Introduction to Forest Bioenergy

Isabel Malico and Ana Cristina Gonçalves

Abstract This chapter introduces and outlines the book “Forest Bioenergy: From Wood Production to Energy Use”, dedicated to biomass, currently the most commonly used renewable energy source, which contributes to 10% of the worldwide energy supply. The majority of bioenergy comes from woody biomass, which is mainly converted into heat (mostly in households, followed by industries). Its conversion to power is also relevant, while the production of transport biofuels is a promising pathway. Modern bioenergy presents numerous advantages: it has a renewable, versatile, local and distributed nature; it helps increase energy security and meet the rising global energy demands; it easily substitutes for fossil fuels; and it presents potential environmental and economic benefits. Carbon sequestration and storage are among the several environmental services provided by forests. The amount of biomass they produce, and consequently, their bioenergy potential, is highly variable. Forest plantations provide the highest bioenergy yields per unit area, while in forest systems managed for other purposes, factors such as stand structure affect residual biomass generation. Assessing and monitoring biomass, along with determining bioenergy potentials, are essential tasks, often based on mathematical models that vary in complexity and span different spatial and temporal scales, frequently with associated cartography.

Keywords Wood · Wood residues · Energy plantations · Biofuels · Bioheat · Biopower

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1 Introduction

Forest bioenergy is a term used to describe the energy obtained directly or indirectly from biodegradable, renewable raw materials from woody shrub and tree species, excluding agricultural ones. The sources of forest bioenergy are diverse and include products, residues and waste, such as fuelwood, wood pellets, residues from forest-based industries and post-consumer wood (*cf.* chapter "Sources and Distribution of Forest Biomass for Energy").

Forests have been providing mankind with fuels for heating and cooking for thousands of years, and they are still the main energy source for millions of people who do not have access to clean fuels and technologies to satisfy their basic needs. As such, they provide an essential service to these populations but, in many circumstances, at a high cost. Severe negative impacts arise when biomass is used in a traditional way through the combustion of solid biomass in inefficient and polluting equipment. Indeed, emissions from inefficient biomass burning cause adverse health problems [1–5] and impact the climate [6–9]. Additionally, the traditional use of biomass leads to a large demand for wood fuels, puts pressure on forests, contributes to forest degradation and has negative effects on gender equity [10–13] (*cf.* chapter "Biomass for Domestic Heat").

In contrast to the traditional use of biomass, modern biomass uses for energy are characterised by more efficient and cleaner technologies. On the condition that forest resources are obtained in a sustainable way and efficient, clean conversion technologies are employed, the use of forest biomass for bioenergy and biofuel production is a valuable and advantageous option to meet energy needs. Many high-income countries, which had, to some extent, forgotten bioenergy during a large part of the last century, have renewed their interest in this form of energy, influenced in part by the environmental advantages of biomass over fossil fuels and its socioeconomic benefits.

Biomass can help meet the increasing energy needs of the growing world population. From 1971 to 2020, the world total energy supply increased by around 150%, from 230.5 EJ to 584.5 EJ (Fig. 1) [14]. In this period, the largest average annual growth rate came from nuclear energy (7.2%), followed by renewable energy sources (RES) (2.2%) and fossil fuels (1.8%). However, in the last decades, increased awareness of the environmental problems caused by fossil fuels and the public perception of the risks of nuclear energy have led to a change in the growth rates of the energy supplied by the different energy sources, especially nuclear. From 2001 to 2020, the largest average annual growth rate in energy supply was associated with RES (2.5%), followed by fossil fuels (1.7%) and nuclear (0.2%).

Despite the relevance of renewable energy sources in general and biomass in particular, fossil fuels still dominate the global energy mix today. In 2020, they were the energy sources most used in the world (80%, Fig. 2). Crude oil and oil products accounted for 29.5% of the world total energy supply, closely followed by coal (27%), natural gas (24%) and renewable energy sources (15%), with biomass being the largest contributor among all the RES.

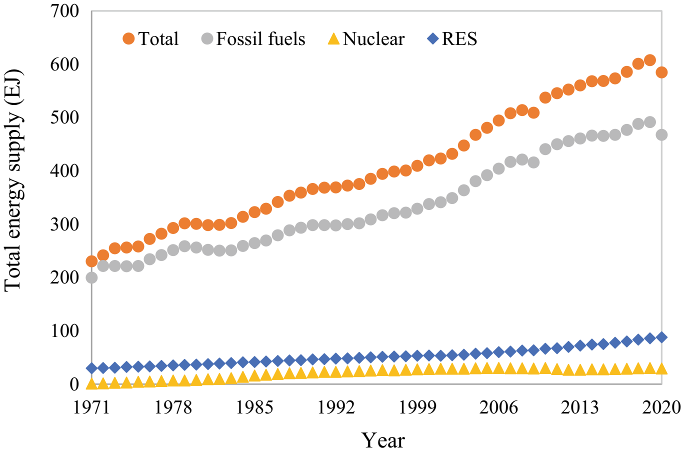
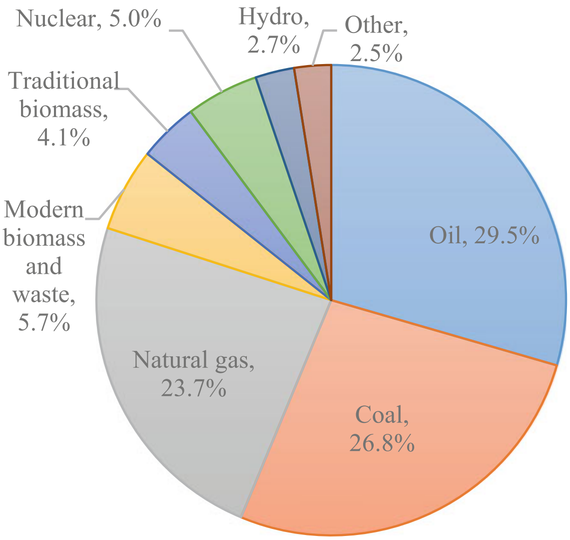


