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Using Timber as a Renewable Resource for Energy Production in Sustainable Forest Management

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Abstract: Using timber from multifunctional forests for energy production can be economically viable and environmentally friendly when it is consistent with the principles of sustainable management; otherwise, it could be harmful from both an ecological and commercial point of view. The objective of this paper was to present the overall balance of timber biomass from felled trees in multifunctional forests and assess what kind and how much of this biomass can be used for energy purposes. The research material consisted of data on forest resources and the volume of timber removal in Polish State Forests in 2016–2020. The biomass of branches and stumps of felled trees was determined using biomass expansion factors (BEFs). The results obtained in this study indicated that industrial timber, energy wood, and biomass left in the forest as a source of deadwood are 67%, 20%, and 13% of the total woody biomass, respectively. The Polish State Forest's potential for energy wood is estimated at 6.18 million tonnes of biomass annually. Total available energy produced from woody biomass amounted to 104.8 PJ y^{-1}.

Keywords: energy wood; renewable energy; woody biomass; logging residues; retention trees

1. Introduction

Climate change requires increased efforts to reduce greenhouse gases from energy production. One way to reduce carbon dioxide emissions is to replace fossil fuels with renewable energy sources. Consumers increasingly want clean, renewable, and affordable energy from wind, solar, geothermal, hydroelectric, and biomass sources [1]. Biomass for bioenergy feedstocks comes from the following sources: forest residues and industrial wood waste, agricultural crop residues, animal manure, energy crops and woody crops, and municipal solid waste [2].

Using biomass of different origins for energy production is often discussed in the literature. Meerbeek et al. [3] explored the biomass potential for bioenergy in the landscape beyond forests and agricultural land: gardens, roadsides, sports fields, conservation areas, etc., and stated that a large amount of biomass that is created by their regular management should not be considered as waste, but as a sustainable bioenergy resource. Wicke et al. [4] quantified the bioenergy potential from intensifying grasslands in Europe. The production potential of straw harvested over agricultural consumption in Poland and its use for energy purposes were evaluated by Gradziuk et al. [5]. Suardi et al. [6,7] pointed out that pruning residues from olive groves represent an important biomass source.

Wood biomass is particularly suitable for energy production due to its high calorific value and relatively low ash content [8]. Optimizations for different environmental indicators suggest that woody biomass is best used for combined heat and power generation if oil-, coal-, or fuel oil-based technologies can be substituted. The benefits of its conversion to synthetic natural gas (SNG) or ethanol are significantly lower [9–11]. One way to increase woody biomass sources is through the cascaded use of wood [12–14]. Höglmeier et al. [15]

pointed out that wood, as a renewable, but limited and increasingly in demand resource, can be used in cascades, thereby increasing the potential efficiency per wood unit. Waste wood can be used as a secondary raw material for energetic utilization. The idea of reuse is embedded in the legal framework, which follows the EU regulation [16]. An essential source of woody biomass is especially established for this purpose in plantations of fast-growing trees, allowing producing a significant amount of biomass. Species such as eucalyptus [17], poplar [18], black locust [19], willow [20], and birch [21] are characterized by a high production of wood per unit area in short cycles and are often used in such plantations.

The primary source of woody biomass is wood from forests, but unlike plantations, the amount of biomass harvested from forests is limited and should be consistent with sustainable forest management. Some of the wood, usually of the lowest quality, is used for energy purposes and is referred to as energy wood. According to Directive 2018/2001 of the European Parliament and of the Council of the European Union of 11 December 2018 on the promotion of the use of renewable energy sources [22], energy wood is defined as raw wood material that, due to its qualitative-dimensional and physical–chemical characteristics, has a reduced technical utility value, preventing its industrial use. A significant source of biomass that can be used for energy purposes is logging residues. The current use of forest residues for commercial and household energy production is small relative to the availability [23–31]. Model simulations show that, with current strategies, timber overproduction will further increase in the Twenty-First Century, increasing the potential amount of biomass available for energy use [32–34].

