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The Use of Forest Biomass for Energy Purposes in Selected European Countries

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Abstract: The utilization of primary and secondary woody biomass resources, despite controversies, is being promoted to reduce dependence on fossil fuels and due to the need to diversify energy sources and ensure energy security in European Union countries. Forest biomass is one of the renewable and sustainable energy sources that can be used for electricity, heat, and biofuel production. In the context of the ongoing energy crisis in Europe, an attempt was made to analyze the production and consumption of woody biomass for energy purposes (fuel wood, chips, and pellets). Specifically, an analysis of similarities between European countries in terms of biomass utilization was conducted. The analysis was complemented by a forecast of primary biomass production in selected European countries. The similarity analysis was conducted using the Ward method. Artificial neural networks (ANNs), including multi-layer feedforward perceptron (MLP) and radial basis function (RBF) models, were used to predict fuelwood extraction. The study showed that woody biomass remains an important source of bioenergy in Europe, and its significance as a strategic resource guaranteeing energy security is likely to increase. Fuel wood harvesting in Europe generally shows an upward trend, particularly in the Czech Republic, Germany, Estonia, Denmark, and the UK. A decreasing trend was observed in France, Spain, Greece, and Cyprus. The analysis revealed differences between countries in terms of woody biomass consumption. The ANN-based forecasts of fuelwood supply generally showed an increase in primary biomass harvesting.

Keywords: renewable energy; forest biomass; fuel wood productions; biomass management; European countries; similarity analysis

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1. Introduction

1.1. Forest Biomass as a Sustainable Energy Source

The European Commission has set a long-term goal of developing a competitive, resource-efficient, and low-emission economy by 2050. It is expected that the bioeconomy will play an important role in reducing CO_2 emissions [1,2]. EU countries need to transform their energy systems by increasing the share of renewable energy [3–5]. In the face of the ongoing energy crisis, European governments are turning to biomass to meet EU renewable energy targets for 2020 and 2030 [6–8]. One way to achieve this goal is through the effective and sustainable use of forest biomass for energy and biofuel production [9].

Bioenergy continues to be the leading source of renewable energy in the EU in terms of gross final consumption, despite the rapid growth of wind and solar energy over the past decade [10]. Biomass for energy purposes (bioenergy) accounts for nearly 60% of the share of renewable energy in the EU. The heating and cooling sectors consume about 75% of all bioenergy (bioelectricity and biofuels account for 13% and 12%, respectively). In 2017, biomass from forests accounted for 69% of the total biomass used for energy production [11]. The production and utilization of forest resources and forest biomass, both primary and secondary, is expanding worldwide, including their use for energy purposes. This is occurring due to diversification and energy security, climate change mitigation, and reduced dependence on fossil fuels [12–14]. Forest biomass is one of the renewable and sustainable sources of energy that can be used for electricity, heat, and biofuel production. In 2015, forests in the EU covered an area of 161 million hectares, accounting for 38% of the total land area [15–17]. Out of this area, 134 million hectares (84%) are considered accessible forests for wood supply. Since 2000, aboveground biomass resources in the EU have been increasing by 223 million tonnes annually, corresponding to an average annual growth rate of 1.3% (current area over 22 million hectares). Forest biomass, accounting for 60% of biomass used in the EU (44 Mtoe), plays an important role in bioenergy production. Primary biomass (wood from forests and other wooded land) accounts for 32.5% (about 44 Mtoe) of biomass consumed, and secondary biomass (industrial wood residues) accounts for 28.2% (38 Mtoe) [11]. Mantau [18] assumed that the potential supply of forest biomass, stems, logging residues, and bark will remain relatively stable from 2010 to 2030, while the potential from industrial wood residues will increase by about 30% [19].

1.2. Properties of Forest Biomass

The type of material, seasonality of supply, market conditions, and price fluctuations influence the amount of bioenergy produced and the cost of doing so [20]. Wood fuel is a strategic resource for future energy supply and is typically used locally [14]. It has been noted that using available forest biomass for residential heating can result in savings of 48% to 81% compared to other major systems [21]. Forest biomass is not homogeneous and is characterized by diverse chemical composition and properties. The physicochemical properties of biomass, such as moisture content, proportions of bound carbon and volatile substances, ash content, and cellulose/lignin ratio, play crucial roles in biomass conversion and in directing the available feedstock towards energy, heat, or fuel production [22–25]. Coniferous wood species generally have higher carbon content and higher calorific values than deciduous wood species, and the calorific value of wood fuel decreases with increasing wood moisture content [26]. Analyzing 10 types of biomass, Bowman et al. [27] showed that land requirements and power densities are highest for coniferous forests, at 114 W/m^2 (22–267 W/m^2), and green waste at 96 W/m^2 (26–176 W/m^2), respectively.

1.3. Forest Biomass in EU Policy

Biomass is the foundation of the bioeconomy, and its demand is growing worldwide as the transition to a low-emission economy takes place [28]. Studies by many authors have shown that more biomass can be mobilized in Europe compared to the reported utilization levels [29–32]. Policies and government incentives play crucial roles in promoting and encouraging further investments in energy systems [33]. Bioenergy markets are dependent on political decisions, and support systems for the development of renewable energy at the EU level are of great importance. Kohl et al. [34] showed the inconsistency in the new EU forest strategy for 2030, the EU directive on renewable energy, and the land use regulation. The demands that EU instruments impose on the forest economy are not consistent and are dominated by ecological aspects. They do not fulfill the requirements of sustainable multifunctional forest management. In particular, the role of wood as an ecological product has been underestimated. Lindstad et al. [35] emphasized the need to understand the complex interrelationships between bioenergy and broader political and market changes. Identifying these complex interactions can contribute to facilitating the development of policies that promote and regulate the future production and use of forest-based bioenergy, while considering other forest-related objectives. Stojilovska et al. [36] pointed out that firewood has been overlooked in the European energy transition policy, despite its importance as a raw material and energy source for many European households. Banja et al. [37] suggest that supporting a unified EU market for cleaner energy is recommended. This implies the need to implement four policy actions for EU countries: a thorough performance review, integration with RED-2, consistent guidelines for sustainable development, and local impact assessments. Changes in the use of energy carriers are occurring worldwide, particularly in the EU, where the rapid growth of renewable energy (RE) is being observed. Reviewing and analyzing methods and approaches for estimating biomass and forest biomass potential is of great importance for the development of guidelines and bioenergy development policies. Legislative regulations and technological innovations are driving changes in RE production. In the context of growing global issues due to climate change and the ongoing energy crisis in Europe, an attempt has been made to update knowledge on the use and production of wood for energy purposes in Europe. The use of forest biomass for energy purposes and views on this matter are evolving, and consumption patterns are also changing, necessitating an update of knowledge in this area.

