Working Papers of the Finnish Forest Research Institute 118

http://www.metla.fi/julkaisut/workingpapers/2009/mwp118.htm
ISBN 978-951-40-2160-2 (PDF)
ISSN 1795-150X

Global Potential of Modern Fuelwood

Perttu Anttila, Timo Karjalainen and Antti Asikainen

METLA www.metla.fi

Working Papers of the Finnish Forest Research Institute publishes preliminary research results and conference proceedings.

The papers published in the series are not peer-reviewed.

The papers are published in pdf format on the Internet only.

http://www.metla.fi/julkaisut/workingpapers/
ISSN 1795-150X

Office
P.O. Box 18
FI-01301 Vantaa, Finland
tel. +358 10 2111
fax +358 10 211 2101
e-mail julkaisutoimitus@metla.fi

Publisher
Finnish Forest Research Institute
P.O. Box 18
FI-01301 Vantaa, Finland
tel. +358 10 2111
fax +358 10 211 2101
e-mail info@metla.fi
http://www.metla.fi/

Authors
Anttila, Perttu, Karjalainen, Timo & Asikainen, Antti

Title
Global potential of modern fuelwood

Year	Pages	ISBN	ISSN
2009	29 p.	ISBN 978-951-40-2160-2 (PDF)	1795-150X

Unit / Research programme / Projects
Joensuu Research Unit / Bioenergy from Forests / 7290 Global forest energy resources, certification of supply and markets for energy technology

Accepted by
Leena Paavilainen, Director of Research, 1.4.2009

Abstract
The increasing demand for biomass energy also enhances the need for more accurate estimates of the availability of biomass resources. Estimation of the forest energy potential is neither a trivial nor an unambiguous task because of the varying raw material base, constraints on availability, differences in geographical and temporal scopes, incomplete statistics, erroneous models, and intense assumptions of future development. As a result, current estimates may differ as much as two orders of magnitude. To overcome some of these problems globally consistent statistics and methods were utilised with the aim of obtaining rough estimates of modern fuelwood potentials at the continental or subcontinental levels. These estimates could then be used to direct the marketing of technology and further research to promising regions.

Modern fuelwood is wood that is used at an industrial scale and relatively high efficiency compared to traditional fuelwood. The technical potential of the primary forest residues and one quarter of the surplus wood from any positive wood balance were estimated to provide the global fuelwood potential of 5-9 EJ, which represents 1-2% of the global primary energy demand. The most promising regions with respect to modern fuelwood potential are the USA and Canada, Central and Northern Europe, Russia, East Asia, Brazil, and Chile. In South America the potential consists mostly of logging residues from present cuttings, whereas in North America, Europe, and especially in East Asia the contribution of surplus forest growth is considerable. The potential per land area is especially high in many countries in Central and Northern Europe, and Japan.

Keywords
bioenergy, energy wood, forest energy, biomass resources, availability, forest statistics

Available at
http://www.metla.fi/julkaisut/workingpapers/2009/mwp118.htm

Replaces

Is replaced by

Contact information
Perttu Anttila, Finnish Forest Research Institute, P.O. Box 68, FI-80101 Joensuu.
E-mail: perttu.anttila@metla.fi

Other information

Contents

Preface **5**

1 Introduction **6**
- 1.1 Terminology 6
- 1.2 Global forest resources 10
- 1.3 Forest energy potential 11
- 1.4 Literature review 13
  - 1.4.1 Global studies 13
  - 1.4.2 Regional studies 14

2 Material and Methods **16**
- 2.1 Present cuttings 17
- 2.2 Supplementary cuttings 18

3 Results **19**

4 Discussion **21**

References **24**

Preface

Growing concern about climate change, attempts to decrease the dependence on fossil fuels and to increase the security of energy supply are factors promoting the use of bioenergy and other renewable energy sources. Several studies have indicated that the use of biomass for energy production can remarkably be increased from the current level over the next decades when fossil fuels become scarce and more expensive. The use of biomass for energy production will be increased especially in the industrialised countries which are aiming to decrease greenhouse gas emissions. Biofuel markets are currently developing rapidly and becoming more and more international. The trend in biomass utilisation is towards larger refining units and longer transportation distances. Production of bioenergy is largely based on imported biomass in several countries.

This study has been prepared as part of the "Global forest energy resources, certification of supply and markets for energy technology" project at the Finnish Forest Research Institute (Metla). The aim of the project was to estimate the availability of forest biomass for energy production, and to evaluate the certification status and the long term sustainability of forest biomass supply. The project was carried out together with Metla, Technical Research Centre of Finland (VTT) and Lappeenranta University of Technology (LUT). It belongs to the Finnish Funding Agency for Technology and Innovation (Tekes) technology programme Business Opportunities in Mitigating of Climate Change (ClimBus) and was cofinanced by John Deere Forestry Oy, Metso Power Oy, Neste Oil Oyj, Pentin Paja Oy, Stora Enso Oyj, and Vapo Oyj.

The authors would like to acknowledge Mr. Mark Richman about the language editing and valuable comments to this report.

In Joensuu,

Perttu Anttila, Timo Karjalainen, and Antti Asikainen

1 Introduction

Climate change, dwindling oil reserves, and a shift toward self-sufficiency in energy supplies are major forces driving the share of renewable sources of energy production to increase, with bioenergy from forests playing a key role. Forest-derived biomass can be used as a substitute to fossil fuels, and they can also have positive impacts on income and employment, especially in rural areas (Nabuurs et al. 2007).

In 2004, the global demand for primary energy was 458 exajoules (EJ) (Priddle 2006). Depending on the future scenario, this total demand is expected to expand to 553 EJ or even 575 EJ by 2015 (Priddle 2006). The current share of the demand supplied by energy from biomass and waste according to an estimate by Sims et al. (2007) is 46 EJ; this is about 10% of the total. This share of the energy demand met by biomass was further subdivided by Sims et al. (2007) into a total of 36 EJ from trees and shrubs taken from forests and non-forest areas. Of this total about 30 EJ was estimated to be traditional fuelwood and 3 EJ was estimated to be used to make charcoal. Only 1 EJ was estimated to be created from forest residues used to produce modern solid biofuels, like pellets and chips. This suggest that less than 3% of the total energy demand met by biomass from trees and shrubs taken from forests and non-forest areas is modern fuelwood. These figures give a global utilisation level for forest energy, but not the potential.

Karjalainen et al. (2004) and Asikainen et al. (2008) earlier estimated the forest energy potentials for the European Union (EU), based on consistent forest statistics, which included estimation of the proportion of wood available for energy production in each EU member state. The objective for the work presented here was to provide a similar estimation for the world. It is then hoped that the rough estimates of the world potential, at continental or sub-continental levels, can be used to direct future research and marketing of modern fuelwood technology to promising regions.

The use of modern fuelwood includes many benefits. There are jobs offered not only by the harvesting, transportation, and conversion of fuelwood to energy, but there is also work needed to meet the demand for improvement, in terms of the efficiency of the harvesting and combustion technologies. However, if care is not taken in management and planning there can also be negative effects of increased production. This is especially the case when the expansion of plantations to meet demand can compete with essential food production and biodiversity conservation (Nabuurs et al. 2007). Furthermore, forest growth may decrease as a consequence of the increased depletion of nutrients that accompanies the removal of biomass. Intensive research and training produces more effective ways to manage forests, which can then actually be followed to secure cost-effective fuel procurement. Introducing the efficient use of modern fuelwood is also a good basis for projects to be created under either the Joint Implementation or the Clean Development Mechanism of the Kyoto Protocol to the United Nations Framework Convention on Climate Change.

1.1 Terminology

The terms *forest energy*, *forest residues*, *woodfuel*, *fuelwood*, and *energy wood*, among others have been used in various texts to describe the potential of woody biomass for energy use. Caution must, however, be taken when comparing the results of these texts, because different components may be included under the different, and sometimes even under the same, terms. This is why the respective definitive use of each term should be compared first.

There are three process states in the production chains of bioenergy (FAO 2004). Initally, *biomass* comes from various sources in many forms, like whole trees or logging residues. Then, this biomass is processed into some kind of standardised *biofuel*, like wood chips or ethanol. Finally, the biofuels are converted into *bioenergy*, like heat or electricity. The most common unit for biomass is a metric ton (t), but volumetric measures are also used. The volumetric measures used here always refer to solid cubic meters (m^3). Various other units are used to discuss and describe energy. The most common from the International System of Units (SI) are joule (J), and watt-hour (Wh). Also commonly used is the tonne of oil equivalent (toe), although the definition of this unit can vary. These basic units when used at larger scales include prefixes to increase their orders of magnitude; in this work these include petajoules (PJ) and EJ, which are 10^{15} J and 10^{18} J, respectively; terawatt-hour (TWh), which is 10^{12} Wh; and thousand tonnes of oil equivalent (Mtoe). References to energy are in fact allusion to the energy content of the biofuels, or their lower heating value (LHV). The actual energy produced is less than this, since it also depends on the efficiency of the conversion.

Traditional fuelwood or *firewood* is wood that is used on a small scale for energy production and very often relatively inefficiently, this typically includes the cooking within or heating of a household (Yamamoto et al. 2001). Most wood used for energy production in developing countries is traditional fuelwood. Conversely, *modern fuelwood* is used on a larger scale and relatively efficiently, like in power plants. This text concentrates on the potential for modern fuelwood. The terms *forest energy, woodfuel*, and *energy wood* are used synonymously with modern fuelwood, unless stated otherwise.

The term *forest residues* is often used to refer to all energy wood, including whole trees. Furthermore, forest residues can be categorised into primary, secondary, and tertiary residues (Nabuurs et al. 2007). Primary residues are those available directly from forests. Secondary residues are available after the processing of wood into wood-based products. Finally, tertiary residues result after wood-based products reach the end of their useful life. In this work only primary forest residues were considered.

Like forest residues the sources of woody biomass to be used as fuel can be classified. A classification of sources into four groups is: 1) Forest and plantation wood, 2) By-products and residues from the wood processing industry, 3) Used wood, and 4) Blends and mixtures (Alakangas et al. 2006). The great variation in the sources of forest energy is shown in Table 1 with the more detailed division of the first group, forest and plantation wood.

Table 1. Classification of forest and plantation wood used for energy production by the source biomass type (modified from Alakangas et al. 2006).

