Chapter 3

Solid Biomass from Forest Trees to Energy: A Review

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Additional information is available at the end of the chapter

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Abstract

Among the different terrestrial ecosystems, forests are the most important biomass carbon producers and the ones that store the most standing biomass carbon. Consequently, they are also the major source of biomass for energy. Forest biomass has been used as a fuel from early times, and from the late twentieth century onward, there has been a renewed interest in its use to produce heat and electricity. The interest in forest biomass as an energy source relates to some of its features, such as relative abundance and uniformity worldwide and neutrality of CO_2 emissions. Nonetheless, its use is not free of risks, mostly related with the sustainability of the forest systems and their productions. This study reviews the state of the art of the forest sources of biomass for energy, their assessment, their properties as a fuel, as well as the conversion technologies used in the most common energy applications.

Keywords: silviculture, estimation, remote sensing, conversion technologies, heat, power

1. Introduction

Energy has been obtained from forests for thousands of years, forests being the largest contributor to the current global biomass supply [1]. Most of today's production of solid biomass for energy occurs in non-Organization for Economic Cooperation and Development (OECD) countries (in 2015, 83.7%) [2] and is widely used for traditional cooking and residential heating. The traditional use of biomass is inefficient and characterized by severe negative impacts on human health by the combustion smoke [3]. Also, it has been linked to local deforestation and consequent environmental degradation, but the association of the demand of traditional wood for cooking and heating to large-scale deforestation is controversial [4, 5]. The modern uses of woody biomass are characterized by more efficient and cleaner technologies. Its utilization, though, is also linked to controversies as far as sustainability issues are concerned. In developed countries, the interest in bioenergy has been increasing mostly due to greenhouse gas mitigation policies. Wood biomass is a renewable energy source and considered to contribute to a decrease in the anthropogenic CO_2 emissions. This chapter reviews the forest structure (Section 2), the existing methods and techniques to evaluate biomass (Section 3), the types of biomass and biomass residues (Section 4), and the common uses of biomass for energy (Section 5).

2. Forest structure and biomass

The role of forests in providing a large suite of products and services is well known [6–9]. Due to the reduction of the forest area and shortage of woody products, as well as to guarantee the sustainability of forests and ecosystems, the need to evaluate, monitor, and regulate the forest arose [10–12]. Initially, the emphasis of assessment was on the quantity per class of woody products (mainly large- and small-dimension timber), typically with the evaluation of volume [6, 13, 14]. This drove forest stands toward predominantly pure, even-aged stands, either in high forest or in coppice regime, frequently centered in one production, also due to the simpler management [6, 7, 10, 13, 14]. Later in the twentieth century, the stand and forest management were expected to include objectives other than woody products, such as services, sustainability, and conservation of the forests and ecosystems [10, 11]. This originated a shift in forest management to new approaches focused on systems of multiple productions, which have driven silviculture toward uneven-aged and mixed stands. These approaches are focused in the natural processes emulation, which originated a wide suite of methods and techniques to achieve it [10, 15–17]. The overall biomass production, as a result of the management approaches, tends to be periodical in even-aged stands with large time periods between two consecutive harvests, while multiaged stands harvest periodicity tends to be in shorter time periods and rather constant, with a quantity function of the growth, target equilibrium, and proportions of the age classes of the stand [6, 7, 10, 13, 14, 17, 18]. Stand composition, both on the quantity, variety, and quality of biomass, also derives from the management strategy. In the traditional approach, silviculture was oriented toward pure stands, while the new ones are focused on mixed stands. The latter are systems with wider complexity and consequently more difficult to manage but are considered more biodiverse and resilient, and enable risk dispersion due to their multiple productions [6, 7, 10, 14, 18–20]. The challenge is defining and separating pure and mixed stands [21].