Fig. 1 World total energy supply from 1971 to 2020 by energy source. (*Data source* [14, 15])

Fig. 2 Share of energy sources in the world total energy supply in 2020. (*Data source* [14, 16])



The reasons for the dominance of fossil fuels are clear: they have a high energy density and are convenient to use. Coal, the most carbon-intensive fossil fuel, is still the main source of power production worldwide (*cf.* chapter "Biomass for Power Production and Cogeneration"). It is the fossil fuel with the largest and most evenly distributed reserves around the world and with a relatively low cost [17], even though, today, in most markets, renewable energy options are the most cost-effective new sources [18]. Coal is also an important energy source for energy-intensive industries, such as the iron and steel or cement industries (*cf.* chapter "Biomass for Industrial and District Heating"). On the other hand, oil products in liquid form are more energy-dense than coal and very appropriate for use as transport fuel, being, by far, the most used energy sources in this sector (>90% in 2020, [14]). Natural gas, the least carbon-emitting fossil fuel, is very versatile and plays a relevant role in power plants, buildings and industrial facilities (*cf.* chapters "Biomass for Domestic Heat" and "Biomass for Industrial and District Heating" and "Biomass for Power Production and Cogeneration").

In the last two centuries, the large-scale consumption of fossil fuels has allowed for a rapid growth in industrial and agricultural production, enormous technological advances and improvements in the living conditions of humans. However, it also has numerous severe impacts on the environment and public health [9, 19] and affects energy security [20, 21]. As a consequence, a rapid phaseout of fossil fuels is needed, and both energy efficiency and sustainable energy sources should be promoted.

Biomass can substitute for fossil fuels relatively easily since it can be used and stored in similar ways to fossil fuels [22], therefore providing energy when needed (in power generation, biomass is an important complement to intermittent renewable energy sources like solar and wind, providing firm low-carbon electricity [23]). However, unlike fossil fuels, it is a renewable energy source when sustainably obtained, i.e., when the increment of biomass by plant regrowth is equal to or larger than the removal, so that it can be continuously available in large quantities.

Furthermore, the versatile, local and distributed nature of biomass may help to reduce the dependency on imported oil or natural gas, which are much more concentrated geographically [24], and, even though the global international trade of bioenergy will likely increase significantly, this does not necessarily lead to energy security concerns since multiple world regions can act as bioenergy suppliers [25].

Additionally, when modern, efficient and clean energy conversion technologies are used, sustainably produced forest biomass typically presents environmental benefits in comparison to fossil fuels [26–31]. One of the benefits of forest bioenergy might be a contribution to climate change mitigation. This derives from (*i*) avoided fossil fuel use and (*ii*) greenhouse gas emission mitigation during biomass production, including soil carbon accumulation [32]. On the other hand, there are greenhouse gas emissions associated with fossil fuel use in the production, harvesting, transport and processing of biomass, and, in the case of the establishment of energy plantations, land use change and indirect land use change effects have also to be considered.

If the forest biomass harvested for bioenergy is produced sustainably, it is arguably considered "carbon neutral", i.e., it is assumed that the carbon exported from the stands and forests will be sequestered and stored during tree regrowth, thus resulting in the neutrality of the carbon cycle [33]. Overall, the use of biomass for energy releases carbon into the atmosphere that will be absorbed by tree growth [34], which, depending on the species and tree growth rates, will need shorter (young and/or fast-growing species) or longer (old and/or slow-growing species) time [35, 36]. This is not, however, the only definition of carbon neutrality. The authors of a review study on carbon neutrality found eight different concepts for the term but no standardised concept or definition of carbon neutrality [34]. Bioenergy is often justified and promoted on the basis of its inherent carbon neutral status, but carbon neutrality is not an inherent property of biomass; rather, it is a relative characteristic of a bioenergy product [34], depending, for example, on the fossil fuel being displaced, the energy conversion efficiency of the bioenergy pathway followed, the growth rate of forests, the frequency and intensity of biomass harvests, the initial forest carbon stock and the forest management practices used [37].

The carbon storage capacity of forests may be enhanced by biomass removal in certain circumstances. This is the case, for example, when biomass is exported from the forest to reduce the fuel load and prevent wildfires or when thinnings are performed (see chapter "Stand Structure and Biomass" for further information). Other ecological benefits of biomass removals include the control of invasive flora and fauna species to restore natural habitats [38].