1.1.1. Whole trees	1.1.1.1. Deciduous
	1.1.1.2. Coniferous
	1.1.1.3. Short rotation coppice
	1.1.1.4. Bushes
	1.1.1.5. Blends and mixtures
1.1.2. Stemwood	1.1.2.1. Deciduous
	1.1.2.2. Coniferous
	1.1.2.3. Blends and mixtures
1.1.3. Logging residues	1.1.3.1. Fresh/Green (including leaves/needles)
	1.1.3.2. Dry
	1.1.3.3. Blends and mixtures
1.1.4. Stumps	1.1.4.1. Deciduous
	1.1.4.2. Coniferous
	1.1.4.3. Short rotation coppice
	1.1.4.4. Bushes
	1.1.4.5. Blends and mixtures
1.1.5. Bark (from forestry operations)	
1.1.6. Landscape management woody biomass	

Whole trees, or sometimes *full trees,* include all the above ground biomass of trees that are not used to produce industrial roundwood. These can be trees from pre-commercial thinnings or from plantations established to supply fuel.

Stemwood is the part of the tree that normally meets industrial roundwood standards. However, if there is no demand for the roundwood meeting some industrial standards, like pulpwood, then this stemwood can be used as fuel.

Logging residues consist of the tree components that are left on a harvest site or at an intermediate processing site after the removal of industrial roundwood: branches, foliage, and unmerchantable stemwood. The amounts of the different components depend on the tree species, age, and growing conditions. The dry mass of branches, without foliage, can be equal to as little as 5% (e.g. mature Pines and Eucalyptus) of the mass of the harvested industrial roundwood (Senelwa and Sims 1998; Stape et al. 2004; Saint-Andre et al. 2005). In contrast, the crown of a mature Norway spruce, including foliage, can be equivalent to more than 60% of the mass of the merchantable stemwood (Hakkila 1991).

Unmerchantable stemwood is that part of the stem that is unsuitable for industrial use because of undesired dimensions, species, or quality. The amount of unmerchantable stemwood varies from close to zero in well-managed stands to in some cases around 80% of the total volume of roundwood removed (Anuchin 1981).

It is worth noting that the supply of whole trees is generally not dependent on the industrial roundwood harvest, in the way that the supplies of stemwood, logging residues, stumps, and bark are; this is because these latter sources of forest and plantation biomass are usually by-products of industrial roundwood cuttings. Tomaselli (2007) provides modified results from a data bank (SCTP s.a.) and other work (Siqueira et al. 2005) that the crown volume and rejects combined can equate to as much as 150–230% of the industrial roundwood volume from a natural tropical forest in South America and 10–25% of the same from a tropical plantation in the same region. According to a FAO paper, it is not uncommon for some 60 percent of the total harvested tree, or 150% of industrial roundwood volume, to be left in the forest (FAO 1990). Under Scandinavian conditions, unmerchantable stemwood from the harvesting of mature stands is equivalent to about 4–5% of the industrial roundwood volume, while the volume of residues form the crown is equivalent to from 20% to 50% (Hakkila 2004). Another view of the unmerchantable stemwood volume is presented by Asikainen et al. (2008) as for it being equivalent to 10–15% of the industrial roundwood volume. In short, the proportion and amount of logging residues can vary widely.

The term *potential* also needs further clarification. The European Biomass Industry Association (EUBIA 2008) has defined the following types of potential:

- "Theoretical potential: the theoretical maximum potential is limited by factors such as the physical or biological barriers that cannot be altered given the current state of science.
- Technical potential: the potential that is limited by the technology used and the natural circumstances.
- Economic potential: the technical potential that can be produced at economically profitable levels.
- Ecological potential: the potential that takes into account ecological criteria, e.g. loss of biodiversity or soil erosion."

However, distinctions between the types of potential may not be this clear in reality. For example, with relatively high labour costs, it is usually too expensive to collect logging residues after manual harvesting, since the logging residues is scattered unevenly around the harvest site, whereas with mechanised cutting the sorting and collection of logging residues can be integrated into the cutting. Thus the degree of mechanisation can be considered both a technical and economic constraint. In practice, the availability of logging residues as modern fuelwood is also reduced by their procuration for alternative uses, such as traditional woodfuel, animal bedding, soil improvement, and erosion abatement (Smeets et al. 2007). The demand and pre-eminence of these alternatives is extremely difficult to account for on a global scale.

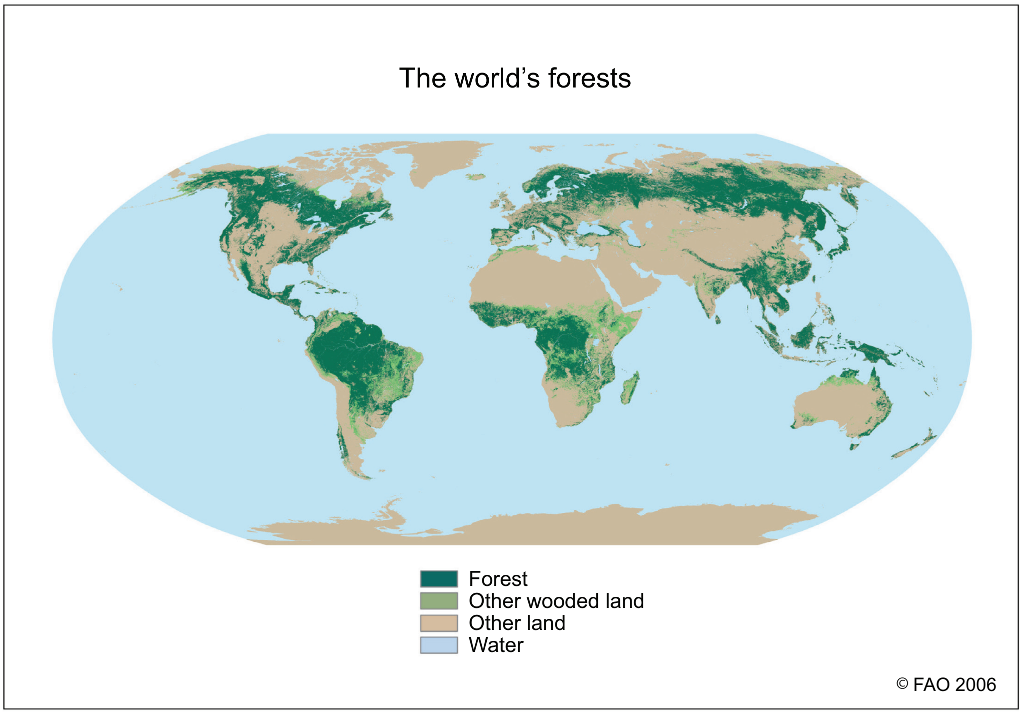

Figure 1. Distribution of the world's forests (FAO 2006).

1.2 Global forest resources

Woody biomass can be harvested from natural/seminatural forests, plantations, or non-forest areas. Harvests from natural/seminatural forests are usually included only under the domain of forestry, whereas, plantations are in some situations considered agriculture. Harvests from non-forest areas may have great local significance, but in terms of the potential production of modern fuelwood, the resources are usually too scattered, and will therefore be excluded here.

According to the Food and Agricultural Organisation of the United Nations (FAO 2006), forests cover one third of the world's land area. However, the forests are not evenly distributed (Figure 1). There are also considerable variations between different forest areas in the growing conditions, site types, species compositions, tenure types, histories of use, associated cultures, quality and availability of relevant infrastructures, and significant differences in forest regulation or at least in enforcement of regulations. All of these characteristics of a forest area affect its potential to provide forest energy.

Productive plantations are forests that consist mostly of introduced species and have been "established through planting or seeding mainly for production of wood or non-wood forest products" (Del Lungo et al. 2006). The total global area of productive plantation forests was 111 million ha in 2005. The most common tree genera are *Eucalyptus* and *Acacia* in tropical and subtropical regions, and *Pinus* worldwide. Most of the planted forests are established or maintained primarily to supply industrial roundwood, however the forest residues from these pulpwood and sawlog plantations could in some cases be used as energy wood. The most extensive pulpwood plantations are located in North America (14 mill. ha), next are those in Asia (7 mill. ha), and then South America (5 mill. ha). There has also been an especially rapid increase of this type of plantation in Asia. The largest plantation area for sawlog production (37 mill. ha) is also in Asia, while Europe has the second largest (17 mill. ha). In addition some plantations have also been established just to produce energy wood (Figure 2). Most of these plantations are in Asia (7 mill. ha) and Africa (1 mill. ha). Other energy wood plantations could be established on degraded land, especially in developing countries, which would offer the possibility to increase the future supply of energy wood. Yet, despite recent interest in bioenergy, the area of bioenergy plantations has increased only slightly (Del Lungo et al. 2006).

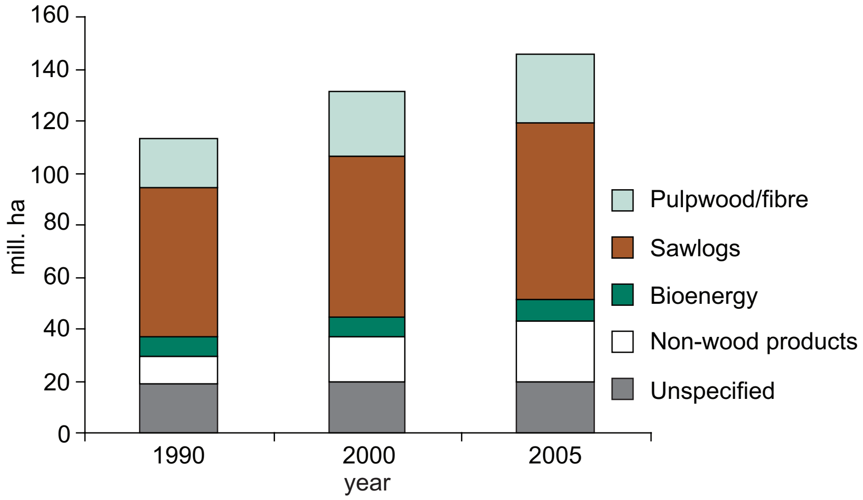

Figure 2. Industrial end uses for planted forests (Del Lungo et al. 2006).