3. Forest biomass evaluation

Forest evaluation started with forest inventories in the Middle Ages, during wood shortage, with the aim of estimating the forest areas, stand composition, and wood volume per dimension class. The expectations, apart from wood, of forests to provide services resulted in the inclusion of a wide set of variables in the inventories, among which is biomass [22–25]; this intensified labor and increased costs [22, 24]. Forest inventories are defined by sampling design, for an assumed threshold error, which is accomplished in two sequential steps: (1) evaluation of forest area and crown cover with remote sensing [24, 26, 27] and (2) survey of field plots to measure several dendrometric variables, being the most frequent diameter at breast height and total height [22, 24, 28–30]. The evaluation on an area basis is done with extrapolation methods [22, 24]. From the 1990s of the last century onward, the development of remote sensing deployed the derivation of a set of functions to estimate several stand absolute density measures such as the number of trees, the basal area, the volume, and the biomass (*e.g.*, [31–36]). These functions enable the rationalization of forest inventory field work, facilitating also the evaluation of forest stands where field work is hard to accomplish [22, 24].

3.1. Forest inventory

Biomass was not traditionally assessed in the forest inventories. It was only from the late twentieth century onward that it was included, compelled by the need to evaluate carbon stocks, sequestration and losses, and biomass for bioenergy. The methods to evaluate biomass can be grouped in two broad classes [22, 24]: the direct methods and the indirect methods. The former, though very accurate, are destructive and frequently used to derive data sets for modeling. The latter are mathematical functions that use as explanatory variables dendrometric variables, frequently diameter at breast height and/or total height. These functions are frequently developed for each biomass component (stem, bark, leaves, branches, and crown), and total tree biomass is obtained by summing all the components. Similarly, biomass per plot is the sum of the biomass of all the trees, and normally referred to a standard area unit, typically the hectare. The functions are species-specific, site-specific, and regime-specific, due to the tree species habit and growth pattern per site and regeneration method (seed for high forest and vegetative for coppice). As a result, a wide range of functions is found in literature [37–45]. The advantage of these functions is their accuracy [27]. The shortcomings are related to the selection of the best function for the stand location, species, and stand structure [46, 47]. The choice might encompass some difficulties when no functions exist or those that exist are not adequate, thus resulting in large estimation bias [48]; and with the extrapolation methods in the evaluation of the forest areas [24], decreasing the accuracy with the increase of the area evaluated due to the variation in stand structure, topography, soil, and climate [49]. The estimation errors with this method are assumed to be between 15 and 40%, with the standard threshold of 25% [50].

3.2. Remote sensing

The major advantage of remote sensing is related to the wide range of working scales, associated with the spectral, spatial, radioactive, and temporal resolutions, as well as to their technology [51, 52], which allow the evaluation of the distribution of the forest area, species, and their physical and biochemical properties [53]. The advantages of biomass estimation with remote sensing methods when compared with those using forest inventory are: (1) can be applied regardless of the area dimension [26, 27], (2) does not need field work, therefore being interesting in areas where it is difficult to implement it or where many field plots are needed to attain the threshold error [24, 27]; (3) short time cycles can be used for data collection, contrary to forest inventory, where cycles shorter than 5–10 years are unfeasible [24, 26]; (4) different scales can be used as function of imagery spatial resolution [26, 27]; and (5) it applies to all the area, thus extrapolation methods are not required [32, 34–36].

The biomass functions that use satellite image data are mathematical functions that use data derived from satellite optical sensors for the explanatory variable [33], such as spectral reflectance, crown diameter, crown horizontal projection, crown cover, original bands and/or vegetation indices [32, 34–36, 54–58]. The statistical methods and techniques used to fit the functions are varied. Examples are linear and nonlinear regression, regression k-nearest neighbor, neural networks, regression tree, random forest, and support vector machine [27, 52]. Remote sensing data is derived from passive or active sensors.