1.4. The Research Objective

The article reviews issues related to the production and consumption of wood, mainly fuel wood (FW), chips, and pellets, for energy purposes in selected European countries. The topic addressed is important due to the need to develop approaches to forest biomass management in the context of optimizing processes, such as planning, production, harvesting, and transportation, as well as technological directions for the use of low-value primary forest biomass for energy purposes. The research focused on analyzing the production and consumption of potentially usable woody biomass for energy purposes and updating knowledge on the significance of forest biomass in providing bioenergy in EU countries. The main objectives of the research were:

1. To analyze the level of production and consumption of primary (firewood) and secondary (wood chips and pellets) forest biomass in European countries;
2. To analyze similarities between European countries in terms of their potential production and consumption of forest biomass and identify factors that contribute to differences or similarities;
3. To forecast primary biomass production in selected European countries, with a particular focus on estimating the supply of firewood.

The assessment of the significance of forest biomass in the development of renewable energy in Europe, as well as the attempt to identify similarities in the production/consumption of wood biomass among European countries using the Ward method (including an attempt to identify differentiating factors of clustering), constituted an original element of the study.

2. Materials and Methods

2.1. Data Source

The research was conducted based on statistical data presented by FAO [38]. The analyses and comparisons were presented at the level of selected European countries (European Union—EU 27, England, Sweden, and Switzerland). Countries where forest biomass has marginal significance (e.g., Malta) were excluded from the analyses. The results were interpreted based on our research (statistical analyses) and data from the literature.

The analysis focused on the level of fuel wood (FW) production and national wood consumption for energy purposes. National consumption was determined as the sum of FW wood production and forest residues. This increased via imports and decreased via exports of primary and post-industrial biomass. The analyses covered the production and consumption of primary forest biomass from 1992 to 2021, as well as the use of residues from wood processing from 2012 to 2021:

- Primary forest biomass (fuel wood (FW)) is directly sourced from the forest and includes roundwood from coniferous and deciduous trees obtained from trunks, branches, and other parts of the tree for use in fuel and the production of charcoal, pellets, and other agglomerates (excluding wood charcoal, pellets, and other agglomerates).
- Biomass consisting of residues from industrial wood processing, which is potentially usable for energy purposes, including: (1) wood chips, particles, and residues (this product category is an aggregate comprising wood chips, particles, and wood residues, which are the volume of roundwood left over after the production of forest products in the wood processing industry); (2) wood pellets and other agglomerates, such as briquettes and wood charcoal (as residues from the industrial wood processing) [38].

2.2. Similarity Analysis

To detect similarities between European countries in terms of forest biomass management for energy purposes (production, consumption), the countries were divided into clusters based on variables related to FW production and consumption in domestic markets. Among the clustering analysis methods, there are several techniques such as hierarchical agglomerative methods, hierarchical divisive methods, areal methods, optimization methods for preliminary object division, and neural networks. In this study, the Ward method was used as the agglomeration technique.

The Ward method belongs to hierarchical agglomerative methods and is considered one of the most effective methods of this type. Its effectiveness is conditioned by meeting a series of conditions for the analyzed dataset, such as set separability, a not-too-large number of units, and the absence of atypical values [39]. In terms of distance estimation between clusters, it exhibits characteristics of analysis of variance, and its operation consists of minimizing the sum of squared deviations of any clusters that can be formed at a given stage of agglomeration. As a result, the cluster class with the least variability is selected [40]. The initial assumption, in this case, is that it is necessary to adopt a number of clusters equal to the number of objects in the analyzed dataset and then reduce their number by merging the most similar objects. This technique has not been used in the field of forest biomass-related bioenergy research.

The next step was to identify the factors influencing the differentiation of the analyzed objects. Variables such as round wood (RW) production, the percentage of FW in RW, growing stock density, forest area of the country, biomass export/import for energy purposes, per capita consumption of forest biomass, the share of solid biomass energy, and the share of renewable energy used for heating and cooling were examined. The significance of differences between the identified clusters was verified using ANOVA and Kruskal–Wallis tests.

2.3. Identifying the Most Important Independent Variables

It was expected that clusters which are distinguished in terms of the level of production and consumption of wood biomass would differ significantly in terms of the above-mentioned independent variables. It was anticipated that the utilization of woody biomass for energy purposes would depend on the share of fuelwood in roundwood. The highest percentage share of fuel wood in industrial wood (RW) was seen in the countries of Southern Europe (Italy and Greece), and the lowest level was found in the Scandinavian countries (mainly Sweden). It was conjectured that countries with larger forest areas and higher growing stock density would have higher production and consumption of wood biomass for energy purposes. The largest forest area is found in the Scandinavian countries (Sweden, Finland, Norway). There are also large forests in the Baltic countries, France and Germany, and the smallest forest area is in Cyprus. The productivity of habitats, species composition, and silvicultural practices are among the factors influencing the level of harvested and utilized woody biomass. The harvest-to-growth ratio remains relatively stable and is below 80% in most European countries. However, this is expected to increase due to the growing demand for woody biomass as a renewable source of energy [41,42].

The average growing stock density in European forests is 163 m^3 per hectare (ha). The most abundant forests in Europe are found in Switzerland (approximately 350 m^3/ha), Slovenia (345 m^3/ha), and Germany (320 m^3/ha). Austria (approximately 298 m^3/ha), as well as Poland, Romania, Czech Republic, and Slovakia (over 260 m^3/ha), also have high stock densities. The lowest growing stock density (m^3/ha) is found in the forests of Southern European countries (Spain, Greece, Cyprus, Portugal, approximately 50–60 m^3/ha). It appears that the export/import ratio for woody biomass influences the increase in biomass consumption, particularly for energy purposes. Currently, over 30% of the net primary production of wood used in the EU comes from imported biomass and biomass products [41]. Biomass plays a significant role in renewable energy production. Hence, connections were expected between the increasing share of renewable energy and the level of production and consumption of woody biomass.

The share of renewable energy in total energy consumption from 2004 to 2021 was high in Norway (around 67%) and Sweden (around 50%). Among the lowest indicators in the EU were the Netherlands (5.7%) and Belgium (6.9%). In 2021, the highest percentage share of renewable energy in total energy consumption was observed in Iceland at around 86%, followed by Scandinavian countries such as Norway (74%), Sweden (63%), and Finland (43%). Slightly lower percentages were observed in the Baltic countries (Latvia—42%, Estonia—38%). The lowest share of renewable energy was found in the Netherlands (12.3%), with an average EU share of 21.8% [42]. However, the countries with the highest growth rate in the share of renewable energy from 2004 to 2021 were Iceland (27%), Sweden (24%), Denmark, and Estonia (19%). Among the EU countries, Slovenia, Romania (approximately 6.8%), Croatia, and Bulgaria (approximately 7.8%) showed low growth dynamics during this period. The share of energy from renewable sources in gross electricity consumption in 2021 was highest in Norway (around 114%) and Iceland (around 100%). Austria (around 77%) and Sweden (76%) had high percentages among the EU countries, with an EU average of 37.5%. In terms of the share of energy from renewable sources for heating and cooling from 2004 to 2021, Iceland and Sweden had the highest percentages, with the EU average at 22.9%. The share of energy from renewable sources in transport in the EU was only 9.1% [43].