1.3 Forest energy potential

Markets for traditional wood-based products determine the amount of forest residues that will be generated. Industrial roundwood harvests have increased by 60% over the last four decades, and are expected to continue to increase in the future, though at a slower rate (Sampson et al. 2005). In 2000, plantations provided 35% of the harvested roundwood, and their proportion of the harvest is expected to rise to 44% by 2020 (Sampson et al. 2005). The highest regional removal of industrial roundwood, over the fifteen year period from 1990 to 2005, has been recorded for North and Central America (Figure 3); this is due to the presence of the United States (USA) and Canada. The second highest removal has been recorded for Europe, where the level fell in 2000 and rose in 2005, due to a hiccup in Russia's economy. In South America the harvests have increased steadily over the fifteen year period. However, China's logging ban combined with the decrease in reported harvesting in Southeast Asia has lead to a constant decline in the removals of industrial roundwood for the whole of Asia.

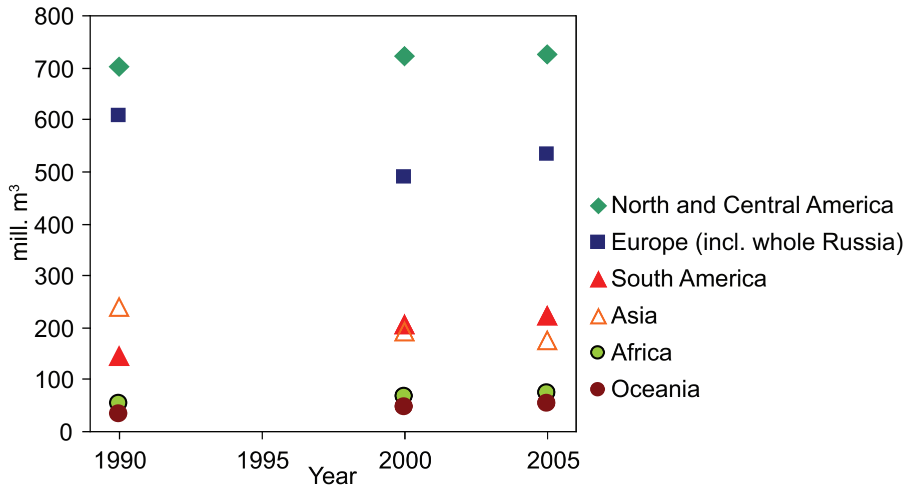

Figure 3. Regional trends in the annual removal of industrial roundwood over the period from 1990 to 2005 (FAO 2006).

In 2005, the total global wood removal including traditional fuelwood was 3 billion m^3 (FAO 2006). On average, the firewood proportion of the removal was 40%, but it varied greatly on a regional basis: for Africa it was 88%, while for the region of North and Central America it was 13%. The total removal of industrial roundwood reported by the statistics was 1.8 billion m^3. However, the actual removal could be considerably higher, since illegal cuttings are not included in the statistics. The country-level removal of industrial roundwood in 2005 was by far the highest for the USA (490 mill. m^3), which accounted for 28% of the global total (Figure 4). Figure 4 shows the ten countries with the largest removal levels, but in essence also represents those with the greatest levels of logging residue accumulation.

Globally most harvested wood comes from final cuttings; this suggests that these cuttings would also provide the greatest portion of the potential fuelwood from logging residues. From the point-of-view of environmental impacts, this may also be the wisest time to harvest these residues. Some professional management practices already support this perspective; in Finland, according to present guidelines (Koistinen and Äijälä 2006) the recovery of logging residues is only recommended after final fellings. If more wood is to be used for energy production in the future, then there will be a move to include more smaller-sized whole trees, which could create real competi-

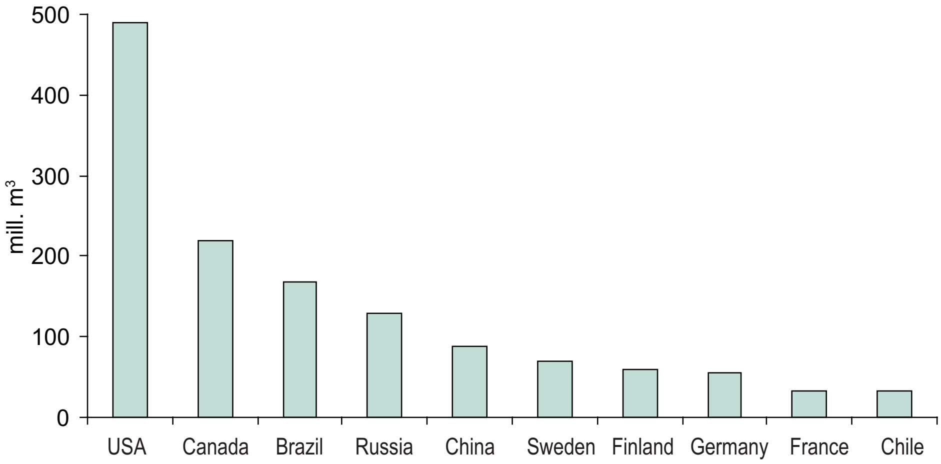

Figure 4. Ten countries with largest removals of industrial roundwood in 2005 (FAO 2006).

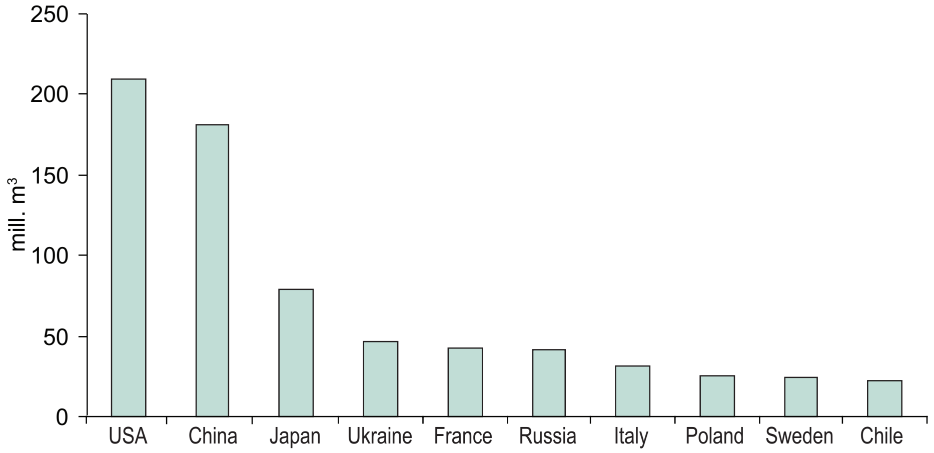

Figure 5. Ten countries with largest estimated positive annual roundwood balance for the period from 2000 to 2005 (FAO 2006).

tion for this resource between modern fuelwood and traditional industrial uses (see EFSOS 2005). In the Tropics, the harvesting of non-commercial species has huge energy wood potential, but this may not be economically or ecologically viable (Vantomme 2006).

In countries where the removal is smaller than the net annual increment, the roundwood balance is positive, this means there is surplus forest growth. In the FAO's (2006) statistics this is shown as a positive annual change rate for growing stock. If the roundwood balance has been positive for a sufficient period of time, then cuttings can be sustainably increased. In the places where there is a surplus of forest growth, this surplus could be utilised as energy wood (Karjalainen et al. 2004). In many countries, this reserve is remarkable. Since 1990, the growing stocks of East, Western, and Central Asia; Europe; Russia; the Caribbean; and North America have been increasing (FAO 2006). The largest positive balance has been reported from the USA and China (Figure 5). Conversely, there has been a decrease in the growing stocks of Africa, South and Southeast Asia, Central America, Oceania, and South America. Yet roundwood balance does not tell the whole truth: if a forest is made-up largely of old stands with slow growth, a sustainable harvesting level can be relatively large even equal to or greater than the annual increment, which produces a small or negative roundwood balance; this is because the standing volume constitutes a large cutting reserve. The utilisation of surplus growth or any other reserve would require that there be a large scale increase in the demand for traditional industrial roundwood and/or political decisions that favour the harvesting of energy wood.

1.4 Literature review

In addition to the poor comparability of studies caused by variations in definitions, there is also disparity in data used by the various studies, which can also cause differences between the study results. Some of the main sources of deviation in data between studies are the level of traditional fuelwood consumption, the annual increment, and the level of efficiency in conversion from biomass to energy (Smeets and Faaij 2007). In addition, statistics on cuttings and biomass functions may be incomplete or contain errors. The perspective of the studies may also vary with some considering the present potential, while others forecast the future. Forecasts are often based on specific assumptions like future political decisions; therefore they can be very speculative.

A multitude of work on bioenergy potentials has been conducted in recent years. From the previous points of discussion above, it can be understood that the estimation of a global energy wood potential is neither a trivial nor an unambiguous task. While the actual ecological and economic potentials are of ultimate interest, it is often a lack of knowledge that limits possible estimation to only a theoretical level. The studies assume a varying raw material base, in addition geographical and temporal scopes also differ. Because of all of the previously mentioned reasons, estimates may differ by as much as two orders of magnitude. This uncertainty complicates the use of these estimates by decision-makers. Some relevant global studies are reviewed and summarised in Table 2, this is followed by discussion of a few interesting regional studies, which are summarised in Appendix 1.

1.4.1 Global studies

Yamamoto et al. (2001) simulated some global modern fuelwood potentials by region. They postulated that because the demand for woody biomass will increase in developing countries, the area of mature forests will then decrease in many of these areas. Therefore, mature forests are predicted to disappear from the Middle East, North Africa, and South Asia, as well as Centrally Planned Asia. Consequently, the future potentials for fuelwood in these areas will be low. According to the simulations, the theoretical global potential of modern fuelwood in the year 2100 will be 379 EJ. More than half of this potential will be in Latin America with an estimated 199 EJ a^{-1}, while the next largest share of 75 EJ a^{-1} is to be in Sub-Saharan Africa. At the same time, the potentials of Western Europe, Japan, the Middle East, North Africa, South Africa, and Centrally Planned Asia will range from only 0 to 6 EJ a^{-1}.

Earlier work by Yamamoto's team was included in a research review by Berndes et al. (2003), who evaluated 17 studies of biomass energy potential. They noted that the potential from forests depends greatly on the basic approach of the study. In those studies, which took the anticipated future demand of industrial roundwood as a restriction for the potential, much lower potentials were reported than for those that were based on forest growth. The annual forest energy potentials in the demand-driven studies ranged from a couple of exajoules for the present time, which would then expand to some 50 EJ for the year 2100, whereas the resource-focused studies estimated that for the year 2050 the potential would range from about 50 EJ to over 100 EJ.

Table 2. Global estimates of the annual forest energy potential.