Traditionally, measuring wood in a forest is performed in volume, often indicating its use (veneer log, sawlog, pulpwood). However, increased interest in the role of biomass of the whole tree and its components (roots, stem, branches, foliage) has led to the development of methods to determine woody biomass in the weight dimension. One of such methods is based on the use of coefficients called biomass expansion factors (BEFs), which allow determining the dry biomass of individual tree components (roots, foliage, branches) based on the tree stem volume. BEF values for particular species and tree components are commonly used to report the amount of carbon sequestration in forest ecosystems [35,36].

In tree plantations with a dominant economic function, most biomass components are removed from a forest area at the end of the production cycle [37]. This is related both to maximizing the financial return (commercial use of biomass) and to the management practices used, in which stumps and branches are removed during the preparation of the area for replanting. In multifunctional forests, the use of biomass should balance economic, social, and ecological functions. Part of the biomass of whole trees (retention trees) and their components (roots, stumps, branches) is left in the forest ecosystem as a source of deadwood and improvement of nutrient flows.

The objective of this paper was to present the overall balance of timber biomass from felled trees in multifunctional forests and assess what kind and how much of this biomass can be used for energy purposes. The paper is organized as follows. First, the concept of determining the residues' biomass using the biomass expansion factor is introduced. Then, the hierarchical system of using woody biomass according to sustainable principles is presented. Finally, the obtained results are discussed with the literature, and some concluding remarks are made.

2. Materials and Methods

2.1. Data

The study material consisted of data about the volume of timber, according to the species and assortments harvested by the Polish State Forests (PSF) in 2016–2020 (Table 1). Data taken for the calculation included 177.3 million m^3 of timber harvested in 5 y, of which softwood and hardwood account for 81% and 19%, respectively [38]. General information about forest resources and the indices of sustainable management in PSF in the years 2016–2020 [39] are given in Table 2.

Table 1. The timber volume harvested annually in Polish State Forests as an average from the period 2016–2020 (in thousand m^3 out of bark).

Species	WB1	W0	S2B	S2A	S2AP	S4	Total
Pine	69.22	10,754.60	3026.92	9405.52	830.22	1110.00	25,196.48
Spruce	0.00	1936.82	176.60	2008.94	526.44	305.00	4953.80
Oak	0.00	547.26	140.72	794.32	178.38	350.00	2010.68
Beech	40.04	1018.78	40.16	928.66	161.88	450.00	2639.52
Birch	93.70	347.24	104.68	1474.60	141.68	720.00	2881.90
Alder	55.24	146.30	42.26	418.82	58.80	209.00	930.42
Total	258.20	14,751.00	3531.34	15,030.86	1897.40	3144.00	38,612.80

WB1—veneer; W0—saw wood; S2B—stacked wood for mechanical processing; S2A—pulpwood; S2AP—low-quality wood; S4—firewood.

Table 2. Characteristics of forest resources in Polish State Forests in the years 2016–2020.

	Per Total Area	Per 1 ha
Total area (ha)	7.11×10^6	-
Standing volume * (m^3)	2.07×10^9	290
Volume increment (m^3)	6.56×10^7	9.21
Removal (m^3)	4.96×10^7	6.96
Dead wood (m^3)	6.14×10^7	8.63

* gross timber volume under the bark.

2.2. Calculations

Shares of particular assortments were calculated as the timber volume from the last five years divided by the total volume of industrial timber harvested in State Forests in 2016–2020. Estimates of total tree biomass were obtained by expanding the stem volume to total biomass with conversion factors called biomass expansion factors (BEFs) [40]. Stand-level BEFs allowed converting stem volume directly to the dry weight of biomass components. In this study, we used BEFs for pine, spruce, and birch developed by Lehtonen et al. [41] and for oak developed by Krejza et al. [42]. The biomass of branches and stumps of felled trees were calculated according to the following formula [41]:

$$W_{i,\,j} = BEF_{i,j} \cdot V_j \tag{1}$$

where: $W_{i,j}$—dry weight (kg) of tree component i (branches, stump) of species j, $BEF_{i,j}$—basal expansion factor (kg m^{-3}) for tree component i of species j, and V_j—stem volume (m^3) of species j.