It was expected that the share of solid biofuels would be a differentiating factor among the identified clusters. The percentage share of primary biomass in gross electricity production from 2012 to 2021 was highest in Finland (16%), Denmark (13%), Estonia (10.2%), Lithuania (7.1%), Latvia (6.7%), Sweden (6.1%), Austria (5.3%), the UK (5.1%), and Portugal (5%). Cyprus, Malta, and Iceland did not utilize biomass for this purpose, while Greece only had a share of 0.02% and France had one of 0.5% [42]. From 2005 to 2016, the share of solid biofuels (wood and charcoal) contained in gross inland consumption of renewable energy in the EU-28 decreased from 56% to 45%.

2.4. Prediction of Fuel Wood Production

Due to the influence of numerous local (natural-economic) and global factors, the level of biomass consumption is increasing, including for energy purposes. Fuel wood (FW) still maintains a high share in the use of forest biomass for energy. In order estimate the future supply of this resource, a forecast of fuel wood production was performed based on data from 1992–2021. The prediction focused on selected European countries (Austria, Estonia, France, Norway, and Poland). The forecast of fuel wood production was conducted using artificial neural networks (ANN). The aim was to test the accuracy of the forecasts and their practical applicability for predicting secondary forest biomass supply (currently, limited availability of data from 2012 onwards restricts the use of time series methods due to a small number of data points). In addition to the level of FW production (time series), the models incorporated exogenous variables such as the forest area of the country, the proportion of FW in round wood (RW), RW production level, and growing stock density.

In this study, a variety of artificial neural network (ANN) models were evaluated, including multi-layer feedforward perceptron (MLP) and radial basis function (RBF) models [44,45]. Each MLP network in the experiment exhibited a different structure (Table 1). The networks were trained using both the conjugate gradient and steepest descent training algorithms.

Table 1. Different structures and types of artificial neural network (ANN) models that were used for each country. The ANN models include MLP (feed-forward multilayer perceptron) and RBF (radial basis function). The RBF networks were trained using two distinct algorithms: BFDS (Broyden–Fletcher–Goldfarb–Shanno algorithm) and RBFT (the default learning algorithm for RBF networks in the Statistica solver). The number of training epochs is provided in brackets, and the evaluation criterion used is SOS (sum of squares).

Countries	Number of Neurons (Input–Hidden–Output)	Learning Algorithms and Iterations	Error Function	Activation Function (Hidden Layer)	Activation Function (Output)
Austria	MLP 4-8-1	BFGS 129	SOS	Exponential	Exponential
	MLP 4-20-1	BFGS 10	SOS	Exponential	Logistic
	MLP 4-11-1	BFGS 10	SOS	Exponential	Logistic
	MLP 4-19-1	BFGS 9	SOS	Exponential	Logistic
	MLP 4-10-1	BFGS 225	SOS	Tanh	Logistic
Estonia	RBF 4-6-1	RBFT	SOS	Gauss	Linear
	RBF 4-8-1	RBFT	SOS	Gauss	Linear
	MLP 4-24-1	BFGS 7	SOS	Logistic	Tanh
	RBF 4-6-1	RBFT	SOS	Gauss	Linear
	MLP 4-5-1	BFGS 12	SOS	Exponential	Logistic
France	MLP 4-15-1	BFGS 104	SOS	Tanh	Logistic
	MLP 4-11-1	BFGS 8	SOS	Sinus	Logistic
	MLP 4-10-1	BFGS 25	SOS	Tanh	Logistic
	MLP 4-20-1	BFGS 8	SOS	Tanh	Logistic
	MLP 4-20-1	BFGS 66	SOS	Sinus	Logistic
Norway	MLP 4-11-1	BFGS 7	SOS	Linear	Sinus
	MLP 4-6-1	BFGS 13	SOS	Logistic	Logistic
	MLP 4-16-1	BFGS 4	SOS	Sinus	Exponential
	MLP 4-8-1	BFGS 5	SOS	Sinus	Tanh
	MLP 4-10-1	BFGS 5	SOS	Logistic	Linear
Poland	MLP 4-5-1	BFGS 20	SOS	Sinus	Linear
	MLP 4-5-1	BFGS 223	SOS	Exponential	Logistic
	MLP 4-13-1	BFGS 41	SOS	Linear	Exponential
	MLP 4-20-1	BFGS 8	SOS	Linear	Exponential
	MLP 4-19-1	BFGS 57	SOS	Logistic	Exponential

The model can be formally stated as:

$$y = F\,(k - 1, k - 2, \ldots, k - N, \ldots) + \varepsilon t \tag{1}$$

where k represents the dependent variable of interest and ε is the error term. The function F is nonlinear. In our approach, F takes the form of an MLP or RBF neural network.

Input data contained information about past fuel wood production, the percentage of FW in RW production, forest area, and growing stock density separately for selected countries, with data about future productions being the network output. Repeated random subsampling validation was used for each ANN (both MLP and RBF models). In total, 15% of randomly chosen data from the learning data set were used for model validation. Validation sets are used to stop training early if the network performance on the validation vectors fails to improve. One round of cross-validation was used to compare the results across different ANNs. We tested the different numbers of internal connections, number of layers, epochs, learning algorithms, and activation functions. All data from the testing set were used for cross-validation. The dataset was divided into two subsets with teaching steps and steps ahead for testing medium-term forecasts. Then, the RMSE and MAE were computed. Each ANN model given in Table 1 was trained 100 times with different initial weight sets. A slight relationship was observed between the initial weights and the final training results after the stop criteria had been met. However, it was found that different initial weight sets did not considerably affect RMSE, with the standard deviation for the errors being less than 0.1%.

The following model statistics were calculated to score the models [46]:

$$\mathrm{RMSE} = \sqrt{\frac{\sum (y_i - \hat{y}_i)^2}{N}} \tag{2}$$

$$\mathrm{MAE} = \frac{1}{N}\sum_{i-1}^{N} |y_i - \hat{y}_i| \tag{3}$$

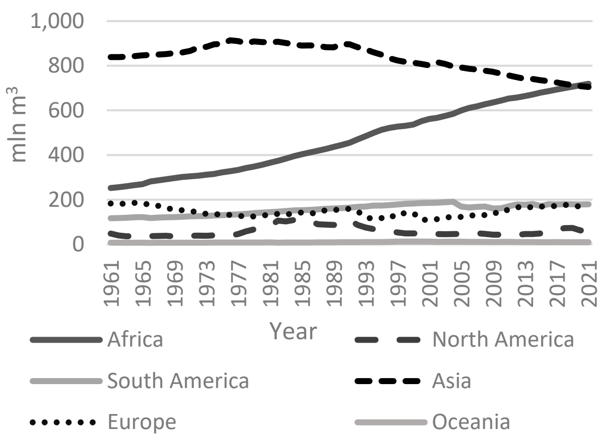
where: $\hat{y}_i$—represents predicted values, y_i—represents observed values.