Another advantage of bioenergy might be its economic attractiveness. The generation of bioheat by combustion is often cost-competitive with fossil fuels [39, 40]. Also, the generation of bioelectricity with low-cost residual biomass might be cheaper than fossil fuel options [41]. However, the cost-effectiveness of bioenergy depends on the specific application, and high costs are a barrier, for example, for the development of many bioenergy options (e.g., advanced biofuels for transportation) or fuel switching (e.g., in high-temperature industrial applications or electricity generation) [41]. On the other hand, rural development, job creation or the promotion of social sustainability are often cited as advantages of bioenergy [39, 42–47].

Despite its many advantages, the use of biomass for energy is not without controversy. Besides the already mentioned problems associated with the traditional uses of biomass, the overall sustainability of bioenergy is often questioned [32, 48–51]. Biomass in general, and forest biomass in particular, are limited resources that require land and water for their growth. Moreover, the energy efficiency of photosynthesis is very low (the most efficient trees do not exceed solar storage efficiencies of 1% [52]). Therefore, in this regard, biomass is not the most effective way to store solar energy. However, storing energy is not the only function of forests, and if sustainably managed, forests provide other important ecosystem services. For example, photosynthesis generates oxygen, which is essential to flora and fauna, and forest areas promote soil and water protection [53] (see chapter "Stand Structure and Biomass" for further information).

To date, bioenergy is substantially sourced from residues and waste, but because their potential is limited, the supply of additional large quantities of biomass is dependent on energy plantations [49]. A large expansion of, especially agricultural, energy plantations in some countries could increase human pressure on the terrestrial biosphere, threaten the ability of global ecosystems to provide essential ecosystem services, and might be associated with substantial ecological costs, such as soil degradation, biodiversity loss or nitrogen release [54]. Furthermore, large-scale energy plantations, especially the agricultural ones, may potentially compete with food production, leading to significant socioeconomic effects [49]. However, if forest species plantations are grown specifically for energy on marginal lands [55] or on current agricultural land that can be diverted from food and feed production without further impairing food security [56], energy plantations can be a source of beneficial renewable energy. For example, Langeveld et al. [57] concluded that including large-scale short-rotation coppices in intensive, arable crop cultivations in homogeneous monocultural landscapes may have both positive and negative effects depending on the exact implementation. As referred to by Robertson et al. [32], prior land use has a significant effect on the benefits of energy plantations. The issue of bioenergy sustainability is, therefore, very complex, with several factors impacting the overall sustainability of bioenergy, among which are the location and scale of production, the type of feedstock and the conversion technology [58, 59].

2 Current Production and Consumption of Bioenergy

In 2020, the world energy supply of biomass and waste was 57.5 EJ [14], which represented around 10% of the total energy supply (Fig. 2). Most of this contribution was modern bioenergy, but a substantial part was still traditional bioenergy used for cooking and heating with basic, inefficient and pollutant technologies [16]. On the other hand, the non-renewable fraction of municipal and industrial waste represented a relatively small fraction of the share of energy supply attributed to biomass and waste.

Even if traditional bioenergy use is not considered renewable because of its severe negative impacts, modern biomass provided approximately half of the global renewable primary energy supply in 2020, making it the largest contributor among RES, followed by hydro. When accounting for traditional biomass use, biomass represented almost two-thirds of the world renewable energy supply.

In the last 30 years, the share of bioenergy and waste in the world total energy supply has remained relatively stable (according to data from the International Energy Agency, IEA [14], the average share from 1990 to 2020 was 9.7%). Nevertheless, the energy supplied by these two energy sources in this period increased slightly less (56%) than the total energy supply (60%).

The vast majority of global bioenergy and waste consumption is attributed to solid biomass. However, over the last three decades, there has been a diversification of bioenergy sources, with other forms gaining relevance (Figs. 3 and 4). This trend is particularly notable in Organisation for Economic Cooperation and Development (OECD) countries, as reported by the IEA [14].

The diversity of bioenergy sources (in solid, liquid or gaseous form) and available energy conversion technologies makes bioenergy very versatile. It is used to provide heat and power and as a transport fuel in a diversity of sectors of activity. Almost half of the biofuels and waste is used in the residential sector worldwide, but the industrial and energy sectors also consume a relevant share of biofuels and waste [14]. On the other hand, even though the transport sector represents a relatively small part of the world supply of biofuels and waste (7% in 2020 [14]), its relevance is also high since, presently, liquid biofuels dominate the renewable energy supply in this sector. Currently, these transportation fuels are essentially first-generation biofuels produced from food crops or vegetable oils [60].