Publication	Temporal scope	Type of potential	Estimate, EJ	Origin
Yamamoto et al. 2001	2100	theoretical	379	modern fuelwood
Berndes et al. 2003	Present–2030	theoretical/technical	c. 5–15	forest residues from industrial roundwood and fuelwood/charcoal production
Berndes et al. 2003	2050–2100	theoretical/technical	c. 5–50	forest residues from industrial roundwood and fuelwood/ charcoal production
Berndes et al. 2003	2050	theoretical/technical	c. 50–100	unspecified forest biomass
Faaij 2007	Present–2050	economic	30–150	forest residues
Smeets & Faaij 2007	2050	theoretical	76.7	surplus forest growth + logging residues
Smeets & Faaij 2007	2050	technical	70.1	surplus forest growth + logging residues
Smeets & Faaij 2007	2050	economic	20.8	surplus forest growth + logging residues
Smeets & Faaij 2007	2050	economic-ecological	5.1	surplus forest growth + logging residues
Nabuurs et al. 2007	2020–2050	technical	12–74	primary residues
Nabuurs et al. 2007	2020–2050	economic	1.2–14.8	primary residues

In a recent report by the International Energy Agency (IEA) a range for the predicted energy potential for forest residues was given for around the year 2050, this had an upper limit of 150 EJ, which represents the technical potential, and a lower limit of 30 EJ, which includes limitations with respect to logistics and cuttings standards (Faaij 2007). This report also gave combined global biomass predictions for around the year 2050, with its most pessimistic value being 40 EJ and the most optimistic 1100 EJ. For this same future period, if the world were to have a common goal of more intensive utilisation of bioenergy then an average global biomass potential was predicted to be in the range of from 200 EJ to 400 EJ (Faaij 2007).

Smeets and Faaij (2007) predicted the forest energy potential for the year 2050. Their theoretical potential of 6.1 billion m^3 a^{-1} (71 EJ a^{-1}) is based on a scenario with a medium level of demand and plantation establishment. In addition their technical potential was given as 5.5 billion m^3 a^{-1} (64 EJ a^{-1}), while their given economic potential was only 1.3 billion m^3 a^{-1} (15 EJ a^{-1}). These (i.e. theoretical, technical, and economic) potentials are based mostly on surplus forest growth. If ecological restrictions are also included, then the resources available would be insufficient to meet the demand.

Nabuurs et al. (2007) reviewed several studies to examine the possibilities for forest energy to mitigate future climate change. For the years 2020 to 2050, they concluded that the technical potential of energy from the forest sector's primary biomass would range from 12 EJ to 74 EJ, while the economic potential would have a range of from only 1.2 EJ to 14.8 EJ.

1.4.2 Regional studies

Ericsson and Nilsson (2006) estimated forest energy potentials for the European Union (EU) member states that included forest residues from thinnings and harvests from mature forests. Their estimate for the annual potential for the fifteen older member states (EU15) had a range of 440 PJ to 880 PJ, while for the combination of the eight new member states and two candidate countries the annual potential was estimated to range from 150 PJ to 290 PJ. In comparison, Alakangas et al. (2007) gave their estimation of the techno-economic potential of forest residues in twenty European countries as 1387 PJ (33.1 Mtoe). In this case, forest residues are defined as "forest residue chips or hog fuel from final cuttings (tops, branches, bark), thinnings (whole tree chips), delimbed small-sized trees (stem chips), or stumps" (Alakangas et al. 2007).

Asikainen et al. (2008) estimated that the technically harvestable forest energy potential of the EU27 would be 1471 PJ (36 Mtoe). This estimation of the potential is based on the inclusion of the following sources of forest biomass: logging residues, stumps, and unmerchantable stemwood from current and supplementary cuttings, and stemwood from supplementary cuttings. Supplementary cuttings were possible since there is a positive roundwood balance. Asikainen et al. (2008) assumed that 25% of the balance could be directed to energy use. More specifically, their potential can be divided into 76.5 mill. m^3 of logging residues, 7.4 mill. m^3 of stump wood, 101.6 mill. m^3 of above ground biomass from supplementary cuttings, and 1.2 mill. m^3 of stemwood from supplementary cuttings.

In Northwest Russia, the technical potential for energy wood from logging, based on the actual 2006 harvests, was estimated to have been nearly 22 mill. m^3 (Gerasimov & Karjalainen 2009). These logging residues were available in harvesting areas and central processing yards as 65% non-industrial roundwood, 19% spruce stumps removed after clearfelling, 8% unused crown mass of branches and tops, and 8% defective wood from logging (Gerasimov & Karjalainen 2009). In addition, over 9 mill. m^3 could have been available in 2006 as by-products from the mechanical wood processing industry. These estimations do not account for the level to which some of the material included in the analysis was actually utilised in 2006 by various other alternatives, like traditional fuel wood. If the estimated 31 mill. m^3 of energy wood, which is assumed to be equal to 62 TWh, were used to meet the energy demands of the whole of Northwest Russia, it could then account for 6% of the region's demand. Based on two theoretical scenarios with different intensities of forest resource use the annual potential energy wood could be increased to 55 mill. m^3 or even 81 mill. m^3. This could then supply 15% to 21% of the current energy demand of the region.

Gan and Smith (2004) assessed the American distribution of logging residues and potential for using logging residues in electricity generation. The potential, when using logging residues from commercialised species, is 14 million dry tons. When logging residues from other sources were also included, the potential reaches 36 million tons; this estimate falls within the range estimated by Walsh et al. (1999). Approximately half of all logging residues are located in the Southeast and South Central regions of the USA. The amount of available logging residues that was calculated to actually have been available in 1997, was predicted to increase by 5%, by 2020, and by 10%, by 2040 (Gan and Smith 2004).

In its Regional Wood Energy Development Programme (RWEDP), the FAO (1997) estimated the wood energy potentials of sixteen Asian countries: Bangladesh, Bhutan, Cambodia, China, India, Indonesia, Laos, Malaysia, the Maldives, Myanmar, Nepal, Pakistan, the Philippines, Sri Lanka, Thailand, and Vietnam. From this work, it was concluded that generally, for the whole region, supply exceeds demand; this includes traditional fuelwood. However, there can be local deficits. The energy content of the sustainable woodfuel harvested from forestland in 1994 was estimated to be equal to 10 EJ, this was predicted to decrease to 9.4 EJ by 2010. For China, Cuiping et al. (2004) evaluated the distribution and quantity of biomass residues; the total theoretical potential from forest residues amounted to 227 Mt, of which 104 Mt is unused. A Japanese report by Harada (2000), of the local potential logging residues was cited by Yoshioka et al. (2006) as giving an estimated total of 3 Mt of dry mass.

2 Material and Methods

The forest energy potential currently available in any region of the world was assumed to consists of three components: 1) the logging residues from present cuttings, 2) the stemwood from supplementary cuttings in those places where there is surplus forest growth (i.e. the roundwood balance is positive), and 3) the logging residues from the supplementary cuttings. The removal of industrial roundwood by country was obtained from consistent statistics and converted to crown mass with biomass expansion factors (BEFs) (Figure 6). Any surplus forest growth was obtained by country from the same statistics, then a portion of this stemwood was assumed to be available as woodfuel. The surplus proportion harvested for fuelwood was then also converted to crown mass with BEFs. Finally, the total potential amount of modern fuelwood resulted from the sum of these three components. For easier comparison to other studies, woodfuel volumes were converted to energy units assuming a lower heating value of 2 MWh m^{-3} (7.2 GJ m^{-3}) (Röser et al. 2008).

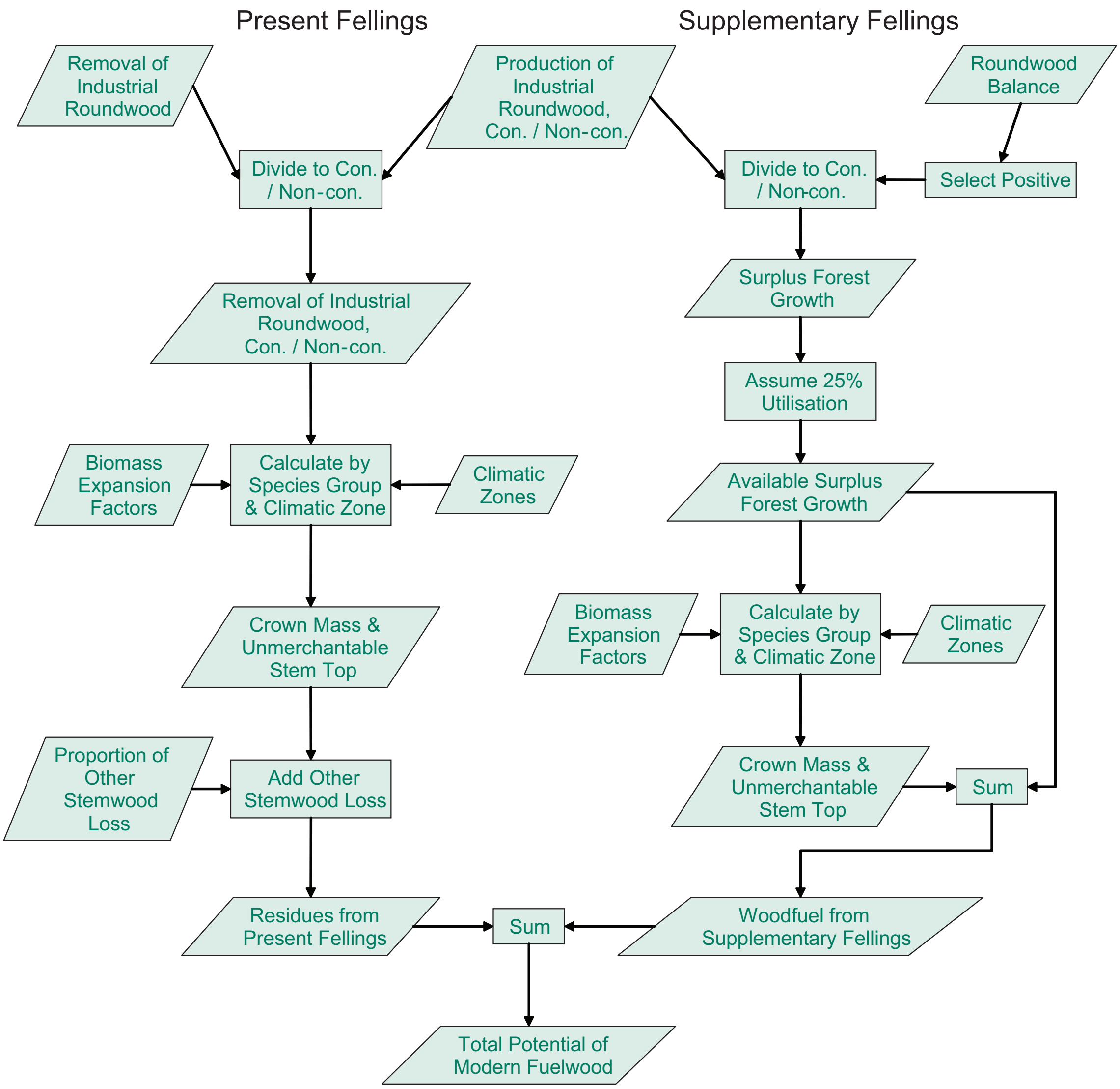

Figure 6. Procedure for calculating the total modern fuelwood potential currently available from a region.