For an optical sensor (passive sensor), the spatial resolution is the main distinctive feature of the satellite images and can be grouped in three broad classes: coarse, medium, and high. The *coarse spatial resolution* satellite imagery (>100 m) comprises: National Oceanic and Atmosphere Administration (NOAA) with the Advanced Very High Resolution Radiometer (AVHRR) sensor, Moderate Resolution Imaging Spectroradiometer (MODIS), and Satellite *Pour l'Observation de la Terre* (SPOT) Vegetation [55, 59–62]. The *medium spatial resolution* satellite imagery (10 to 100 m) includes Landsat, Sentinel, Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER), and Wide Field Sensors (WiFS) [55, 63–65], as well as recently Landsat 8 and Sentinel, free global-scale remote sensing data. The *high spatial resolution* satellite imagery consists of: IKONOS, QuickBird, WordView, and GeoEye satellites, with a pixel size smaller than 5 m [33–36, 66, 67].

The active sensors, Radio Detection and Ranging (RADAR) and Light Detection and Ranging (LiDAR), have gained relevance for biomass estimation in the last years [68–72]. The RADAR use microwaves to obtain information of surface target. It has the advantage of data acquisition being independent of the hour of the day and atmospheric conditions. More recently, the synthetic aperture radar (SAR) sensor, C-band RADARSAT-2, and X-band TerraSAR provide more accurate biomass estimation due to the spatial resolution variability, polarization, and incidence angles [73]. LiDAR systems allow to obtain detailed information about the structure of vegetation (horizontal and vertical tree dimension), considering the distances measured to the object surface [74, 75]. It can be supported by spaceborne, airborne, and terrestrial platforms that create a very precise 3D-point cloud data from vegetation [76] and are used to develop models for several vegetation biophysical parameters, such as tree height, crown dimensions, volume, and canopy density [52]. The statistical methods most frequently used to develop biomass functions are linear and multilinear regression [52] and machine learning algorithms [70, 71].

Some studies used a combination of LiDAR and multispectral or hyperspectral data to identify the different forest areas where the spectral response is similar, to improve the biomass estimation [77–81]. Related to the satellite spatial resolution is the target area of estimation, which can be at regional or local scales [32, 34–36, 82–86] or national scales [87–90]. However, some difficulties in the estimation of biomass with accuracy may arise due to the variability of the stands and forests, especially in the tropical forests [91, 92].

4. Forest biomass and forest residues

Forests are the terrestrial ecosystems that produce and store the most biomass, which explains why biomass for energy has been derived mainly from forests for a long time [8, 13, 14, 93, 94]. The forest biomass varies according to site, stand structure, topography, climate, management system, and disturbances [91, 95, 96]. The two features that make biomass a primordial source for energy are their availability and uniformity at a global level [8, 97, 98]; more recently, the neutrality in CO_2 emissions is also an important factor [97, 99].

In general, all forests produce biomass that is mainly removed in harvests, though in smaller quantities also in silvicultural operations (thinnings and prunings). Forests can be grouped in two broad types considering the biomass removal for energy purposes [95, 100]: energy plantations, where all biomass is harvested for energy and forest systems managed for timber and/or other products and services, where all or part of forest residues can be removed from the stands for energy purposes.

4.1. Energy plantations

Several terms have been used to describe the forest systems whose main, and frequently the only, production is biomass for energy [94, 101, 102] and that are characterized by specific spatial and temporal features [93, 99]. The most important features of these systems, when compared with agricultural crops or other forest systems, are their low risks, high economic viability, harvest flexibility, availability worldwide, biodiversity enhancement (especially if incorporated in agricultural crops portfolio), and the possibility of use for phytoremediation purposes [97, 100, 103–107]. The energy plantations are well represented in Europe, though to a lesser extent in the southern countries [103, 105], USA [108, 109], Canada [110], and China [111]. For the establishment of the energy plantations, the selection of species, density, rotation, harvest cycles, site, and management practices has to be considered.