Worldwide, the majority of solid biofuels, primarily consisting of forest biomass, are used in the residential sector (Fig. 5). However, the share of this sector has been

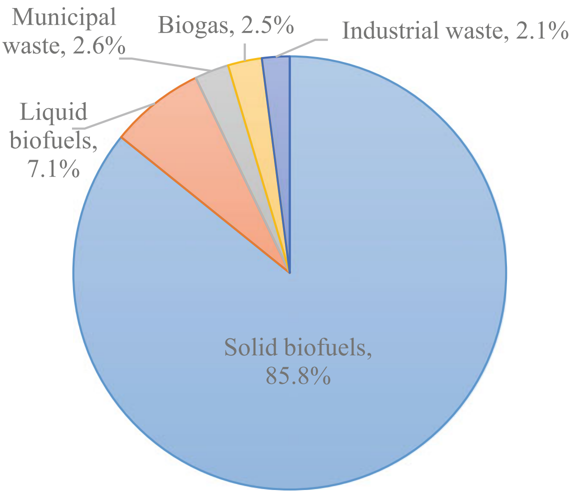


Fig. 3 Share of the various sources in the biomass and waste energy supply in 2020 in the world. (*Data source* [16])

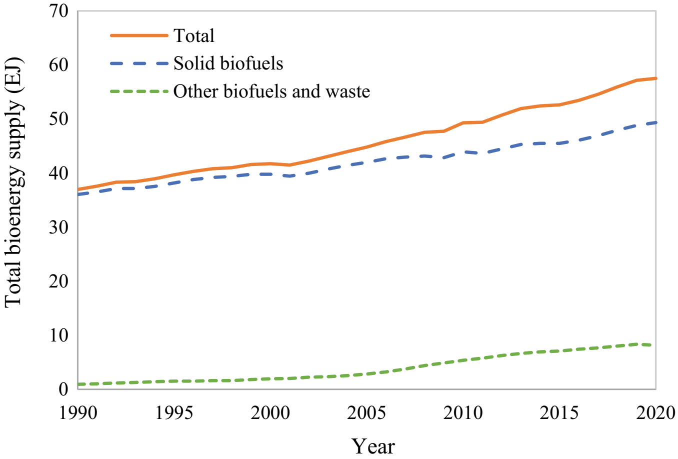


Fig. 4 World total bioenergy and waste supply from 1990 to 2020 by energy source. (*Data source* [14])

declining over the last few decades. In 1990, residential use represented 70% of solid biofuel consumption, but by 2020, it had decreased to 53%. In both years, the industrial sector was the second largest consumer of solid biofuels, followed by "other transformation", which includes charcoal production. The conversion of solid biomass into electricity in dedicated power plants has gained significance in the last 30 years. In 1990, it accounted for only 1% of solid biofuel consumption, but by 2020, it had increased to 8%. These power plants consumed around 70% more solid

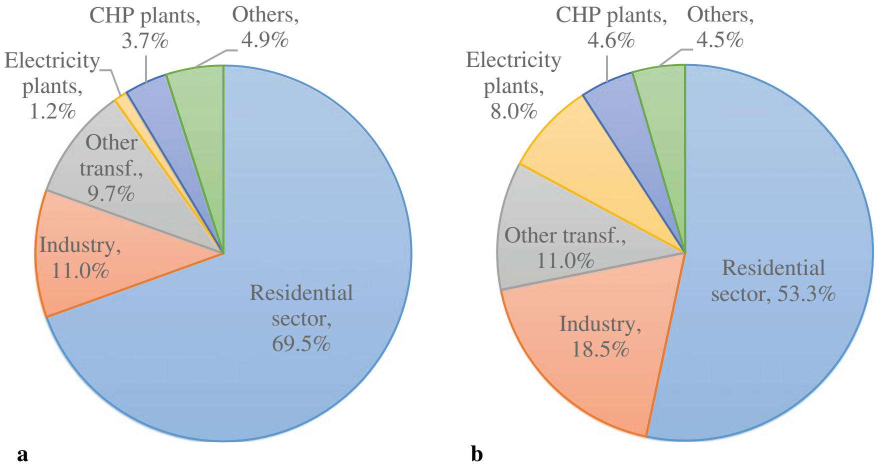


Fig. 5 Share of the various sectors in the consumption of solid biofuels in the world in **a** 1990 and **b** 2020. (*Data source* [14])

biomass in 2020 worldwide than the more efficient combined heat and power (CHP) plants. In the "others" category, the largest consumers of solid biofuels in 2020, in descending order, were commercial and public services, energy industry own use, agriculture and heat plants. In conclusion, to date, solid biofuels are mainly converted into heat and, to a lesser extent, electricity, while the production of transport biofuels from solid biomass is still not commercial and faces several challenges (*cf.* chapter "Forest Biomass as an Energy Resource").

In the group of OECD countries (Fig. 6), which accounted for 17% of the world solid biofuel use, the sector that consumed most of the solid biofuels in 2020 was industry (34%), closely followed by the residential sector (32%). As far as electricity production is concerned, CHP plants represent 15% of solid biofuel consumption, a higher share than the less efficient electricity-only plants (12%). Heat and charcoal production are included in the category "others".

3 Forest Biomass as an Energy Source

Of all the possible solid biofuel sources (e.g., firewood, forest residues, wood-based industry residues, post-consumer wood, agricultural residues, agro-industrial solid residues), forest biomass is, by far, the most used nowadays and, therefore, has a very important contribution to the world renewable energy share [61].