2.1 Present cuttings

The 2005 harvests of industrial roundwood provided by the FAO's (2006) Global Forest Resources Assessment (FRA) were the basis for estimation of the logging residues for the present cuttings. The FRA also includes a value for the woodfuel removal, but since this mostly concerns traditional fuelwood, it was not considered here. The removals of industrial roundwood are given as a volume of roundwood over bark. They exclude felled trees left in the forest, which could be utilised as energy wood.

In principle, the amount of crown mass accumulating from the harvesting of industrial roundwood should be determined from the merchantability standards and a biomass function for each species. However, data of this type is not readily available for all species. The biomass expansion factors (BEFs) published by the Intergovernmental Panel on Climate Change (IPCC) (Penman et al. 2003) were used to assess the amount of crown mass for different species groups. There was concern that the BEF values for tropical broadleaves (Table 3) were rather high for plantations, probably since they are meant to include all the species from natural forests. Since it was assumed that most tropical broadleaf residues would come from plantations, where the quantities of crown residues would be less than for natural forest, the BEF values for temperate broadleaves were used also for the tropical broadleaves. Two BEF values are given in Table 3, the "low" values approximate mature forests or those with high levels of growing stock, whereas the "average" values are for younger forests with lower levels of growing stock. Woodfuel estimates were calculated with both values.

The BEFs were first applied to the data available on each countries industrial roundwood removals according to which of three climatic zones the country was assigned. Assignment of the zone for each country was subjectively determined with the aid of the global biome mapping of Olson et al. (2001). The final classification is very general, with each country assigned to a single climatic zone (Figure 7). After the climatic zone was determined, the roundwood removals also had to be divided into the two species groups, coniferous and broadleaf (i.e. non-coniferous) for the application of the correct BEF. This was accomplished using the statistics for industrial roundwood production (FAO Statistics Division 2008). These statistics were considered less reliable than the FRA data, but sufficiently reliable for species grouping. Therefore, the same proportion provided for the industrial roundwood production of each country was used to divide its industrial roundwood removal into the coniferous and non-coniferous groups.

Table 3. Biomass expansion factors (BEF) used to estimate crown mass (modified from Penman et al. 2003).

Climatic zone	Species group	BEF	
		low	average
Boreal	Conifers	1.15	1.35
	Broadleaf	1.15	1.3
Temperate	Conifers	1.15	1.3
	Broadleaf	1.15	1.4
Tropical	Conifers	1.15	1.3
	Broadleaf	1.15	1.4

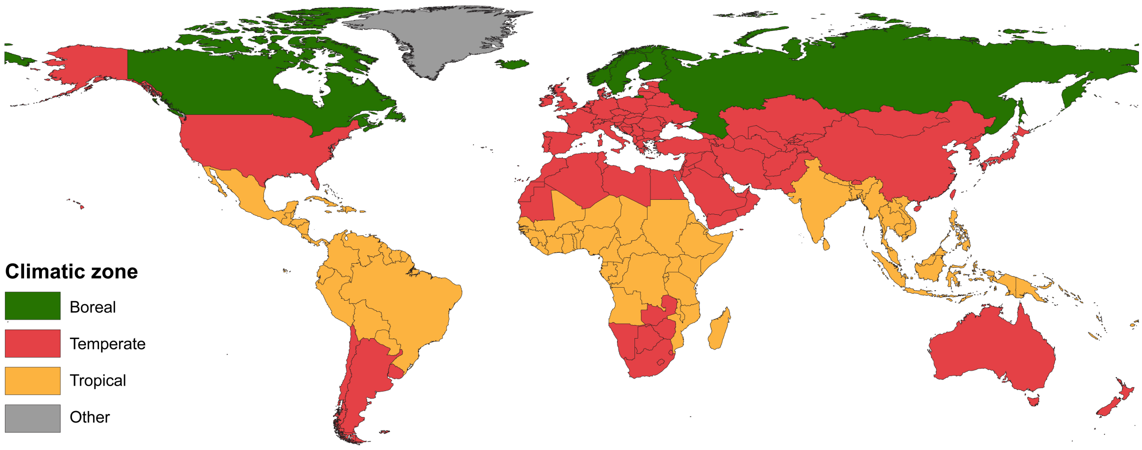

Figure 7. Generalised climatic zones used in application of the biomass expansion factors (BEF) (modified from Olson et al. 2001, with map boundaries provided by ESRI Data and Maps).

The amount of logging residues and unmerchantable stem tops was estimated for a country as follows:

$$V_{residues} = \sum_{s} R_s \cdot (BEF_{c,s} - 1),$$

where R = industrial roundwood removals for a specific country,
c = climatic zone, and
s = species group.

To account for the amount of unmerchantable stemwood to be associated with the known quantities of industrial roundwood removals, low and high values were used that corresponded, respectively, to 5% and 15% of a specific removal quantity. To determine a range for the total amount of logging residues (i.e. crown mass and unmerchantable stemwood), two estimates, an upper and lower limit, were made. The upper estimate used the average BEF values and high unmerchantable stemwood values, while the lower used the low BEF values and low unmerchantable stemwood values.

Stump and root wood is presently collected in most regions only on a limited basis. For example in Finland, this collection is made at suitable sites, while in Sweden and the United Kingdom (UK), some experiments into this type of collection have been carried out. It is, however, not likely that harvesting of stump and root wood would become common worldwide, and therefore accounting for the harvesting of these components was not included in the calculations.

2.2 Supplementary cuttings

The estimation of the roundwood balance was based on the annual change rate for growing stock from the Global Forest Resources Assessment (FAO 2006). It was presumed that the roundwood balance pertains only to commercial growing stock; therefore this balance is assumed to be zero for non-commercial growing stock.

It was presumed that supplementary cuttings could be carried out in countries, where the annual rate of change in growing stock was positive between 1990 and 2005. An educated guess was used to assign one quarter of any positive roundwood balance to be available for woodfuel

(Asikainen et al. 2008). From any projected supplementary cuttings, the amount of surplus, but otherwise merchantable stemwood that could be used as fuelwood was the same as the estimated positive roundwood balance for the period from 2000 to 2005 divided by four. Accessing the amount of potential logging residues from the projected supplementary cuttings used the same method as used for the present cuttings, with the removal data for applicable countries replaced by a quarter of their estimated positive roundwood balance.

3 Results

A geographical distribution of the upper limit values for the modern fuelwood potential is given by Figure 8. As a result of both the upper limits of the removals and surplus forest growth, the potential in the USA was clearly greater than elsewhere. Other countries with large total potentials were Canada, China, Brazil, and Russia. The total potential in Canada may be even greater than estimated, because there was no data for Canada in the FRA for the annual rate of change in the growing stock. Country-level potentials of selected countries are given in Table 4.

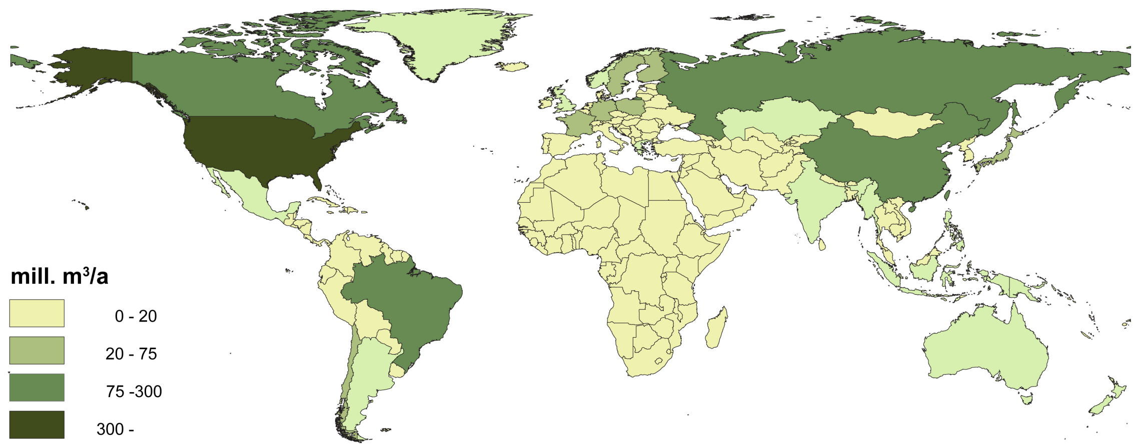

Figure 8. The technical upper limit potentials of modern fuelwood in 2005 for the countries of the world (map boundaries provided by ESRI Data and Maps).