The ***selection of species*** is of primordial importance. The species better suited for energy plantations are those that have high biomass production in dry weight, good sprouting ability, fast juvenile growth, narrow crowns or large-sized leaves in the upper crown, biomass with high specific energy and quality, adaptability to a wide range of sites, and resistance to biotic and abiotic agents [100, 112, 113]. Hybrids are frequently used to increase productivity, for their adaptation to the environmental conditions and resistance to pathogens [104, 114, 115]. From the many potential species suited for energy plantations, the three most referred in literature are: *Populus* spp. [101, 111, 112, 115–118], *Salix* spp. [101, 112, 114, 116, 118], and *Eucalyptus* spp. [97, 101, 112, 119, 120].

Density, ***rotation***, and ***harvest cycles*** are strictly linked, since the main goal of energy plantations is to attain the highest production in the shortest time (*e.g.*, [104, 116, 117]). Thus, three principles regulate density and rotation; namely the law of final constant yield, the development of social classes in a stand, and self-thinning law [93]. However, there is a large variability of densities from 1000 stems ha^{-1} to 310,000 stems ha^{-1} [99, 108, 114, 116, 118, 121, 122] and rotation lengths between 1 and 20 years [99, 108, 114, 116, 118, 121, 122]. Also, a dichotomy seems to exist between density and rotation [101], frequently higher densities and shorter rotations [104, 114, 115, 121, 122], or lower densities and longer rotations [97, 118–120]. Harvest cycles depend on stump mortality and ability to resprout and cutting cycles of 10 to 30 years are indicated in the literature [83, 99, 104, 117].

Site selection is directly related to survival, growth, and yield of the tree species or clones. To obtain high productivities, sites should be of good quality with long growing seasons [83, 100, 101], and steep slopes should be avoided when mechanization is foreseen [99, 101, 104]. Control of natural vegetation to reduce competition between spontaneous vegetation and energy plantations is better suited during site preparation [101, 104, 115], though it might also be necessary after each harvest [93, 104, 123].

Two main options are available for the ***selection of planting techniques***: plantation of cuttings or seedlings. While the former is use with *Salix* spp. [101, 104, 124–126], the latter is chosen for *Populus* spp. or *Eucalyptus* spp. [101, 124, 126]. Similarly, two approaches are available for management: the plantation with a cut after 1 year in order to promote coppicing or first harvest at the end of the rotation length [93, 104, 121, 122].

Other management practices include fertilization to promote yield [93, 101], though there is some controversy in the literature, with some authors stating that fertilization does not increase yield (*e.g.*, [124, 126, 127]), while others state the opposite (*e.g.*, [128, 129]). The control of pathogens should be primordially done by choosing resistant species or clones or by the increasing diversity (*e.g.*, [101, 130]) and, if this is not enough, with phytopharmaceuticals [93, 98, 101, 115]. Irrigation should be used when water stress and growth reduction are expected [93, 131, 132].

4.2. Stands managed for timber and other products and services

The main goal for stands managed for timber and other products and services is not biomass for energy. The latter is a secondary production, composed of residues, which are growing stock unused parts, such as tops, limbs, stems, stumps, and that result from harvest (cuttings or late thinnings) or silvicultural practices (noncommercial or early thinnings) [8, 133]. Regarding forest residues, two management options can be considered: their maintenance in the stand to preserve or improve stand productivity and site fertility or their removal when negative impacts are not expected [134–136]. The amount of forest residues depends on the species, stand structure, and stem quality, which generate a wide variability on their quantity (*e.g.*, [8, 89, 137]). Two constraints should be considered: the proportion of residues that is feasible to remove from a stand, which depends on its spatial distribution, 50% when scattered and 65% when stacked [8, 138]; and the distance between the stands and the places where it will be used, a 20–50 km radius is frequently used [8, 88, 137, 139].