Forest trees, stands and forests are important to biomass (and carbon) sequestration and stocking [62] due to the longevity of trees [63], their large dimensions [64] and their worldwide distribution [65]. Stands and forests have provided for thousands of years a large set of products and services such as wood of several dimensions

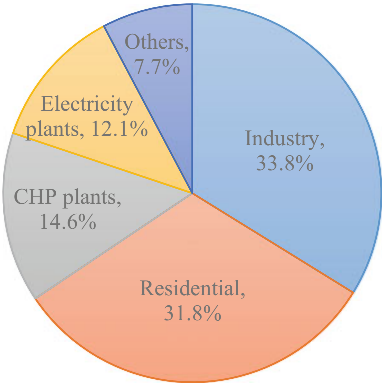


Fig. 6 Share of the various sectors in the consumption of solid biofuels in OECD countries in 2020. (*Data source* [14])

(including woody products for energy), protection of soil and water, conservation of flora, fauna and habitats, many non-woody products (e.g., honey, mushrooms, medicinal plants), aesthetics, recreation and biomass and carbon storage [66, 67].

Biomass sequestration and storage present high variability (*cf.* chapter "Sources and Distribution of Forest Biomass for Energy", Fig. 9). This results from the variability in species, stand structure and site (*cf.* chapter "Stand Structure and Biomass"). In general, biomass storage increases with age due to the increase in the dimension of trees [68], whereas sequestration decreases per unit of light intercepted due to the increase in respiration [35]. Thus, biomass and carbon sequestration are more efficient when trees are in the early stages of development, as growth rates are higher than in mature trees [36]. Yet, the biomass and carbon stocks are higher at late development stages due to tree dimensions [64]. The dynamics of biomass sequestration in stands and forests are more complex than those of individual trees due to their dependence on species, stand structure, site, silvicultural system and silvicultural practices (*cf.* chapter "Stand Structure and Biomass"). This variability is reflected in the biomass partitioning. In general, in forest stands, biomass can be broadly divided into tree and soil (organic matter). Tree biomass can be further divided into live (above and below ground) and dead (above and below ground) biomass [69].

Forest biomass for energy purposes results from harvesting. Yet, differences in biomass yields, amounts of biomass harvested and exported and the share of biomass that can be used for timber and energy vary per species, stand structure, silvicultural system, silvicultural practices, site, harvest equipment and market (e.g., [70, 71]). In terms of biomass for energy, forest systems can be broadly divided into two groups: energy plantations (*cf*. chapter "Energy Plantations"), where all above ground biomass is harvested for energy [72] and forest systems oriented for timber production or agroforestry systems, where forest residues from cuts, thinnings and/or prunings are used for energy [71, 73].

Energy plantations are intensively managed forest systems with the main goal of producing biomass for energy [72]. These forest systems use species or clones with high growth rates, thus high rates of biomass (and carbon) sequestration [74]; are frequently established in sites (soil and climate) near the optimum of the species traits in order to optimise their growth [72]; and are established in marginal lands or set aside agricultural lands in order to avoid competition with agricultural lands [75]. These forest systems give high yields, and are thus able to provide larger amounts of biomass per unit area and per time unit than the other forest systems [76] and release the pressure on other forest systems for bioenergy supply [77].

The main goals of forest systems oriented for timber production and agroforestry systems are the production of timber and other woody and non-woody products (e.g., cork, fruit, honey, medicinal plants) and services [78, 79], and forest residues may or may not be used for bioenergy [71, 73]. Forest residue quantities depend on several factors, such as the dimensions and quality of the woody products, forest system sustainability and harvesting. The dimensions of the woody products and their market prices constrain their use. In general, woody products of large dimensions and good quality are used for timber [80], which has a higher market price than forest residues [71].

The export of forest residues is related to the sustainability of the forest stands and their products. Forest residue exports always imply the export of biomass, carbon and nutrients and have impacts on hydrology and diversity [81]. Moreover, the sustainability of forest systems is related to the biomass storage/export ratio [82]. Forest residues are generated during harvest (cut, thinning and/or pruning). Their removal, apart from the sustainability of the forest systems, is related to stand structure, function, topography, site, harvesting equipment, logistics and costs [83]. In general, in stand structures (*cf.* chapter "Stand Structure and Biomass") that are more uniform and when the removal of wood is made mainly in one cut (pure even-aged stands under clearcut systems), the export of forest residues is facilitated due to their large amounts, higher recovery rates and lower costs than in stands with higher structural diversity (pure or mixed uneven-aged stands under selection or shelterwood systems and/or under protection or conservation status) [84–86]. Furthermore, site and topography may increase forest residue quantity, mainly due to damage during tree harvesting [83].

Restrictions to the collection of forest residues and subsequent energy use may exist, imposed, for example, by regulations in protected areas or difficulties in collecting biomass in areas with difficult accessibility (e.g., steep slopes) [87–90] or because of the dispersion of the residues in the stands. Additionally, losses in the collection, transport and use stages of the feedstock need to be considered [91–95]. Another issue that may reduce the availability of residual biomass for energy is the existence of other uses for biomass and, therefore, a competition between the same biomass resources [71, 80, 96–98]. The consideration of these restrictions and the conversion of feedstock mass to energy lead to the determination of the amount of available biomass energy, that is, the biomass energy content that is potentially available for energy production [71, 97, 99]. Several authors [100–105] also consider sustainability criteria for stands, forests and productions that constrict the available amount of biomass. Batidzirai et al. [106] reviewed the key factors and drivers affecting the determination of biomass availability for energy and analysed a selected set of country-based bioenergy potential studies. They conclude that generally not all the basic elements expected in an ideal bioenergy assessment are included in the analyses, that the methods used are not always harmonised, which leads to different energy potential results, and that studies have different levels of methodological transparency. It is recommended that the analyses include all key factors that are critical determinants of bioenergy potentials, employ high-resolution georeferenced data sets and account for potential feedback effects [106].