Numerical experiments were implemented in R version 4.1.2 and Statistica version 13.1 [47,48].

3. Results

3.1. Forest Biomass Trends Production in Selected European Countries

The amount of FW for energy purposes has varied over decades in different continents. From 1961 to 2021, the highest average production of FW was in Asia (around 50%) and Africa (around 28%). In 1961, Asia accounted for approximately 58% of FW production (838.8 million m^3), while Africa accounted for about 17% of global production (252.4 million m^3). Currently (2021), production in Asia has decreased by 20%, while in Africa it has increased by over 20% (from 17.5% to 39% share in global FW production). In Europe, FW production from 1961 to 2021 has shown variability, with the largest declines occurring from 1990 to 2000. However, a slight upward trend in FW production in Europe can be observed from 2000 to 2021 (Figure 1). The highest share of FW export and import overall is related to European countries.



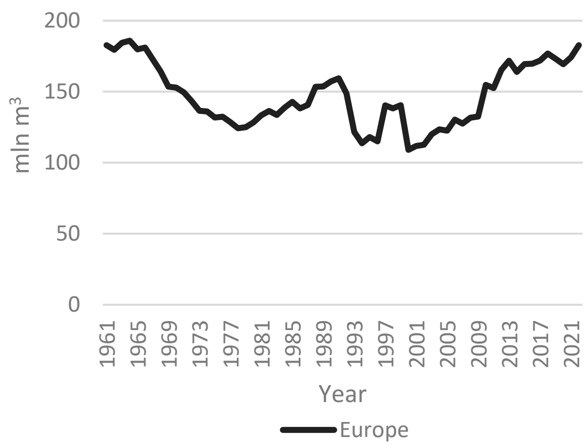


Figure 1. Supply of fuelwood in 1961–2021.

From 2017 to 2021, imports in European countries accounted for an average of about 3/4 of the global import volume, while exports during this period were also at a high level. From 2012 to 2021, Estonia had the highest rates of biomass export for energy purposes in Europe, with exports exceeding the amount of imported biomass by a factor of 14. Latvia, Croatia, and Bulgaria also showed disproportionately high levels of exports compared to imports. The main importing countries for biomass in Europe include the United Kingdom, Italy, Denmark, Finland, Sweden, Belgium, and Austria (Figure 2).

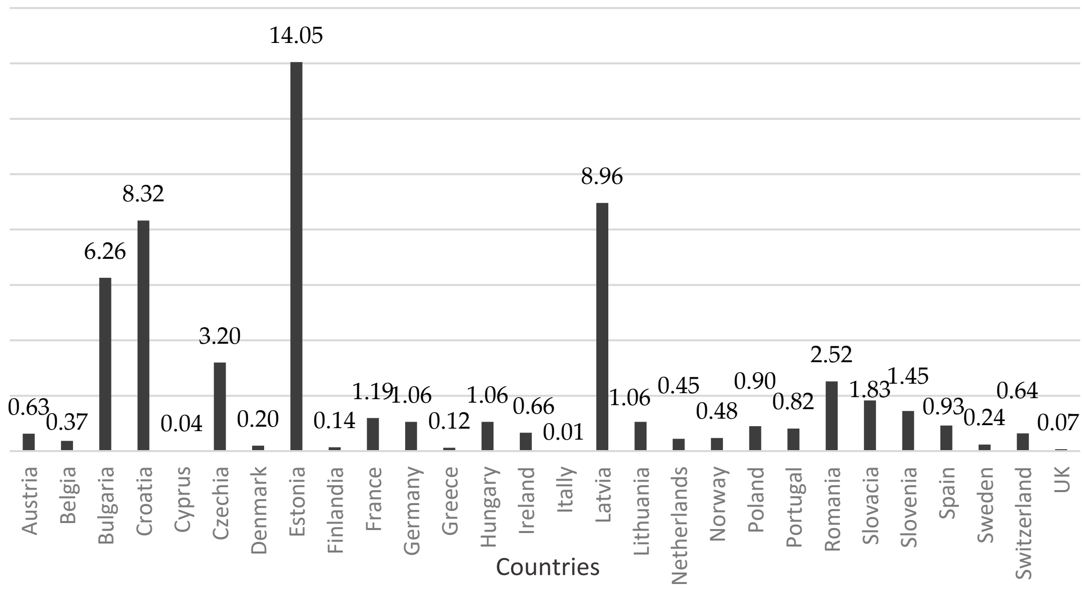


Figure 2. Forests biomass export to import ratio in 2012–2021.

Over the period 1992–2021, the highest percentage share of FW in RW production was observed in Italy (approximately 70%), Greece (67%), France (50%), Hungary (48%), and the Netherlands (45%). On the other hand, the lowest proportion of fuel wood about industrial roundwood was found in Ireland (4.3%), Slovakia (6.1%), and Portugal (6.9%). Low indicators were also observed in Sweden (8%), England (10%), Finland (10.9%), Poland, and the Czech Republic (approximately 11%) (Figure 3).

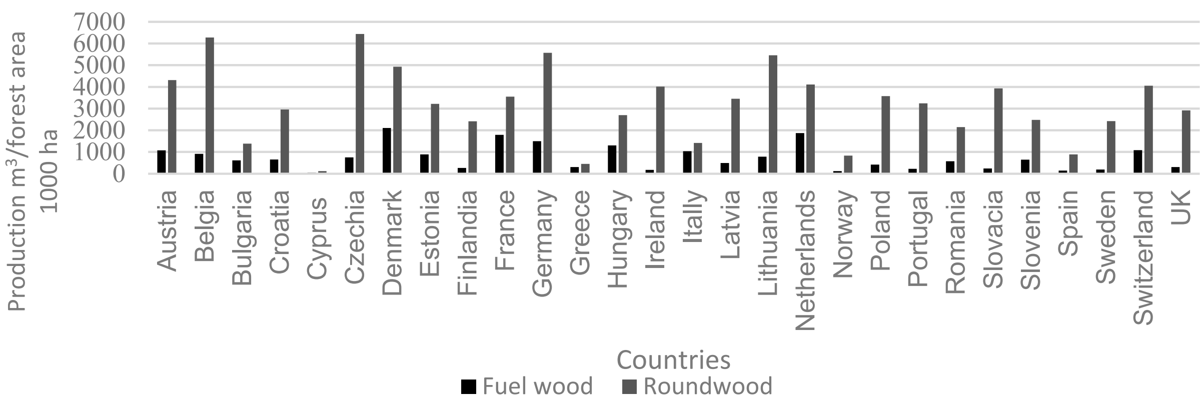


Figure 3. Roundwood (RW) and fuelwood (FW) production in 1992–2021.