Considering the different stand structures, the ones that potentially originate larger amounts of forest residues are even-aged, mixed managed stands, where some species are not well suited for timber or with timber of bad quality, and pure or mixed unmanaged stands, with high density, individuals of small diameter and bad timber quality [8]. Noteworthy are also the agroforestry systems, where the forest portfolio can include energy plantations [140, 141] and stands managed for timber and other nonwoody products and services from which forest residues can be obtained [140, 142–144]. The latter, frequently in rather small quantities, are mainly derived from thinnings and prunings but also from sanitary cuttings or trees that have reached the end of their lifetime cycle [142, 144, 145].

5. Uses of forest biomass for energy

One of the advantages of biomass over other renewable energy sources is its versatility. Biomass in general, and forest biomass in particular, can be converted into electricity, heat, or transportation fuels. In practice, though, forest biomass is mainly used for heat and electricity production. The transformation of forest biomass into biofuels that can be used in the transport sector still faces various challenges, which have hindered its commercialization [146, 147].

5.1. Current status

Despite its advantages and despite being the most used renewable energy source, the current share of bioenergy in the world is still very limited. In 2015, bioenergy and renewable wastes accounted for 9.4% of the world's energy supply [2]. Among the various biomass sources, solid biofuels accounted for 63.7% of the global renewables supply (liquid biofuels, biogas, and renewable municipal waste accounted respectively for 4.3, 1.7, and 0.9% and the other renewable energy sources for the rest) [2]. In OECD countries, where biomass is mostly used in modern systems, the share of biomass and renewable wastes is even lower, with these fuels accounting for 5.2% of the total primary energy supply in 2015 and solid biomass accounting for 36.1% of the renewable energy supply [2].

Solid biofuels, which are almost entirely composed of wood, wood residues, and wood fuels, are used to produce electricity and heat. Direct heat is by far the most common application of solid biomass. In this case, biomass is used directly by the end users (*e.g.*, residential, industrial, commercial, agriculture) and not by the energy transformation sector (*e.g.*, power plants, combined heat and power (CHP) plants or heating plants). The dominance of the use of solid biomass for heating applications is mostly justified by its traditional use in the African and Asian countries for heating and cooking [1].

Looking at the situation in Europe, where biomass is mostly used in a modern way, the utilization of solid biomass by the energy transformation sector has a bigger prevalence. Power plants for the production of electricity have a 9% share, CHP plants both for the production of electricity and heat 16% and district heating plants 5% [148]. In total, the European energy transformation sector accounts for 30% of the solid biomass consumption, contrasting with the world average, which is around 9%.

5.2. Feedstock characterization

Biomass for energy uses comes from various sources. Generically, it can be divided into forest, agricultural, and residual biomass. From these three categories, biomass from forestry is by far the most significant source of biomass for energy production. In 2014, it generated more than 87% of the world biomass feedstock, while agriculture contributed with 10% and municipal solid wastes and landfill gas with 3% [1].

	Eucalyptus wood	Poplar wood	Willow wood	Beech wood	Bark (pine)	Wood chips (pine)	Pellets (wood)
Proximate Analysis (wt% dry)							
Fixed carbon	18.80	13.05	13.73	14.53	26.60	19.40	12.65
Volatile matter	80.40	80.99	73.18	84.87	71.80	80.00	83.64
Ash	0.80	1.16	1.68	0.60	1.60	0.60	3.71
Ultimate Analysis (wt% dry)							
Carbon	51.20	47.05	43.06	49.38	53.90	51.80	49.12
Hydrogen	6.00	5.71	5.49	6.17	5.80	6.10	7.82
Oxygen	41.69	41.00	38.36	43.55	38.26	41.19	38.77
Nitrogen	0.20	0.22	0.44	0.28	0.40	0.30	0.56
Sulfur	0.02	0.05	0.00	0.01	0.03	0.01	0.02
Moisture content (wt%, on wet base, as received)	4.00	4.80	11.40	15.20	5.00	3.87	4.70
LHV (MJ kg^{-1}) (dry)	18.50	18.19	18.05	17.97	20.10	19.56	17.42

Table 1. Forest biomass fuel properties [153].