The volume of industrial timber assortments in m^3 was converted to dry biomass in tonnes multiplying the volume of the assortment by the wood density factor of a given species [43]. The amount of energy possible to obtain from individual components of biomass ($E_{s,j}$) was determined according to the formula:

$$E_{s,\,j} = W_{s,j} \cdot \gamma_{i,j} \tag{2}$$

where: $W_{s,j}$—dry biomass (kg) of assortment s and tree species j and $\gamma_{s,j}$—timber calorific value (MJ kg^{-1}) of tree species j and assortment s.

The net calorific value of timber in an air-dried state was taken from [44]: 17.2 MJ kg^{-1} and 16.6 MJ kg^{-1} for softwood and hardwood, respectively.

3. Results

The amount of residues and stumps of the biomass of felled trees is shown in Table 3. With an average stem volume of harvested trees at the level of 38.61 million m^3 (24.52 million tons of dry biomass), the dry biomass of branches and stumps was 3.52 million tonnes and 1.84 million tonnes, respectively.

Table 3. The biomass of branches and stumps of trees felled annually in Polish State Forests.

Species	Volume (m³)	Biomass (Tonnes)	
		Branches	Stumps
Pine	2.52×10^7	2.04×10^6	1.19×10^6
Spruce	4.95×10^6	4.92×10^5	2.42×10^5
Oak	2.01×10^6	2.51×10^5	9.65×10^4
Beech	2.64×10^6	3.30×10^5	1.27×10^5
Birch	2.88×10^6	3.07×10^5	1.38×10^5
Alder	9.30×10^5	9.90×10^4	4.47×10^4
Total	3.86×10^7	3.52×10^6	1.84×10^6

The balance of woody biomass and hierarchical use of the particular biomass components according to economic and ecological sustainable principles is presented in Figure 1.
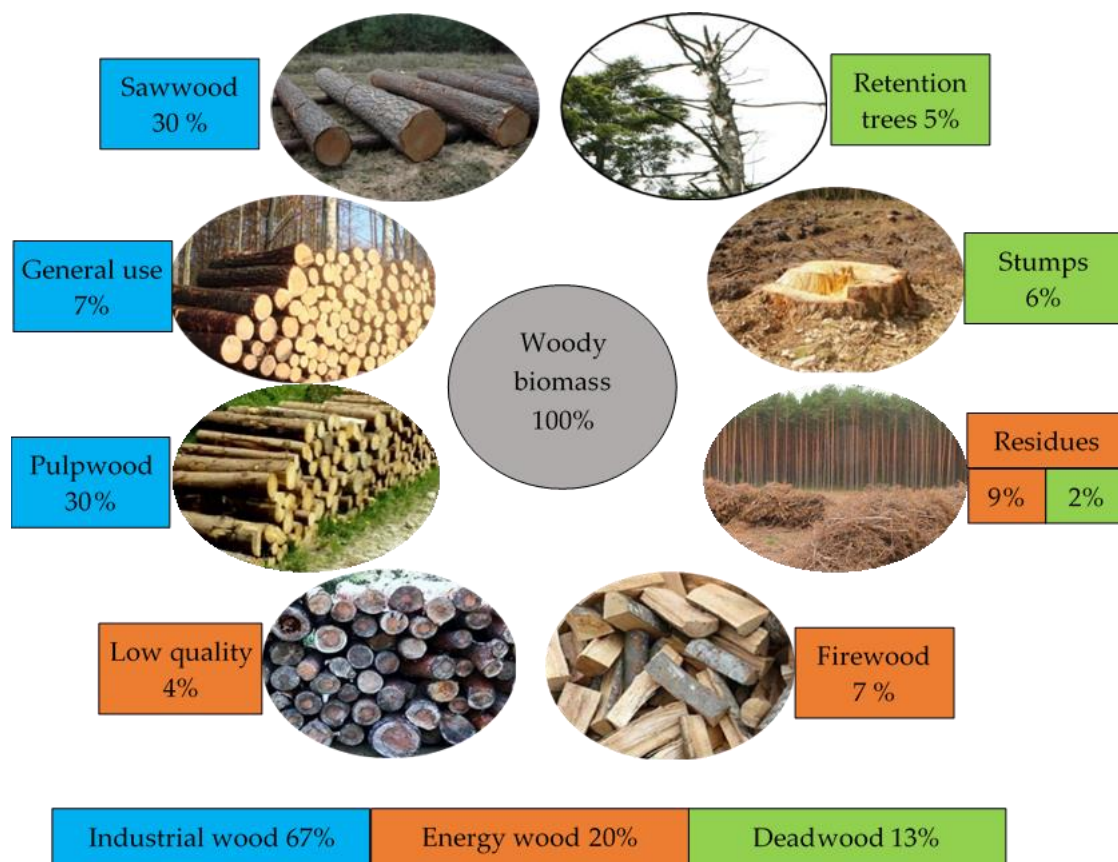
Figure 1. The balance and hierarchical use of the woody biomass according to economic and ecological principles.