In terms of forest biomass consumption (primary and pellet) per capita, the highest values were observed in Estonia (5 m^3/capita), Finland (4.66 m^3/capita), and Sweden (approximately 3 m^3/capita). The lowest values were found in Cyprus, Greece, Spain (0.14 m^3/capita), and England (0.17 m^3/capita). Over the period 1992–2021, an increase in the consumption of primary forest biomass (for energy purposes) per capita was observed in almost all European countries except Greece, Spain, and France. Estonia experienced a significant increase in consumption, which rose from 0.6 m^3/capita in 1992 to 3 m^3/capita in 2021. Similar increases were seen in Lithuania, the Czech Republic, Finland, and Germany (Figure 4).

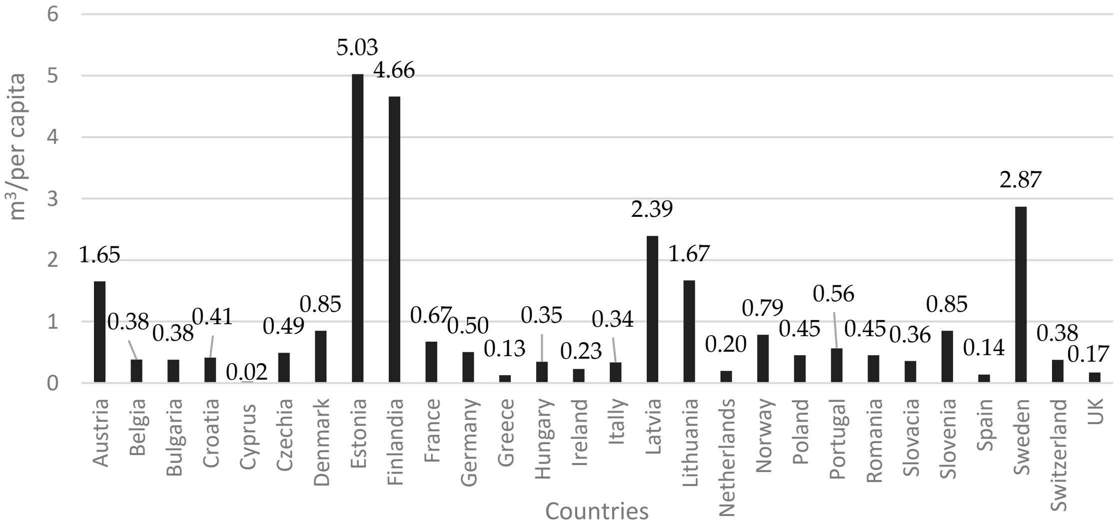


Figure 4. Consumption of fuelwood, chips and pellets and other agglomerates per capita in 2012–2021.

On the other hand, the highest consumption per unit area was found in Austria (180 m^3/km^2) as well as Estonia, Denmark, and Germany. The lowest fuel wood consumption per unit area was in Cyprus, Greece, Norway, and Spain (Figure 5).

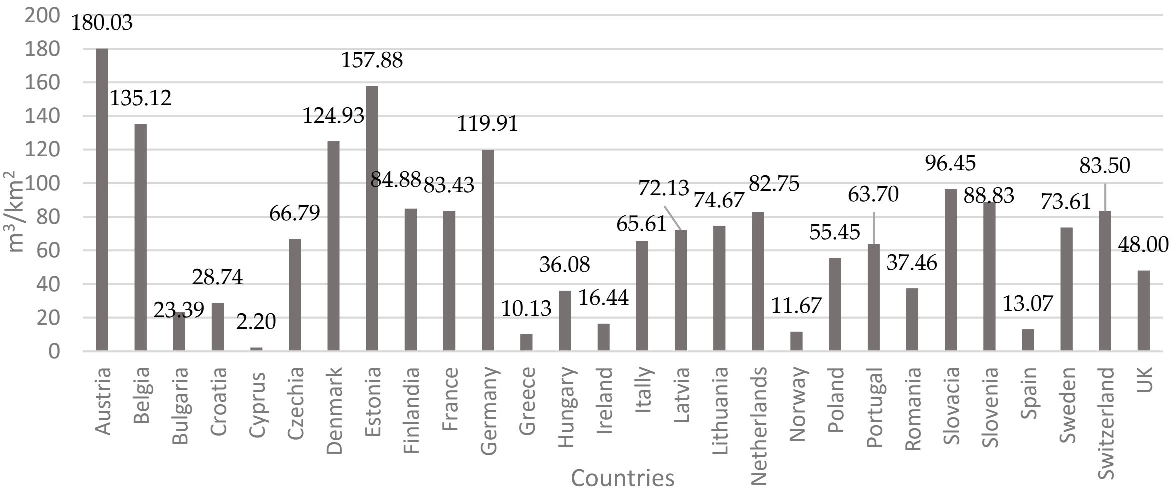


Figure 5. Consumption of fuel wood, chips and pellets and other agglomerates per km^2 of the country in the years 2012–2021.

3.2. Analysis of Similarities between European Countries in Terms of Production and Consumption of Forest Biomass for Energy Purposes

To divide the analyzed EU countries based on the similarity in production and consumption of forest biomass, the Ward agglomeration method was used, utilizing a 1-r Pearson distance. European countries were grouped into clusters, representing similar patterns in the production and consumption of wood for energy purposes. Figure 6 presents examples of the division of European countries into clusters based on the production of forest biomass. ANOVA testing did not yield the expected results in terms of identifying external variables influencing the presented country classification. The analyses did not reveal statistically significant differences between clusters in terms of forest biomass production and the adopted explanatory variables.

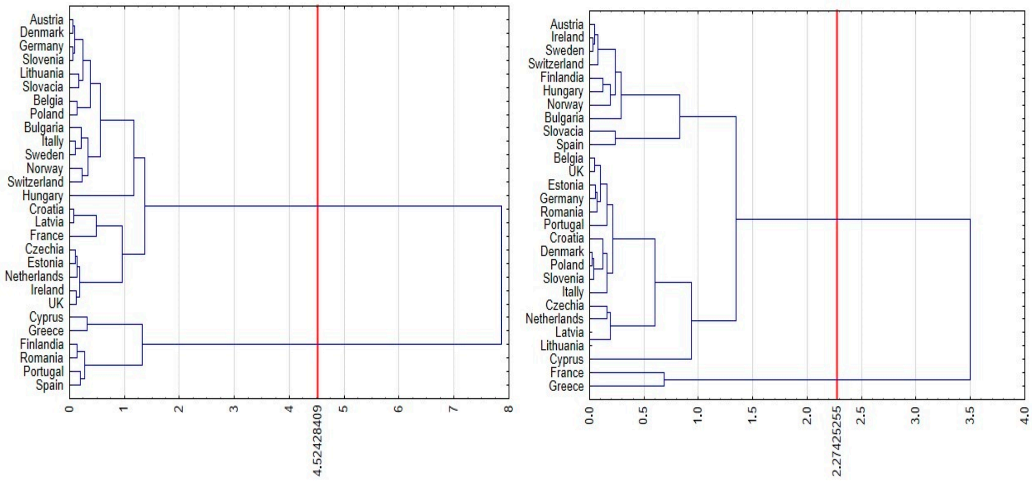


Figure 6. Grouping dendrograms according to: (1) FW production, pellets, chips and other agglomerates $m^3/1000$ ha (2) FW production $m^3/1000$ ha.

