$/GJ, that is, when industrial roundwood use for energy starts to increase. From this perspective, forest industry requirements to prevent industrial roundwood use for energy become more reasonable.

Converting unmanaged forest to managed forest and harvesting a higher share of logging residues tends to cause biodiversity loss and soil depletion (FAO, 2008; Walmsley and Godbold, 2010). However, there are large uncertainties associated with the measurement of these effects (Persson, 2013; Ramage et al., 2013). Moreover, by setting aside high biodiversity and vulnerable forest areas we can decrease these effects significantly without sacrificing too much energy wood potential as shown in Chapter 3.4. In addition, by following the sustainable forest management practices many environmental consequences of forest management intensification can be avoided (EEA, 2007; Brockerhoff et al., 2008). Hence, the environmental consequences of extensive woody biomass use for energy may be less dramatic than some researchers have argued (Schulze et al., 2012).

Considering that industrial roundwood prices have stayed below 100$/m³ and energy wood prices below 50$/m³ for most of the time during the last 50 years (Raunikar et al., 2010), a price increase in these of up to 200$/m³ due to increased demand for energy wood would imply a significant structural changes for the forest sector. Forest owners would gain by obtaining higher prices for energy wood. However, the environmental consequences of extensive woody biomass use for energy may be less dramatic than some researchers have argued (Schulze et al., 2012).

¹⁴ The potential shares of woody biomass energy in primary energy consumption are calculated by using energy wood and fuelwood volumes at energy wood price 30 $/GJ (Figs. 1 and 4) and MESSAGE baseline scenario primary energy consumption projection for 2050 (GEA, 2012) (World 1038 PJ/year, EU27 112 PJ/year, Africa and Middle East 183 PJ/year, Russia and rest of Europe 72 PJ/year, Asia and Ocean 458 PJ/year, North-America 130 PJ/year, Central- and South-America 76 PJ/year).

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returns for their forests, while forest industries could gain or lose depending on their ability to move increased raw material costs into final product prices and to benefit financially from their by-products being used for energy. From the viewpoint of the energy sector, high energy wood prices would mean higher raw material costs. Considering that current coal prices are around 35$/GJ and that they are expected to stay more or less constant in the future (IEA, 2010), it is difficult to imagine the energy sector would voluntarily pay 13–245$/GJ for biomass when they could use coal instead. Hence, to meet the biomass use targets by using woody biomass would require either large subsidies for woody biomass use for energy or high taxes for fossil fuels.

To conclude, the limiting factor in the woody biomass use for energy is not woody biomass resources, but rather the accessibility of these resources and transport costs, and the resulting price. It is possible to satisfy 18% (or 14% if primary forests are excluded) of the world’s primary energy consumption in 2050 by woody biomass. However, to achieve this would require an extensive tax/subsidy policy in the energy markets and would lead to substantial higher woody biomass prices compared to their current level. An alternative to the subsidy/tax policy would be a supply side policy, which would facilitate woody biomass supply such that we could meet the biomass use targets at lower woody biomass prices and thereby avoid negative implications for woody biomass use for material products. Examples of this type of policy would be public investments in transport infrastructure and national forest programs promoting up-to-date forest management practices.

References

Openshaw, K., 2011. Supply of woody biomass, especially in the tropics: is demand substantially higher woody biomass prices compared to their own use for material products. Examples of this type of policy would be public investments in transport infrastructure and national forest programs promoting up-to-date forest management practices.