Biomass from the forest sector (*e.g.*, fuelwood, forest residues, and wood industry residues) is mostly used as raw material and not subjected to an upgrading process. However, the use of upgraded biomass has been gaining importance and, for example, pellets are one of the fastest growing bioenergy carriers [1]. Some advantages of upgraded forest biomass over raw biomass are the fact that it is more uniform and convenient to use and especially well suited when biomass is consumed in a place far away from its production site. As a disadvantage it has a higher cost compared to the correspondent raw biomass fuel [149].

The most relevant properties in terms of energy conversion for some forest biomass fuels are presented in **Table 1**. Due to the variability for a specific species, they should be considered as illustrative. Untreated wood is characterized by low carbon content and high volatile matter and oxygen contents when compared to solid fossil fuels. This leads to the lower heating values of wood, which in combination with its low density results in low values of energy density. The lower heating value of oven-dry wood of different species does not have a large variation [150]. However, in practice, in many applications wood is not oven-dried and contains a certain amount of water. Typically, fresh timber has a moisture content between 50 and 60%, while timber stored for a summer and for several years have, respectively, 23–35% and 15–25% water content [150]. The lower heating value of wood fuels is very dependent on the water content of the fuel. The more water content the wood has, the lower is its energy content. The ash content of wood is typically low [151], but it can be significantly higher in bark [152]. Additionally, the harvesting process can introduce inorganic materials in the feedstock.

5.3. Conversion technologies

Combustion is by far the most common way of converting forest biomass into energy [154]. It is performed in batch or continuous systems, depending on the scale, and to produce heat, power, or combined heat and power. The focus of this chapter is not on the traditional equipment to burn wood, but a review can be found, for example, in Ref. [155].

5.3.1. Heating applications

Depending of the scale, different combustion equipment can be used. In Europe, most of the biomass is burned in small-size units for ***household heating***, whose scale is typically of the order of a few kW_{th}. Equipment such as stoves, fireplaces, furnaces, and boilers are used to produce heat (a description can be found in [156, 157]). The most common fuels are firewood, wood pellets, and wood chips. The conversion efficiencies depend on the equipment. The traditional open fireplaces have efficiencies lower than 20% [158] and should not be considered a heating solution. At the high end of the range, wood pellet boilers can achieve efficiencies of more than 90% [159]. The scale of nondomestic applications is very variable and can go up to several MW_{th}. Heat can be produced in main activity heating plants or in industrial facilities. It is in Europe that most ***district heating*** is used [160]. Most of the biomass heat sold by the European energy sector comes from CHP plants. Biomass heat-only plants are important in small-scale district heating systems [161]. The combustion technologies used in district heating power plants are mainly fixed bed, bubbling fluidized bed, and circulating fluidized bed furnaces (a description can be found in [157, 162, 163]). Fixed-bed boilers are less efficient (60–90%) than fluidized bed boilers (75–92%) [164]; they present lower costs and are typically used for smaller capacities than fluidized bed boilers [157]. Heat distribution losses have to be taken into account to know the overall efficiency of district heating. Several parameters affect heat losses, such as linear heat density, pipe diameter, or temperature level [165]. In the industrial sector, ***process heat*** is typically generated by boilers, dryers, kilns, furnaces, and stoves. Wood and wood-upgraded fuels (*e.g.*, torrefied pellets and charcoal) can be burned to provide the broad spectrum of temperatures required by the industries [166]. For low and medium temperature process heat, mainly boilers are used, while for high temperature process heat, direct heat is supplied [167]. The equipment used for direct heating is very diversified and dependent on the process itself. For example, Ref. [168] and Ref. [169] describe the equipment used in the iron and steel industry, while Ref. [170] in the cement, lime, and magnesium oxide industries. The combustion technologies used for indirect process heating are similar to the ones used in district heating. The industries that use biomass for process heat generation are mainly those that generate biomass residues (*e.g.*, pulp and paper and the wood and wood products industries). An example of a sector that does not produce biomass residues but uses solid biomass for the partial substitution of fossil fuels is the cement industry [171].