Table 4. Modern fuelwood potentials in 2005 for selected countries.

	mill. m^3		PJ		TWh	
Country	lower	upper	lower	upper	lower	upper
United States	158	304	1140	2191	317	609
Canada	44	108	316	774	88	215
China	70	104	503	747	140	208
Brazil	34	86	242	621	67	173
Russia	38	77	273	554	76	154
Germany	29	46	207	331	58	92
Sweden	21	42	149	305	41	85
Japan	27	36	196	262	54	73
Finland	17	35	122	253	34	70
France	19	30	136	218	38	61
Poland	14	24	99	170	28	47
Chile	13	23	94	166	26	46
Austria	7	12	52	86	14	24
Czech Republic	5	10	39	71	11	20
Latvia	5	9	37	62	10	17
Slovakia	3	5	22	37	6	10

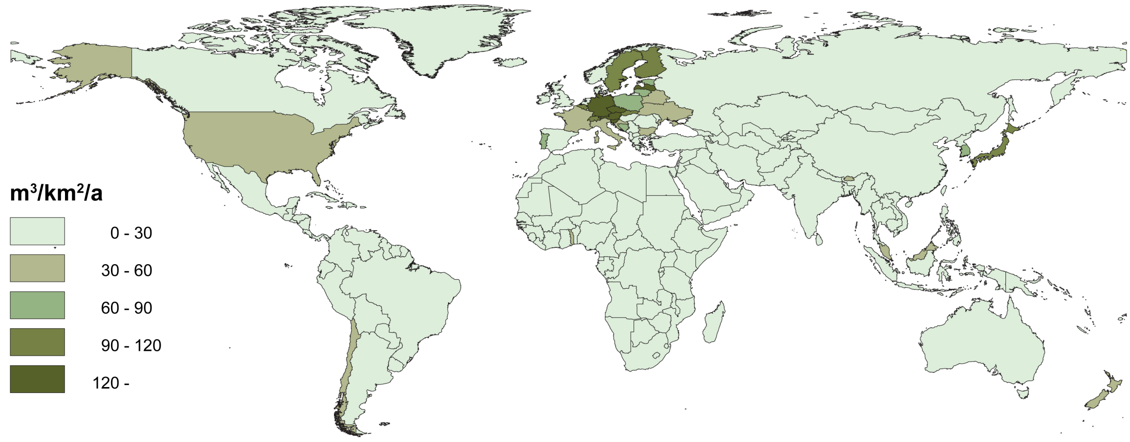

Figure 9. The technical upper limit potentials of modern fuelwood per unit of land area in 2005 for the countries of the world (map boundaries provided by ESRI Data and Maps).

When the potential is scaled to account for the size of a country, the USA still has a large potential (Figure 9). However, the modern fuelwood potential is especially large for Japan and many countries in Central and Northern Europe. Because of the relative size of these countries they would, thus, have reasonably short transportation distances for local utilisation of the fuelwood. At the same time these countries are also known to have well-developed transportation networks, which further improves their possibilities to use their woodfuel resources.

Figure 10 illustrates the modern woodfuel potentials aggregated by the larger regional divisions used in the FRA from 2005. The regional potentials are sub-divided into the fractions that are derived from present cuttings and supplementary cuttings. In South America the potential consists mostly of logging residues from present cuttings, whereas in North America, Europe, and especially in East Asia the contribution of surplus forest growth is considerable. The potential in other regions is minor compared to these four regions. The total potential of modern fuelwood for the whole world in 2005 was from 4.7 EJ (0.7 billion m^3) to 8.8 EJ (1.2 billion m^3). The woodfuel potential results using a different regional aggregation that was used by Pahkala et al. (2009) are presented in Appendix 2 for comparison to the global agrobiomass potential that they estimated in a parallel project.

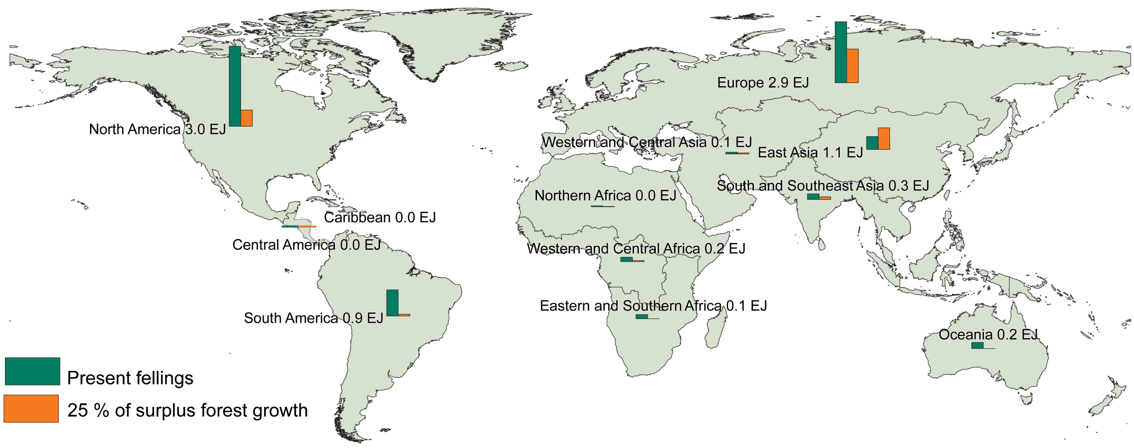

Figure 10. Regional upper limit forest energy potentials for 2005 (map boundaries provided by ESRI Data and Maps).

4 Discussion

The calculation method used here with its rough approximations and very general assumptions is acknowledged to have several weaknesses. The quality of the results is, however, sufficient to meet the aim of directing future research and marketing of modern fuelwood technology to promising regions. In the following section there is more detailed discussion of the shortcomings, then the results are compared and evaluated, and finally some brief conclusions are presented.

The greatest difficulty encountered with the calculation of biomass potentials is a lack of data. The biomass from harvesting residues available as crown mass is only an estimation, but it is based on initial data from the FRA and IPCC that are as globally consistent, as possible. Because data on the removals by species and timber assortment are only available for a few countries, the statistics that were used, were selected since they would provide a consistent coverage of the world. Some variation in data quality exists, but an effort has been made to standardise the data. The ratio between crown mass and industrial roundwood, or BEF, depends on the species, age, previous management treatments, and site, but biomass functions for all commercial species are unavailable. Therefore it was not possible to determine species level BEFs. In addition, data on unmerchantable stemwood is extremely limited. To improve the results with the methodology used here calls for more accurate biomass functions and statistics on removals and unmerchantable stemwood.

Another shortcoming, because of the data used, is that the scale of the results is limited to the spatially rather variable country level. For the larger countries like Russia, China, Canada, the USA, and Brazil this approach is too coarse and of little value with respect to positioning the actual potential resources relative to the local demand and infrastructure. In addition to this, the estimates are limited in time to the relative present.

Furthermore, technical, economic, and ecological constraints are only partially included. It can be assumed that the harvesting sites of the present cuttings of industrial roundwood have been feasible with respect to these constraints, but this does not guarantee the fulfillment of the technical, economic, and ecological criteria with respect to the procurement of logging residues. For the supplementary cuttings the available reserve of timber for these cuttings was based on the positive wood balance and the assumption that the data only reflected commercial forests. The change in the growth of non-commercal species was thus assumed to be zero. This is a generalised assumption since it holds true for old growth forests where growth and natural losses are equal, and if there are no cuttings. However, this is not the case everywhere, for example, the annual rate of change may be negative for protected forests where illegal cuttings may occur, and positive for young plantations established for soil conservation or other protective functions. It was also estimated that the sustainable potential harvest of the reserves would be one quarter of the surplus forest growth. This proportion is a rather rough educated guess, but based on many years of experience with forest based bioenergy. The potential in this study can be considered a technical potential. The economic potential in some regions is much lower. For example, in Russia much of its vast potential is located far from any infrastructure, thus it is economically intangible.

Despite the many flaws, the results provide benefits. They estimate the order of magnitude of forest biomass based energy production. They can also be seen as indicative in showing where the potential exists globally. The results of this analysis are also in line with previous work. For example concerning the twenty-seven countries of the European Union (EU27) the results are similar to those of Asikainen et al. (2008) (Figure 11). The upper limit total for the above-ground biomass potential from logging residues for the EU27 was 284 mill. m^3 (2 EJ), while Asikainen et al. give a value of 312 mill. m^3. The main reason for the difference in the results was that Asikainen et al. had subdivided the conifer species group into spruce and pine groups, which increased the crown mass potential in those countries where the spruce proportion was high, including: Austria, the Czech Republic, Finland, Germany, and Sweden. Taking this into account, the method used here with coarser data seems to give satisfactory results at least for the EU. It could therefore also be assumed that this method produced applicable results elsewhere. More thorough studies should be carried out on the most promising areas identified by the results of this work.

The potential "hot spots" for modern fuelwood are: the USA, Canada, Russia, China, Japan, Brazil, Chile, and most of Central and Northern Europe. When compared to the previous studies, the calculated potentials can be taken as relatively consistent considering the different constraints, raw material bases, and wide error margins. For example for the USA, the range of the potential from the result here is 1.1–2.2 EJ a^{-1}, whereas Gan and Smith (2004) estimated that the economic potential would be 0.69 EJ a^{-1}. For China, the results here gave a potential range of 0.5–0.7 EJ a^{-1}, while the theoretical potential according to Cuiping et al. (2004) was 2.0 EJ a^{-1}.

Both the global potential production of, and demand for, modern fuelwood are unevenly distributed. The developed countries have a relative advantage with regard to the infrastructure necessary for using modern fuelwood, and they are also committed to increasing its use through international agreements. In addition if prices for fossil fuels are to be at increasingly higher levels, as trends suggest, then the biofuels will be more economically competitive. This will lead to an increasing trade in biofuels (Hillring 2006; Junginger et al. 2008).

Theoretical future estimates can be very high, but as the future becomes the present with more limiting technological criteria, the smaller the potentials become (Figure 12). According to this study, the total potential of the whole world in 2005 was from 4.7 EJ to 8.8 EJ. This represents only 1–2% of the present global primary demand for energy.

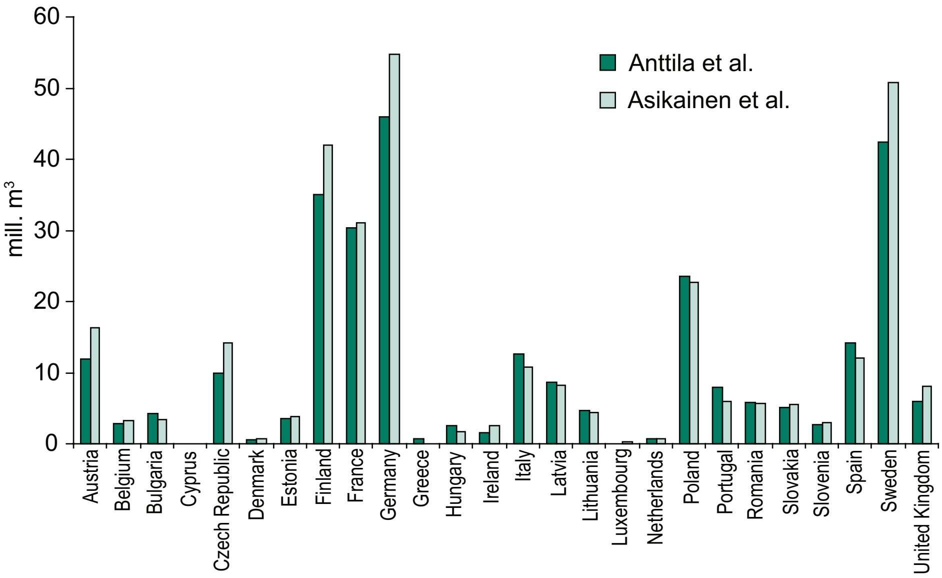

Figure 11. The upper limit results of the estimated annual total above-ground potentials for each of the EU27 countries compared to the results of Asikainen et al. (2008).