Analyzing the dendrogram above, it can be assumed that the number of clusters is 3 (Figure 7). By using the criterion of the first significant increase in agglomerative distance, the dendrogram in Figure 7 can be cut, for example, at a linkage height of 2.26, which allows for the identification of three groups of countries. The first group consists of Austria, Germany, Slovenia, Denmark, Finland, Switzerland, Romania, Belgium, Poland, Lithuania, Spain, Bulgaria, Hungary, Norway, and Sweden. The second group includes Croatia, Latvia, Czech Republic, Portugal, Netherlands, Estonia, the UK, Ireland, and Slovakia. The third group consists of Cyprus, France, and Greece. This division confirms a higher similarity in terms of biomass consumption among the countries within the clusters. The presented results are dynamic in nature and refer to the years 2012–2021.

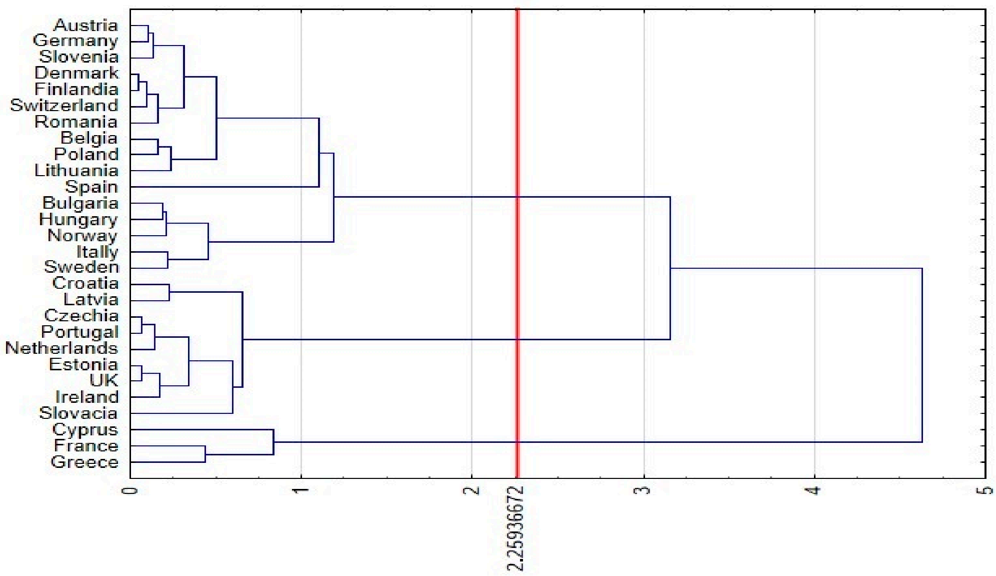


Figure 7. Grouping dendrograms according to domestic consumption of FW, pellets, chips, and other agglomerates.

To identify differentiating factors among the analyzed groups, an ANOVA test was conducted. Based on the analysis of variance (ANOVA), the influence of potential independent variables such as the FW share in RW, growing stock density, forest area, biomass export/import for energy purposes, the share of solid biomass energy, and the share of renewable energy used for heating and cooling were verified for the variables of production and consumption of wood for energy purposes within the analyzed countries.

Regarding biomass consumption, the analysis showed significant differences within the FW share in roundwood production. The Kruskal–Wallis test (p = 0.05) revealed statistically significant differences between the first and second clusters (Table 2). The utilization of wood for energy purposes in the identified clusters is related to the level of FW production and its share in roundwood. The identified clusters of countries significantly differ in terms of the utilization of primary forest biomass (FW) for energy purposes. The other analyzed independent variables did not have an impact on the dependent variable, making it difficult to interpret the results of the cluster analysis unambiguously (the identification of clusters may be influenced by unconsidered external variables).

Table 2. The results of the significance of differences between clusters, due to the level of domestic consumption of fuel wood (based on the analysis of variance and the Kruskal–Wallis Test).

Subsidiary: Fuel Wood (WF) Share [%] in Round Wood (RW)	Value for Multiple Comparisons; Participation of FW [%] in Round Wood (ANOVA) Independent (Grouping) Variable: Clusters Kruskal–Wallis Test: H (2, N = 28) = 8.015189 p = 0.0182		
	1 R: 9.5556	2 R: 24.667	3 R: 15.375
1		2.755499	1.697874
2	2.755499		1.795354
3	1.697874	1.795354	

3.3. Fuel Wood Production in Selected European Countries

The analysis was performed for selected countries (referred to as representative countries—cluster analysis, groups 1, 2, and 3). The sensitivity analysis yielded ambiguous results, meaning that the quality of the obtained models in the analyzed cases was influenced by different variables depending on the country. In the case of Austria and Norway, the most important variable was the percentage share of FW in roundwood, with values of 3 and 1, respectively. For Estonia, the growing stock density proved to be the most important predictor (3.7). When using ANN in France, the forest area had the most significant impact on model fitting and forecast results (3.54). In Poland, the results between variables such as growing stock, forest area, and roundwood volume were similar, but the variable with the highest influence on the forecast quality was roundwood volume (4.5) (Table 3).

Table 3. Sensitivity analysis (best prediction).