The total biomass of trees designated to be harvested consists of three main groups: industrial wood (blue in Figure 1), energy wood (red), and ecology wood (green), which represent: 67%, 20%, and 13%, respectively. We can remove the first and second groups (87%), whereas the third group (13%) should remain in the forest as a source of deadwood. Industrial wood consists of large-sized wood (veneer and saw wood 30%), medium-sized wood for mechanical processing (7%), and pulpwood 30%. According to the cascaded use of wood, these groups of assortments, due to their use in the furniture industry, construction, paper, and other wood products, are not and should not be used for energy purposes. According to the cascaded use of wood, high-quality timber should be first used for sawn wood; after that, it could be re-utilized for wood-based panels, and then, waste panels can be combusted for energy recovery. Recycled wood is not included in the woody biomass

balance presented here; this would require a life cycle assessment of the individual wood products and is beyond the scope of the presented work. Low-quality wood constitutes 4% of the total biomass and, depending on demand, can be used as energy wood or for particleboard production. Fuelwood accounts for 7% of biomass and is entirely destined for energy purposes, mainly used as firewood in local households. Residues account for 11% of the total biomass, of which 80% can be used for energy purposes, while 20% should remain in the forest.

The potential of energy availability from woody biomass is presented in Table 4. The total energy of the biomass source consists of low-quality wood, firewood, and residues with shares: 20%, 34%, and 46%, respectively. The Polish State Forests' potential for energy-wood was estimated at 6.18 million tonnes of dry woody biomass yearly, giving an average of 0.87 tonnes of biomass per 1 ha of forest. Therefore, the total available energy from woody biomass amounted to 104.8 PJ yearly. This figure shows the approximate amount of energy stored in woody biomass. Estimating the amount of energy that can be delivered to the users should consider the energy inputs incurred in producing, harvesting, and transporting the biomass [45,46]. However, presenting an energy balance of woody biomass is beyond the scope of this paper.

Table 4. Energy available yearly from wood biomass in State Forests in Poland.

	Biomass (Thousand Tonnes)			Energy Available (PJ y^{-1})			
	Low-Quality Wood	Firewood	Residues	Low-Quality Wood	Firewood	Residues	Total
Softwood	814.00	849.00	2026.26	14.00	14.60	34.85	63.46
Hardwood	419.53	1283.85	789.15	6.96	21.31	13.10	41.38
Total	1233.53	2132.85	2815.41	20.96	35.91	47.95	104.83

4. Discussion

The possibilities of using woody biomass from multifunctional forests for energy purposes were analyzed in this study. The starting point was determining the allowable level of tree felling according to sustainable forest management criteria. The total volume of felled trees in the amount of 38 million m^3 yearly represents 70% of the annual volume increment in Polish State Forests [47]. The utilization on a similar level in the last five years increased the standing volume by 88 million m^3. Lippke et al. [48] emphasized that forests managed for wood production are considered sustainable if the harvests are planned not to remove more timber than is grown (i.e., the forest inventory is not declining over time). Furthermore, forests managed for sustainable multiple ecosystem values would attempt to include a sustainable balance between ecosystem values, timber outputs, and economic or social values.