5.3.2. Power applications

The primary combustion technologies used in biomass-fired power plants are similar to that of district heating and industrial plants with indirect heating applications: fixed and fluidized bed boilers. Additionally, pulverized combustion is also used; it is used as well in industrial applications, but not so commonly [157]. Pulverized biomass-fired boilers are very efficient but require a considerable amount of fuel pretreatment [172] when the biomass is not already generated in fine particles (*e.g.*, in sawmills or cork industry). As far as secondary technologies are concerned, today biomass-fired power plants are mostly based on steam turbines [173]. The electrical efficiencies of these plants depend on the size of the power plant and tend to be within the range of 18–33% (for installed capacities of 10 to 50 MW_e, respectively) [174]. Higher efficiencies in larger systems have been reported in the literature [172]. The size of biomass power plants is typically much smaller than that of fossil fuel power plants due to the restricted availability of local biomass sources and transport costs. Co-firing of wood and coal is a strategy to reduce greenhouse gas emissions, improving the overall efficiency of power plant with no need for a continuous supply of biomass [175]. It enables the advantages of the larger coal-fired power plants, while partially using a renewable energy source. Gasification of forest biomass into syngas followed by combustion of the syngas is an interesting alternative to combustion only systems, which offers higher efficiencies especially for smaller capacity power plants [176]. The most mature technology is gasification coupled with an internal combustion engine [177]. They are used in smaller systems than steam turbines [178].

5.3.3. CHP applications

Combined heat and power is the simultaneous generation of electricity and useful heat. It is a much more efficient way to burn forest biomass than biomass-fired power plants, since the overall efficiencies of CHP plants is much higher (global efficiencies above 85% can be achieved [179]). CHP biomass systems have an important application in industries that generate wood residues, such as the pulp and paper and wood industries [180, 181]. The other important CHP application is district heating plants [160]. CHP power plants for capacities above 2 MW_e are dominated by burning biomass in steam turbines (Rankine cycle) [182]. Steam turbines are a mature technology and applied in a wide range of powers. However, in small decentralized plants their electrical efficiency is low [159]. In this case, CHP plants should be operated in a heat-controlled mode with low power-to-heat ratios [159]. For systems smaller than 2 MW_e, the biomass CHP conversion technologies are not so well established [182]. In this power range, one of the commercial technologies available is the organic Rankine cycle (ORC). Its electric efficiency is relatively low, but the investment and maintenance costs are lower than that of the conventional Rankine cycles [183]. Another commercially available technology for small capacities is the steam piston engine [159]. Its nominal efficiency is comparable to that of steam turbines, having in efficiency little variation at partial load, contrary to steam turbines that have low part-load efficiencies [159]. Stirling engines are not commercially available yet [184]. They are a promising technology suitable for CHP plants below 100 kW_e and achieve relatively high electrical efficiencies [182]. From all the commercially available technologies for sizes below 2 MW_e, gasification is the one that presents higher efficiencies [182].

6. Conclusions

The primordial source of biomass for energy is derived from stands and forests. Due to the wide range of stand structures, the amounts of biomass available for energy are also quite variable. Higher quantities per unit area are attained in energy plantations. Pure or mixed even-aged high forests managed for timber potentially originate larger amounts of forest residues when compared with the other types of stands. The renewed interest of biomass as a source of energy brought about the challenge of its estimation. Remote sensing is a useful tool that enables a more cost-efficient evaluation and monitoring when compared with the forest inventory approach. Forest biomass is a very versatile renewable energy source, yet its share on the world energy supply is relatively small. It is mainly converted to energy in combustion systems used for heat generation, but CHP and electricity production are also common. For most applications, the use of raw biomass is adequate, but it might be necessary and/or more appropriate to upgrade it.

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Conflict of interest

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