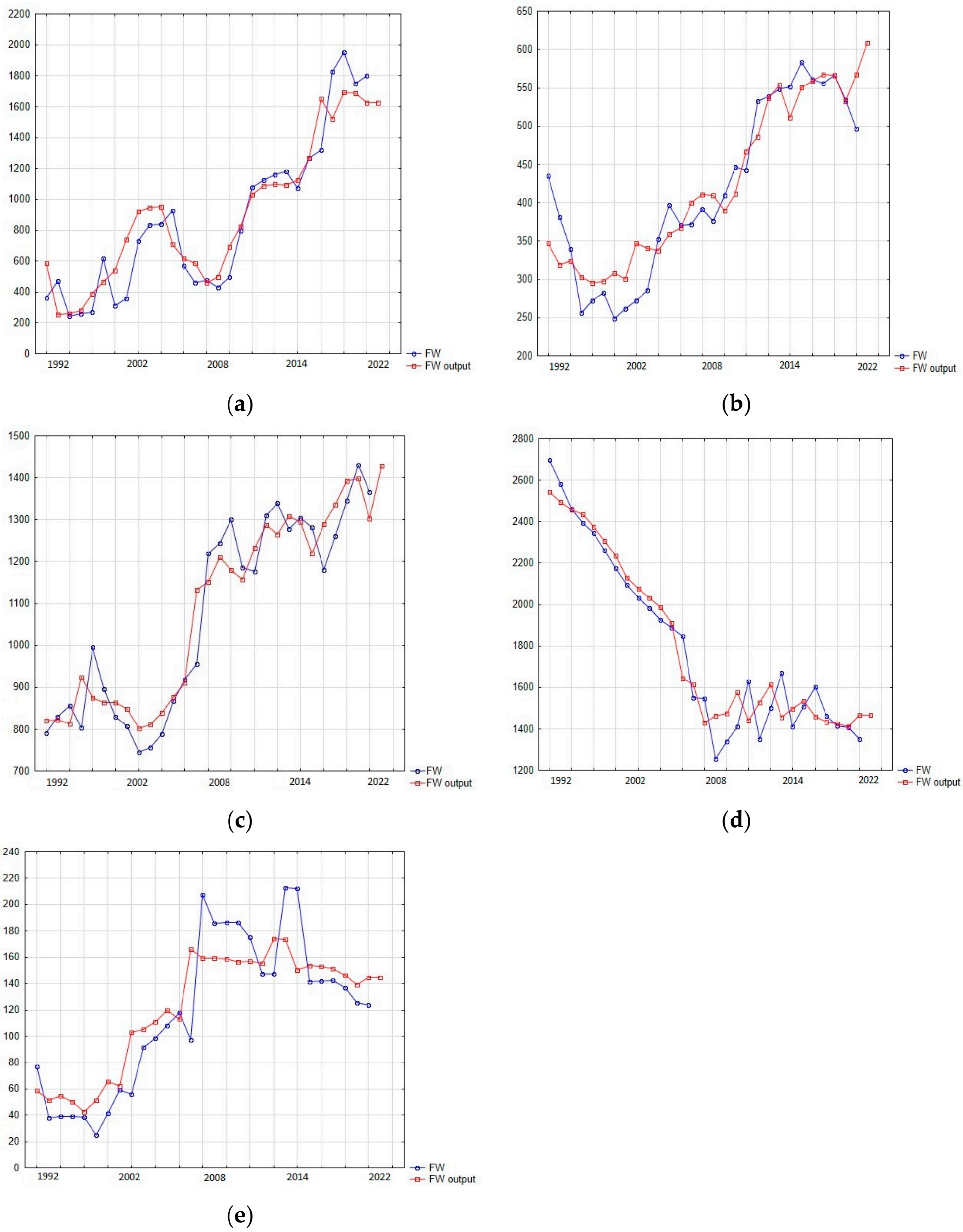
ANN Network	Growing Stok	Forest Area of the Country	RW	FW [%] Shere in RW
Austria	1.34	3.46	2.23	3.82
Estonia	3.67	2.67	2.97	2.21
France	1.04	3.54	2.65	1.67
Norway	1.17	1.14	1.63	1.94
Poland	4.07	4.16	4.52	2.95

The use of ANN RBF and MLP in forecasting fuel wood production/supply has yielded favorable results, particularly in relation to MLP. The models used for forecasting FW production showed errors at different levels and indicated model fit depending on the country. The ex-post accuracy measures of the forecasts, based on the comparison of predicted and actual production/harvest volumes, are summarized in Table 4. The most favorable overall ANN forecasts were obtained for Norway and Poland. Additionally, the difference between MAE and RMSE values for these countries was low (indicating low deviations between the predicted and actual values), suggesting small forecast errors during the forecast period. The highest MAE and RMSE values were observed for Estonia and Austria, and the differences between error values were also the largest in these cases.

Table 4. Accuracy measurements of the artificial ANNmlp, ANNrbf models.

Error/Countrys	Austria	Estonia	France	Norway	Poland
MAE	55.73	133.52	91.00	22.01	31.46
RMSE	168.26	168.26	11.20	27.47	39.25

Figure 8 shows a comparison of the FW production forecast for each country with the actual values. The charts display the predicted amount of FW from 1992 to 2021, with the forecast for 2022 included. These time series provide a detailed picture of the predictive capabilities of the models, which could be overlooked by interpreting only the forecast errors.



(**a**) (**b**) (**c**) (**d**) (**e**)

Figure 8. Simulation results for MLP (RBF) models (m^3/1000 ha) in 1992–2022: (**a**) Estonia, (**b**) Poland, (**c**) Austria (**d**) France, (**e**) Norway.

The ANN models performed well in forecasting atypical cases in the time series and outlier values. The results show that the neural network models are well-fitted to both maximum and minimum values. For the analyzed countries, the best forecasts were obtained using MLP models. The exception was Estonia, where RBF networks performed better (having higher goodness-of-fit indicators). However, Estonia also had the worst forecast result. In the first half of the study period, the forecast results had slightly higher values. Conversely, in the second half, the ANN models underestimated the forecasts, resulting in lower predicted values compared to the actual values. A similar forecast result was obtained for Norway (with ANN models overestimating values in the years 2008–2015). The ANN models performed best in forecasting FW production in France, with the forecast closely matching the actual values throughout most of the study period, except for the last years of the forecast. Regarding Austria and especially Poland, in the last period of the forecast, the ANN models significantly overestimated the results compared to the actual values. The forecasts were not in line with the real values, particularly in the 2021–2022, where the ANN predicted an increase in production, whereas it decreased in reality.

4. Discussion

A forest economy can support sustainable development in order to achieve low-emission or carbon-neutral conditions by 2050. This can be achieved through a 70% increase in the utilization of biomass and waste [49]. Both the production and consumption of forest biomass are dependent on numerous variables: political, natural, economic, social, and technological. Legislation enacted in the EU and national laws in member countries influence the situation in the EU and domestic bioenergy markets. National policies, particularly the availability of renewable energy sources (RES) and technological capabilities (know how), impact market participants. Each EU country utilizes available RES, and its potential to do so depends mainly on geographical location (solar, wind, water, geothermal potential) and technological progress in the country (its innovativeness). The utilization of forest biomass for energy purposes also depends on the prices of conventional energy carriers such as natural gas, coal, and wood in domestic markets. The level of domestic wood consumption is influenced by both the scale of production and trade exchange (export and import of forest biomass). From a biophysical perspective, the resources of woody biomass are sufficiently large to cover a significant portion of global primary energy consumption by 2050. Considering that forests occupy almost one-third of the world's land area, woody residues and low-quality wood will serve as potential sources for bioenergy production. However, these resources have alternative uses, and their availability is limited, which reduces their competitiveness compared to other forms of energy [50].