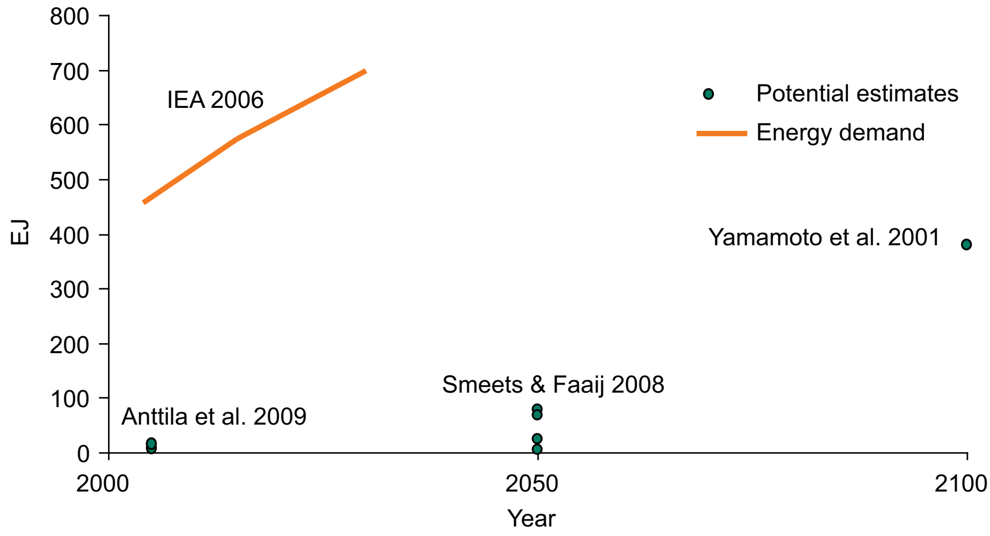

Figure 12. Selected annual estimates of global potential of modern fuelwood together with predicted demand for primary energy. Note that the studies represent different types of potential. The potential in this study is technical, in Yamamoto et al. (2001) theoretical whereas in Smeets and Faaij (2007) it ranges from economic-ecological to theoretical.

As previously described, economic and ecological restrictions make the real availability of fuelwood much lower than the basic results of this work suggest. In addition, part of the energy content is lost in the collection, preparation, transportation, storage, and conversion of fuelwood to primary energy. These steps also need external energy, which in turn increases the level of needed primary energy. Taking these facts into account, it can be concluded that forest energy can only make a minor contribution to the total global primary energy demand. Regional and local situation, however, may be very different.

References

Alakangas, E., Heikkinen, A., Lensu, T. & Vesterinen, P. 2007. Biomass fuel trade in Europe – Summary Report VTT-R-03508-07. EUBIONET II project. 55 p. Available from: http://www.aebiom.org/IMG/pdf/WP1_EUBIONET_Final_12042007.pdf.

Alakangas, E., Valtanen, J. & Levlin, J.-E. 2006. CEN technical specification for solid biofuels – Fuel specification and classes. Biomass and Bioenergy 30, 908–914.

Anuchin, N. 1981. Сортиментные и товарные таблицы [Assortment and merchantability tables]. Moscow: Lesnaya Promyshlennost (Lesprom). (In Russian).

Asikainen, A., Liiri, H., Peltola, S., Karjalainen, T. & Laitila, J. 2008. Forest energy potential in Europe (EU27). Metla Working Papers 69. Finnish Forest Research Institute (Metla). 33 p. Available from: http://www.metla.fi/julkaisut/workingpapers/.

Berndes, G., Hoogwijk, M. & Broek, R.v.d. 2003. The contribution of biomass in the future global energy supply: a review of 17 studies. Biomass and Bioenergy 25: 1–28.

Cuiping, L., Yanyongjie, Chuangzhi, W. & Haitao, H. 2004. Study on the distribution and quantity of biomass residues resource in China. Biomass and Bioenergy 27: 111.

Del Lungo, A., Ball, J. & Carle, J. 2006. Global planted forests thematic study: results and analysis. Planted forests and trees working paper 38. FAO. 168 p. Available from: http://www.fao.org/forestry/site/10368/en/.

EFSOS 2005. European Forest Sector Outlook Study. 1960–2000–2020. UNECE/FAO. 265 p. Available from: http://www.fao.org/docrep/008/ae428e/ae428e00.htm. [Cited 23 March 2009].

Ericsson, K. & Nilsson, L.J. 2006. Assessment of the potential biomass supply in Europe using a resource-focused approach. Biomass and Bioenergy 30: 1–15.

EUBIA. 2008. EUBIA – European Biomass Industry Association: Biomass resources and production potential. Available from: http://www.eubia.org/215.0.html. [Cited 21 February 2008].

Faaij, A. 2007. Potential Contribution of Bioenergy to the World's Future Energy Demand. International Energy Agency (IEA) Bioenergy, ExCo: 2007: 02. 12 p. Available from: http://www.ieabioenergy.com/MediaItem.aspx?id=5586.

FAO (Food and Agricultural Organization of the United Nations). 1990. Energy conservation in the mechanical forest industries. FAO Forestry Paper 93. FAO. 118 p. Available from: http://www.fao.org/docrep/T0269e/T0269e00.htm.

– 2004. Unified bioenergy terminology. UBET. FAO. 50 p. Available from: http://www.fao.org/docrep/007/j4504e/j4504e00.htm.

– 2006. Global forest resources assessment 2005: Progress towards sustainable forest management. FAO Forestry Paper 147. FAO. 320 p. Available from: http://www.fao.org/forestry/site/fra/en/.

– Statistics Division. 2008. Production of industrial roundwood in 2005. Available from: http://faostat.fao.org/site/626/default.aspx#ancor [Cited 26 February 2009].

Gan, J. & Smith, C.T. 2004. Availability of Logging Residues and Potential for Electricity Production and Carbon Displacement in the U.S. [Presentation]. IEA Bioenergy Task 31 Workshop, Sweden and Norway.

Gerasimov, Y. & Karjalainen, T. 2009. Assessment of energy wood resources in Northwest Russia. Metla Working Paper 108. Finnish Forest Research Institute (Metla). 52 p.

Hakkila, P. 1991. Hakkuupoistuman latvusmassa [Crown mass of trees at the harvesting phase]. Folia Forestalia 773.

Hakkila, P. 2004. Developing technology for large-scale production of forest chips. Technology programme report 6/2004. Tekes. 99 p. Available from: http://akseli.tekes.fi/opencms/opencms/OhjelmaPortaali/ohjelmat/Puuenergia/en/etusivu.html.

Harada, T. 2000. Energy usage of biomass from forest. Research Journal of Food and Agriculture 23, 39–44.

Hillring, B. 2006. World trade in forest products and wood fuel. Biomass and Bioenergy 30, 815.

Junginger, M., Bolkesjø, T., Bradley, D., Dolzan, P., Faaij, A., Heinimö, J., Hektor, B., Leistad, Ø., Ling, E., Perry, M., Piacente, E., Rosillo-Calle, F., Ryckmans, Y., Schouwenberg, P.-P., Solberg, B., Trømborg, E., Walter, A.d.S. & Wit, M.d. 2008. Developments in international bioenergy trade. Biomass and Bioenergy 32: 717.

Karjalainen, T., Asikainen, A., Ilavský, J., Zamboni, R., Hotari, K.-E. & Röser, D. 2004. Estimation of energy wood potential in Europe. Working Papers 1795–150X. Finnish Forest Research Institute. 43 p. Available from: http://www.metla.fi/julkaisut/workingpapers/.

Koistinen, A. & Äijälä, O. 2006. Energiapuun korjuu. Forestry Development Centre Tapio. 40 p.

Nabuurs, G.J., Masera, O., Andrasko, K., Benitez-Ponce, P., Boer, R., Dutschke, M., Elsiddig, E., Ford-Robertson, J., Frumhoff, P., Karjalainen, T., Krankina, O., Kurz, W.A., Matsumoto, M., Oyhantcabal, W., Ravindranath, N.H., Sanz Sanchez, M.J. & Zhang, X. 2007. Forestry. In: Metz, B., Davidson, O.R., Bosch, P.R., Dave, R., Meyer, L.A. (Eds.), Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 541–584.

Olson, D.M., Dinerstein, E., Wikramanayake, E.D., Burgess, N.D., Powell, G.V.N., Underwood, E.C., D'Amico, J.A., Itoua, I., Strand, H.E., Morrison, J.C., Loucks, C.J., Allnutt, T.F., Ricketts, T.H., Kura, Y., Lamoreux, J.F., Wettengel, W.W., Hedao, P. & Kassem, K.R. 2001. Terrestrial Ecoregions of the World: A New Map of Life on Earth. BioScience 51(11): 933-938.

Pahkala, K., Hakala, K., Kontturi, M. & Niemeläinen, O. 2009. Peltobiomassat globaalina energianlähteenä. Maa- ja elintarviketalous 137. MTT. 53 p. Available from: http://www.mtt.fi/met/pdf/met137.pdf.

Penman, J., Gytarsky, M., Hiraishi, T., Krug, T., Kruger, D., Pipatti, R., Buendia, L., Miwa, K., Ngara, T., Tanabe, K. & Wagner, F. 2003. Good Practice Guidance for Land Use, Land-Use Change and Forestry. Intergovernmental Panel on Climate Change. p. Available from: http://www.ipcc-nggip.iges.or.jp/public/gpglulucf/gpglulucf.html.

Priddle, R. (editor). 2006. World energy outlook 2006. International Energy Agency (IEA). 601 p. Available from: http://www.iea.org/textbase/nppdf/free/2006/weo2006.pdf.

Röser, D., Asikainen, A., Stupak, I. & Pasanen, K. 2008. Forest energy resources and potentials. In: Röser, D., Asikainen, A., Raulund-Rasmussen, K. (Eds.), Sustainable use of forest biomass for energy. A synthesis with focus on the Baltic and Nordic region. Springer, Dortrecht, pp. 9–28.

Saint-Andre, L., M'Bou, A.T., Mabiala, A., Mouvondy, W., Jourdan, C., Roupsard, O., Deleporte, P., Hamel, O. & Nouvellon, Y. 2005. Age-related equations for above- and below-ground biomass of a Eucalyptus hybrid in Congo. Forest Ecology and Management 205, 199–214.