Biomass evaluation and monitoring have to be done in order to quantify woody products and forest residues. This evaluation is frequently done with mathematical models that vary in complexity and spatial and temporal scales (*cf.* chapters "Modelling Biomass" and "Overview of the Biomass Models"), usually with associated cartography.

The availability of forest biomass for energy has been estimated with mathematical models at both regional or local scales [87, 107–116] and national scales [96, 117–122]. Yet, the above ground biomass specificity, particularly in the tropics, makes accurate generalisations at regional or landscape levels difficult [123, 124]. Moreover, biomass is not static in space or time. Several disturbances, either management-related or natural (*cf.* chapter "Stand Structure and Biomass"), can cause the reduction of biomass. In a review, natural disturbances (drought, fire, wind and bark beetle) were evaluated for their effect on biomass dynamics [125]. Although forest systems are quite resilient to disturbances, climate change can drive the systems to their turning point, especially if the regime of disturbances is outside its historical range of variation. The maintenance of the resilience of the stands and forests then requires proactive and reactive adaptive measures in the management of the forest systems [125]. Another study refers to the losses of biomass due to windstorms [126], while another evaluated the effect of wind and bark beetle disturbances on carbon sequestration based on a landscape model [127]. According to the simulations, the forest areas will be a carbon sink until the end of the twenty-first century [127]. However, climate change might result in a change in the disturbance regime, which might lead to a reduction in the ability of the forests to sequester carbon, and thus turning them from a carbon sink to a carbon source [127].

The assessment of energy potentials is challenging. Two main reasons were identified to justify the variability in the results of several studies on energy potentials for the same geographical region [116]: (*i*) the various energy potential concepts subjacent to the analyses and (*ii*) the spatial variability of the data used for their estimation. Harmonisation of data can be used to overcome this variability. Scaramuzzino et al. [116] proposed a four-step harmonisation framework (Fig. 7): (1) identify the best-suited territorial unit, which should satisfy two conditions: (*i*) data must be reliable for the territorial unit or simple to calculate, and (*ii*) the territorial unit should be easily identified (e.g., NUT2, NUT3); (2) select the sources of renewable energy (e.g., forest residues, agricultural residues, livestock residues, waste) and review their potential (e.g., with data available from databases such as Eurostat, FAO and/or Copernicus Land Monitoring Service); (3) harmonise the indicators of the energy potential per unit area (e.g., $\mathrm{PJ \cdot km^{-2}}$, $\mathrm{PJ \cdot inhab^{-1}}$); (4) select and harmonise the non-energy territorial indicators due to the selected territorial unit (e.g., selection of topographic and climatic data and harmonisation with the median per territorial unit).

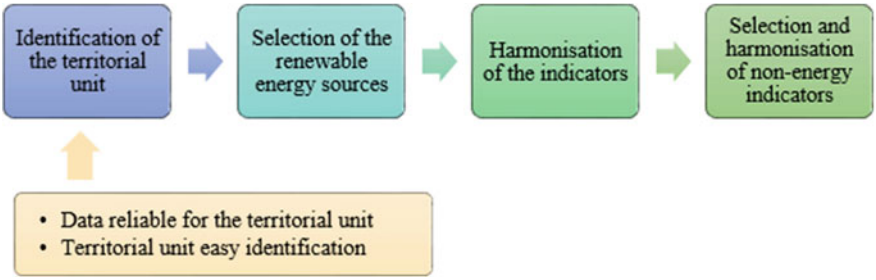


Fig. 7 Four-step harmonisation framework for energy potential assessment studies

The biomass evaluation and monitoring have been done, in particular for large areas, with geographical information systems (GIS) and with geographic decision support systems (DSS), resulting in the development of specific methodologies and techniques to identify and quantify the potential of biomass for energy purposes, namely for the installation of energy systems based on combustion [85, 114, 117, 128–135] or gasification [45, 132, 133, 136] or for the production of biofuels [135, 137–140]. The aforementioned methodologies were used to evaluate biomass in existing [84, 141–144] or potential [84, 87, 88, 112, 145, 146] forest areas, in both forests and farmland [114, 128, 131, 133] or specifically in forests for timber production and other products and services [87, 108, 117, 147]. Some studies were focused on evaluating the economic viability of implementing biomass systems [121, 128, 131, 146, 148].

When evaluating residual biomass, the residue production yields have to be known in order to relate them to the total available biomass (Fig. 8). These ratios, generally expressed in tonnes of residues per year and unit area, are dependent on species, stand structure and silvicultural operations and thus can have significant local and regional variation [87]. In some cases, they are expressed on an as-received basis, others on a dry basis [149, 150]. An alternative to explicitly reporting the residue production yields is to consider the percentage of the total mass of the tree that can be used for energy purposes [151].