The results obtained in this study indicate that industrial timber, energy wood, and biomass left in the forest as a source of deadwood are 67%, 20%, and 13% of the total woody biomass, respectively. Similar results were obtained by Šafařík et al. [49], who analyzed the potential of forest biomass resources for renewable energy production in the Czech Republic, not considering the biomass of stumps. They stated that the share of industrial wood, fuelwood, and logging residues was estimated: at 74%, 14%, and 12%, respectively, and indicated that for energy, 26% of removed biomass is dedicated (fuelwood and logging residues). The results obtained in our study showed that for energy purposes, 23% of removed woody biomass (low-quality wood, firewood, and four-fifths of residues) could be used. According to the principles of forest silviculture [50], 5% of the tree volume in stands scheduled for final cutting should remain in a stand as retention trees. Stumps of felled trees constituted a significant part of total biomass (6%) and also should remain in the forest (partly because of the high energy consumption and destructive influence on the soil when harvested). Leaving some parts (20%) of the residues in the forest is intended to improve the ecological conditions.

Karjalainen et al. [51] analyzed energy wood potential in Europe and estimated yearly harvestable residues to be 63 million m^3 and about 9 million m^3 of stump wood for energy production. Kärkkäinen et al. [52] studied the relationships between energy timber production, wood removal, and biological diversity in North Karelia (Finland). They stated that a moderate amount of woody chips and firewood could be harvested without negatively impacting timber production's potential or biological diversity. Dupuis et al. [53] analyzed the bioenergy conversion potential of decaying hardwoods and stated that biomass from decayed trees for bioenergy production should not alter the conversion efficiency and, hence, support their use as feedstock for bioenergy production. However, removing decaying trees is not recommended in multifunctional forests as this kind of biomass (deadwood) plays an essential ecological role in forest ecosystems.

Winder and Bobar [16] pointed out that the principal use of timber from boreal and temperate forests should be evaluated from a holistic perspective, i.e., it needs to include forest carbon flows related to forest management. They stressed that a scenario where timber is used for 100% energy production is economically unlikely and may create a significant carbon change, whereas multiple end-uses are financially feasible and typically achieve far better overall greenhouse gas (GHG) emission reductions. Smeets and Faaij [34] evaluated the global energy production potential of woody biomass from forestry for 2050. They stated that forests can become a significant source of bioenergy and that the use of this bioenergy can be realized without endangering the supply of industrial wood and firewood without further deforestation. However, regional shortages in the supply of industrial timber and wood fuel can occur in some regions, e.g., the Middle East and South Asia.

The production of woody biomass and its transport requires some energy input. Energy balance in integrated commercial timber production (saw wood and pulpwood) and energy wood (small dimensions wood and logging residues) was calculated by Routa et al. The analyses considered energy inputs during the whole production cycle and harvesting and transport. The results obtained indicated that the primary energy use incurred during the entire production cycle is relatively small (less than 3%) compared to the increased potential of energy forest biomass. Therefore, the energy balance of the production and transport of woody biomass in multifunctional forestry is beyond the scope of the presented work and is not included in this article.

5. Conclusions

This paper aimed to present the overall balance of timber biomass from felled trees in multifunctional forests and assess what kind and how much of this biomass can be used for energy purposes. The total biomass of trees designated to be harvested consists of three main groups: industrial wood, energy wood, and ecology wood, which represent: 67%, 20%, and 13%, respectively. The total energy biomass source consists of low-quality wood, firewood, and residues with shares: 20%, 34%, and 46%, respectively. The Polish State Forests' potential for energy wood is estimated at 6.18 million tonnes of biomass yearly, giving an average of 0.87 tons of biomass per 1 ha of forest. Total available energy produced from woody biomass amounted to 104.8 PJ y^{-1}. About 13% of the woody biomass designated to felling should be left in the forest to improve ecological conditions in the stands as a source of deadwood. Further research on the effects of woody biomass harvesting costs and transport distances from the forest to the power plant on the economic viability of using different woody biomass components as bioenergy resources is needed.

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