Sampson, R.N., Bystriakova, N., Brown, S., Gonzalez, P., Irland, L.C., Kauppi, P., Sedjo, R., Thompson, I.D., Barber, C.V. & Offrell, R. 2005. Timber, fuel, and fiber. In: Hassan, R., Scholes, R., Ash, N. (Eds.), Ecosystems and Human Well-being: Current State and Trends, Volume 1. Island Press, Washington, Covelo, London, pp. 243–269.

Senelwa, K. & Sims, R.E.H. 1998. Tree biomass equations for short rotation Eucalypts grown in New Zealand. Biomass and Bioenergy 13, 133–140.

Sims, R.E.H., Schock, R.N., Adegbululgbe, A., Fenhann, J., Konstantinaviciute, I., Moomaw, W., Nimir, H.B., Schlamadinger, B., Torres-Martínez, J., Turner, C., Uchiyama, Y., Vuori, S.J.V., Wamukonya, N. & Zhang, X. 2007. Energy supply. In: Metz, B., Davidson, O.R., Bosch, P.R., Dave, R. & Meyer, L.A. (editors.). Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 251–322.

Siqueira, J., Ferreira, A. & Lange Jr., F. 2005. Increase in efficiency in conversion of tropical timber and utilization of residues from sustainable sources. PD 61/99 rev. 4(I).

Smeets, E.M.W. & Faaij, A.P.C. 2007. Bioenergy potentials from forestry in 2050. An assessment of the drivers that determine the potentials. Climatic Change 81, 353–390.

Smeets, E.M.W., Faaij, A.P.C., Lewandowski, I.M. & Turkenburg, W.C. 2007. A bottom-up assessment and review of global bio-energy potentials to 2050. Progress in Energy and Combustion Science 33, 56.

Stape, J.L., Binkley, D. & Ryan, M.G. 2004. Eucalyptus production and the supply, use and efficiency of use of water, light and nitrogen across a geographic gradient in Brazil. Forest Ecology and Management 193, 17–31.

STCP Data Bank. 1983–. STCP Engenharia de Projetos Data Bank. Curitiba, Brasil.

Tomaselli, I. 2007. Forests and energy in developing countries. Forests and energy working paper 2. FAO. 32 p. Available from: http://www.fao.org/forestry/webview/media?mediaId=13444&langId=1.

Vantomme, P. 2006. Wood waste for energy: lessons learnt from tropical regions. In, International seminar on energy and the forest products industry, Rome.

Walsh, M.E., Perlack, R.L., Turhollow, A., de la Torre Ugarte, D., Becker, D.A., Graham, R.L., Slinsky, S.E. & Ray, D.E. 2000. Biomass Feedstock Availability in the United States: 1999 State Level Analysis. Available from: http://bioenergy.ornl.gov/resourcedata/index.html. [Cited 6 March 2008].

Yamamoto, H., Fujino, J. & Yamaji, K. 2001. Evaluation of bioenergy potential with a multi-regional global-land-use-and-energy model. Biomass and Bioenergy 21, 185–203.

Yoshioka, T., Aruga, K., Nitami, T., Sakai, H. & Kobayashi, H. 2006. A case study on the costs and the fuel consumption of harvesting, transporting, and chipping chains for logging residues in Japan. Biomass and Bioenergy 30, 342

APPENDIX 1.

Table 1. Regional estimates of modern fuelwood potential. 1 EJ = 277.8 TWh.

Region	Publication	Temporal scope	Type of potential	Estimate, EJ a^{-1}	Origin
EU15	Ericsson & Nilsson 2006	Present	theoretical	0.44–0.88	forest residues
ACC10	Ericsson & Nilsson 2006	Present	theoretical	0.15–0.29	forest residues
EU20	Alakangas et al. 2007	Present	techno-economic	1.39	forest residue chips or hog fuel from final fellings (tops, branches, bark), thinnings (whole tree chips), delimbed small-sized trees (stem chips) or stumps
EU27	Asikainen et al. 2008	Present	technical	1.47	stumps and roots, needles, tops, branches, unmerchantable stemwood (current fellings and roundwood balance); stemwood (roundwood balance)
Western Europe	Yamamoto et al. 2001	2100	theoretical	0–10	modern fuelwood
West Europe	Smeets & Faaij 2007	2050	theoretical	2.7	surplus forest growth + logging residues
West Europe	Smeets & Faaij 2007	2050	economic-ecological	0.8	surplus forest growth + logging residues
East Europe	Smeets & Faaij 2007	2050	theoretical	0.9	surplus forest growth + logging residues
East Europe	Smeets & Faaij 2007	2050	economic-ecological	0.2	surplus forest growth + logging residues
OECD Europe	Nabuurs et al. 2007	2020–2050	technical	1–4	primary residues
OECD Europe	Nabuurs et al. 2007	2020–2050	economic	0.1–0.8	primary residues
USA	Gan & Smith 2004	Present	economic	0.69	logging residues
USA	Walsh et al. 2000	Present	economic	0.46–0.86[a]	logging residues and rough, rotten, and salvable dead wood
North America	Yamamoto et al. 2001	2100	theoretical	20–30	modern fuelwood
North America	Smeets & Faaij 2007	2050	theoretical	8.2	surplus forest growth + logging residues
North America	Smeets & Faaij 2007	2050	economic-ecological	1.8	surplus forest growth + logging residues
OECD North America	Nabuurs et al. 2007	2020–2050	technical	3–11	primary residues
OECD North America	Nabuurs et al. 2007	2020–2050	economic	0.3–2.2	primary residues
Centrally Planned Asia	Yamamoto et al. 2001	2100	theoretical	0–10	modern fuelwood
Southeast Asia	Yamamoto et al. 2001	2100	theoretical	20–30	modern fuelwood
East Asia	Smeets & Faaij 2007	2050	theoretical	2.0	surplus forest growth + logging residues
East Asia	Smeets & Faaij 2007	2050	economic-ecological	0.8	surplus forest growth + logging residues
China	Cuiping et al. 2004	Present	theoretical	2.0[a]	residues from forest and non-forest land - firewood
RWEDP countries	FAO 1997	1994	theoretical	10	sustainable woodfuel from forest land
RWEDP countries	FAO 1997	2010	theoretical	9.4	sustainable woodfuel from forest land
South Asia	Yamamoto et al. 2001	2100	theoretical	0–10	modern fuelwood
South Asia	Smeets & Faaij 2007	2050	theoretical	0.3	surplus forest growth + logging residues
South Asia	Smeets & Faaij 2007	2050	economic-ecological	0.3	surplus forest growth + logging residues

Table 1. Continues.

Japan	Yamamoto et al. 2001	2100	theoretical	0–10	modern fuelwood
Japan	Smeets & Faaij 2007	2050	theoretical	0.1	surplus forest growth + logging residues
Japan	Smeets & Faaij 2007	2050	economic-ecological	0.1	surplus forest growth + logging residues
Japan	Yoshioka et al. 2006	Present	?	0.06	logging residues
Oceania	Yamamoto et al. 2001	2100	theoretical	10–20	modern fuelwood
Oceania	Smeets & Faaij 2007	2050	theoretical	0.7	surplus forest growth + logging residues
Oceania	Smeets & Faaij 2007	2050	economic-ecological	0.2	surplus forest growth + logging residues
Middle East & North Africa	Yamamoto et al. 2001	2100	theoretical	0–10	modern fuelwood
Middle East & North Africa	Smeets & Faaij 2007	2050	theoretical	0.1	surplus forest growth + logging residues
Middle East & North Africa	Smeets & Faaij 2007	2050	economic-ecological	0.1	surplus forest growth + logging residues
Sub-Sahara Africa	Yamamoto et al. 2001	2100	theoretical	75	modern fuelwood
Sub-Saharan Africa	Smeets & Faaij 2007	2050	theoretical	2.8	surplus forest growth + logging residues
Sub-Saharan Africa	Smeets & Faaij 2007	2050	economic-ecological	0.2	surplus forest growth + logging residues
Africa	Nabuurs et al. 2007	2020–2050	technical	1–10	primary residues
Africa	Nabuurs et al. 2007	2020–2050	economic	0.1–2	primary residues
Latin America	Yamamoto et al. 2001	2100	theoretical	199	modern fuelwood
Latin America	Nabuurs et al. 2007	2020–2050	technical	1–21	primary residues
Latin America	Nabuurs et al. 2007	2020–2050	economic	0.1–4.2	primary residues
Caribbean & Latin America	Smeets & Faaij 2007	2050	theoretical	26.1	surplus forest growth + logging residues
Caribbean & Latin America	Smeets & Faaij 2007	2050	economic-ecological	0.5	surplus forest growth + logging residues
Former USSR & Eastern Europe	Yamamoto et al. 2001	2100	theoretical	30–40	modern fuelwood
C.I.S. and Baltic States	Smeets & Faaij 2007	2050	theoretical	32.8	surplus forest growth + logging residues
C.I.S. and Baltic States	Smeets & Faaij 2007	2050	economic-ecological	0.2	surplus forest growth + logging residues

[a] 1 t = 19.19 GJ (Gan & Smith 2004)

APPENDIX 2.

Table 2. Annual potentials of modern fuelwood for Global Times regions.

	mill. m^3		PJ		TWh	
Region	lower	upper	lower	upper	lower	upper
Africa	21	48	0.1	0.3	0.03	0.08
Australia-New Zealand	10	24	0.1	0.2	0.03	0.06
Canada	44	108	0.3	0.8	0.08	0.22
China	70	104	0.5	0.7	0.14	0.19
Central and South America	55	127	0.4	0.9	0.11	0.25
Eastern Europe	36	63	0.3	0.5	0.08	0.14
Former Soviet Union	69	123	0.5	0.9	0.14	0.25
India	2	3	0.0	0.0	0.00	0.00
Japan	27	36	0.2	0.3	0.06	0.08
Middle-East	5	10	0.0	0.1	0.00	0.03
Mexico	2	4	0.0	0.0	0.00	0.00
Other Developing Asia	16	34	0.1	0.2	0.03	0.06
South Korea	6	7	0.0	0.1	0.00	0.03
United States	158	304	1.1	2.2	0.31	0.61
Western Europe	130	224	0.9	1.6	0.25	0.44
Total	651	1220	4.7	8.8	1.31	2.44

For a list of countries of each region, see Pahkala et al. 2009.