Several maps of biomass have been produced [152–154]. The maps of biomass are dependent on the data input and the methods used. One important issue is the harmonisation of the input variables to reduce the uncertainties of the maps [152, 154]. The variability of the species, stand structure, site and management results in a wide variability in biomass. This may increase the errors. For example, Avitabile and Camia [152] reported, for Europe, a trend towards overestimation in forest areas with low biomass (<100 Mg·ha^{-1}) and underestimation for medium and high biomass (>100 Mg·ha^{-1}). Furthermore, the errors increased from national spatial resolutions (29–40%) to higher spatial resolutions, 58–67% [152]. Moreover, care should be taken when analysing maps as uncertainties related to site and management change forest stand dynamics, development and yield, both positively and negatively [155]. Thus, it is recommended that the maps of biomass be complemented with the quantification of the uncertainties [154].

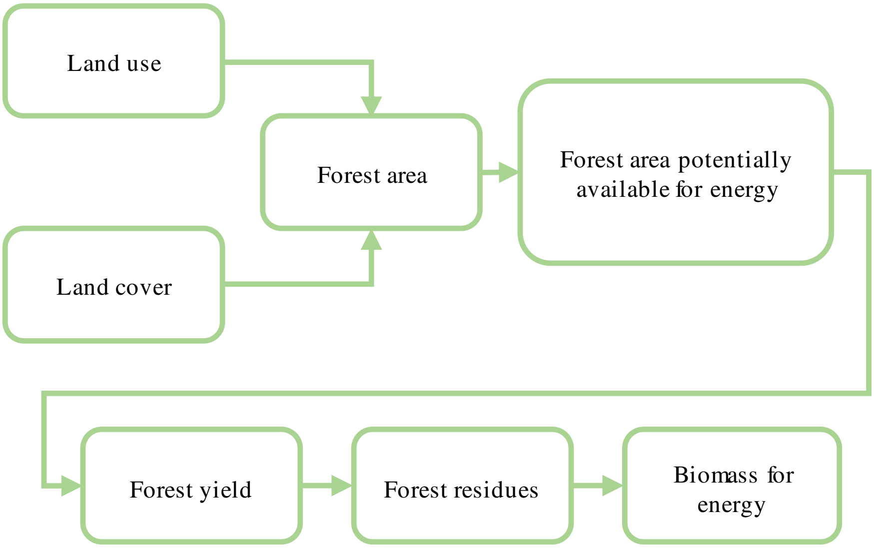


Fig. 8 Flowchart for the evaluation of the areas to produce forest biomass residues. (adapted from [87])

The determination of the areas for energy plantations (*cf*. chapter "Energy Plantations") should consider the following restrictions [146]: (*i*) guarantee food production; (*ii*) avoid losses of biodiversity; (*iii*) mitigate greenhouse gas emissions; (*iv*) minimise negative impacts on soils, water and air. This results in areas potentially available for energy plantations being those either set aside by agriculture or without suitability for agricultural crops, which are not under conservation or protection [146].

One issue related to biomass for energy is the identification of the areas available for energy plantations. These areas can be determined following a methodology in four steps [112]: (1) selection of the species to be used and assessment of their ecological and cultural characteristics; (2) determination of the suitability of the sites, which refers to the selection of a set of data, frequently in a geographical information systems environment, including soils, land morphology, climate, protected areas and administrative boundaries and a suite of assumptions and a subsequent set of operations that enable the identification of the areas where the selected species can be grown; (3) determination of the availability of land, which refers to the identification of the potential areas available, considering the existing restrictions, whether economic or social; (4) assignment of the land, which refers to the definition of a decision process that enables the determination of the areas where the energy plantations can be installed (Fig. 9). The areas identified are dependent on the initial assumptions made. If only the optimal conditions that could potentially generate higher yields are considered, the area estimation could be rather conservative [112].

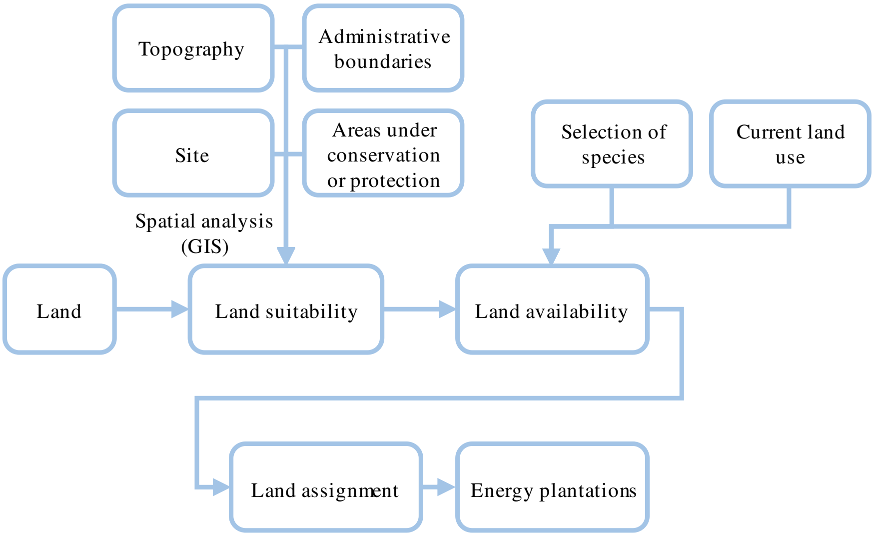


Fig. 9 Flowchart for the selection of areas to install energy plantations. (adapted from [112])

4 Outline of the Book Chapters

This book presents the state of the art of forest biomass production, assessment, characterisation and conversion into heat and power. After the overview presented in this chapter, in chapter "Sources and Distribution of Forest Biomass for Energy", forest biomass is defined and the different categories of forest biomass are characterised, starting with the forest biomass directly sourced from land use systems, passing through the residues of the wood-based industries and ending up in the residues and waste recovered from economic and social activities outside the forest sector.

Forest stands are communities of trees with competitive and facilitation interactions over a long timeframe. These interactions are dynamic in space and time and depend on stand structure, silvicultural systems and silvicultural practices, as well as species and site. In general, the biomass of a tree increases with age. Yet, the rate of biomass storage is dependent on the site (availability of growing space) and interactions between trees in a stand (competition *versus* facilitation). The dynamics of biomass at stand level are more complex to analyse as they are dependent not only on individual tree growth (and thus biomass storage) but also on the balance between live biomass and biomass exports. The intensity, frequency and quality of biomass exported influence the sustainability of the system. In chapter "Stand Structure and Biomass", definitions and concepts of silviculture that allow the analysis and discussion of biomass dynamics and stand sustainability are introduced. The stand structure, silvicultural systems, silvicultural practices, biomass partitioning and dynamics, forest system sustainability and biomass yields, harvest and exports are analysed.

Forest stands are the major sources of woody products, including biomass for energy. Energy plantations are forest stands designed to produce high quantities of biomass in short timeframes for bioenergy. These forest stands have the advantage, apart from producing large amounts of biomass for energy, of releasing the pressure on other forest stands to provide bioenergy. Chapter "Energy Plantations" characterises the energy plantations in terms of species, density, rotation, harvest cycles, site selection, management practices, harvesting and yields.

Biomass cannot be directly measured. The two basic methods for estimating biomass are the direct method, which is destructive, labour-intensive and expensive, and the indirect method, which uses mathematical functions. The use of models has the advantage of enabling the evaluation, monitoring and prediction of biomass in time and space. Yet, the models are dependent on species, site, tree biomass partitioning, stand structure and spatial and temporal scales. As a result, many models have been developed. Chapter "Modelling Biomass" reviews the data sets available for biomass modelling, the mathematical methods and techniques to fit the functions and the model uncertainties.

Modelling biomass is a challenge due to the variability of tree allometry and stand structure, which has resulted in a high number of biomass functions. At tree level, diameter at breast height and height are the most frequently used explanatory variables. However, due to the variability in tree allometry, other explanatory variables have been used, such as development stage, site or tree social status. At the area level, many explanatory variables have been used, derived from forest inventory, remote sensing and ancillary. Moreover, many mathematical models have been utilised to fit the biomass functions. There has been a constant search for models that are able to accommodate the variability of biomass. Chapter "Overview of the Biomass Models" reviews the biomass models at tree and area levels, according to the data used (destructive, forest inventory, remote sensing and ancillary) and mathematical methods and techniques (from parametric to non-parametric).

As far as the conversion of forest biomass to energy is concerned, in the last decades, the role of forest biomass for cooking and household heating has been losing importance and the energy uses of biomass have diversified. Today, different conversion technologies are commercially available or, if still in the research and development stage, considered promising. Chapter "Forest Biomass as an Energy Resource" presents an overview of the most relevant processing technologies for the conversion of forest biomass into energy and fuels, their applications and their readiness levels. Also important for the use and development of these technologies is the knowledge of the properties of biomass that are relevant for its conversion into energy and fuels. Chapter "Forest Biomass as an Energy Resource" provides an overview of the most relevant characteristics of forest biomass and reviews commonly used pre-treatment methods aimed at upgrading raw forest biomass into more suitable feedstocks for specific conversion technologies.

Chapter "Forest Biomass as an Energy Resource" is followed by three chapters that describe in more detail the most common uses of forest biomass for energy and the associated technologies. The first of these chapters, chapter "Biomass for Domestic Heat", is dedicated to residential heat production, which is where presently more solid biomass is consumed. Even though modern technologies should be promoted, the fact is that inefficient and polluting traditional technologies are still widely used, so chapter "Biomass for Domestic Heat" presents the available traditional technologies alongside the modern ones. The impacts of the traditional use of biomass are also reviewed, followed by the improvements to traditional technologies.

Chapter "Biomass for Industrial and District Heating" focuses on the sector that globally consumes more energy nowadays: the industrial sector. After a brief description of how energy is consumed by the industry, the most important technologies used to produce process heat, which is the industrial end-use that requires more energy, are described. Since the energy conversion technologies used in industrial facilities are similar to those used in district heating plants, the chapter also describes district heating systems and the role of biomass for this use.

Due to the relevance of process heat in industrial energy consumption, chapter "Biomass for Industrial and District Heating" only focuses on the production of heat. However, combined heat and power is also commonly generated in energy-intensive industrial facilities. CHP technologies are described in chapter "Biomass for Power Production and Cogeneration", which is dedicated to electricity production with forest biomass. After a general description of the power sector, chapter "Biomass for Power Production and Cogeneration" describes the technologies commonly used to produce electricity from forest biomass in dedicated biomass plants and in co-combustion plants.

The last chapter of this book, chapter "Conclusions and Future Research Needs", is dedicated to some conclusions and a description of possible future research.

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