The analysis of renewable energy policies in the United States and Europe demonstrates that the use of forest biomass, combined with other renewable sources, offers the potential to mitigate climate change by replacing fossil fuels in the electricity and transportation sectors [12]. It is projected that bioenergy will account for up to 27% of the total primary energy demand in the EU, increasing from the current 5 EJ to 18 EJ per year [51]. At the EU level, bioenergy is the most flexible and intensively utilized renewable energy source, with an electricity consumption level of 5.6 EJ/yr [52]. It is worth noting that the current bioenergy potential of EU forests exhibits the highest variability, with estimates ranging from 0.8 to 6.0 EJ/yr^{-1}. Estimates for output in 2050 range from 0.8 to 10.6 EJ/yr^{-1} [19]. In recent years, there has been a significant increase in the potential of both forest biomass (from 4.8 EJ per year to projected 15 EJ per year) and agricultural biomass (from 2.3 EJ per year to projected 7 EJ per year). Based on available statistics, it can be concluded that the availability of forest biomass in domestic markets primarily influences the level of biomass consumption for energy purposes, which is determined by the level of primary forest biomass production (forest area, species composition, age of stands), as well as secondary production and imports. The growing demand for biomass energy in EU countries is partially balanced by imports from non-EU countries [53].

The significance of primary and secondary forest biomass in supplying bioenergy (biomass heat) is currently very high, as evidenced by its utilization for energy purposes in many EU countries. The importance of post-industrial biomass is growing, but the production and consumption of primary forest biomass also show an increasing trend in Europe. In the EU, the majority of energy is consumed for heating (space heating), accounting for approximately 63% of energy consumption in households [43]. Primary biomass for energy purposes is primarily used in countries with the potential for wood biomass production (due to proximity to the resource), as well as in poorer countries. Studies conducted in Portugal, Slovakia, Hungary, Austria, and North Macedonia have shown that firewood is a central and multifunctional tool in combating energy poverty as it provides energy security and access, both of which outweigh its negative environmental and health impacts [36]. Furthermore, densely populated countries such as the UK, Netherlands, and Belgium show a high level of consumption of secondary biomass, mainly in the form of pellets—90%, 75%, and 68%, respectively. Pellets are also popular in Denmark, with approx 70% of consumed wood biomass being in pellet form. The utilization of forest chips for energy purposes as a renewable energy source has also increased in recent years and is expected to continue in the future [54]. The highest national consumption of forest chips in total forest biomass in the last decade has occurred in Ireland (83%), Finland (72%), Portugal (73%), Sweden (75%), Slovakia (75%), as well as Austria (65%), Latvia (63%), and Lithuania (56%).

Based on cluster analysis, three clusters can be identified which group European countries based on their utilization of primary and secondary biomass for energy purposes. The largest cluster includes Scandinavian countries, as well as Austria, Germany, Slovenia, Switzerland, Belgium, Poland, Lithuania, Spain, and Hungary. The majority of countries in this cluster are considered wealthier nations (high GDP per capita). However, this cluster also includes countries with lower GDP per capita, such as Romania and Bulgaria. These results align closely with the findings of Piekut's research [55]. Piekut demonstrated that Western European countries and Scandinavian countries have been making efforts for years to increase the share of renewable energy in total energy production. These countries are adopting increasingly advanced technologies for renewable energy generation and have implemented tax incentives, public subsidy systems, and educational measures [56,57]. Scandinavian and Baltic countries are leading the way in replacing fossil fuels with renewable energy sources. The productive forests of Nordic and Baltic countries cover an average of 51% of the land area. The short-term growth of woody bioenergy through wood utilization will range from 236 to 416 TWh, depending on legal regulations and operational constraints [58]. Börjesson et al. [59] suggest that Sweden may experience additional demand for woody fuels of around 30 TWh in 2030 and 35–40 TWh in 2050. Future demand depends on the pace and scale of energy efficiency improvements and electrification in various sectors. Lindroos [60] demonstrated the significant importance of firewood in Sweden. In Finland, firewood is used on a small scale, with industrial processing residues playing a significant role [61]. In the Baltic Sea region, woody fuels are subject to international trade on a relatively large scale, with trade primarily occurring from Baltic countries to Sweden and Denmark [49]. The highest degree of utilization of renewable energy in households is observed in Eastern and Southern Europe. In these countries, the dominant category of renewable energy sources, due to lower living standards, is primary solid biofuels, with a majority of this being wood and pellets [55,62]. In Slovenia, considering that forests cover over half of the country's surface area, forest biomass is of significant importance. Wood biomass for heat production is utilized in almost 40% of Slovenian households [63]. The obtained results correspond to the identified second cluster during the analysis, which includes the following countries: Croatia, Latvia, Czechia, Portugal, Netherlands, Estonia, the UK, Ireland, and Slovakia. This category encompasses countries with the highest consumption of wood biomass for energy purposes, as well as leaders in biomass import for energy purposes, namely, the UK, Netherlands, and Ireland. The Baltic countries of Lithuania, Latvia, and Estonia are excellent producers of forest biomass. In Latvia, firewood remains the traditional primary heating source for individual households, while natural gas is the primary fuel in centralized heating systems (70%). However, one-fourth of centralized heating systems still utilize firewood [60]. Czechia, which has faced an oversupply of wood due to natural disasters in recent decades, has supplied significant amounts of biomass to the European market. Šafaˇrík and Hlaváˇcková [9] estimated the annual amount of dendromass available for energy production in Czechia until 2036 to be 13.473 million tons. They concluded that the dendromass resources for energy production in Czechia are insufficient to achieve the ambitious EU target of climate neutrality by 2050. On the other hand, Croatia has a significant energy potential from solar systems, an amount that greatly exceeds current and future energy needs [55]. Croatia is also rich in biomass, resulting in high utilization of solid biofuels [64]. Portugal has a large biomass potential that can be used for energy production, although it is already being utilized in industrial applications. The availability of biomass is limited by technical constraints on harvesting (e.g., terrain inclination) [65]. The inclusion of Cyprus, France, and Greece in the third category is not surprising, as these countries consume the least amount of wood biomass for energy purposes due to their access to alternative installations, mainly solar technologies in Greece and Cyprus, or the extensive nuclear power system of France. Investments in renewable energy sources are growing throughout the Mediterranean region. The importance of plantations for energy purposes is also increasing. The small-scale use of forest biomass for bioenergy purposes can increase socio-economic benefits at a decentralized level, address energy poverty, and reduce the risk of forest fires [66–68]. The absolute leaders in the utilization of renewable energy by the household sector are France, Germany, and Italy. These countries also experience the highest growth in renewable energy consumption in households. According to Piekut [55] Germany and Slovakia have handled the energy transformation better than other countries. Among European countries, Poland is still on a long path to energy transformation [69]. In the years 2018–2020, Polish forests annually generated over 4 million m^3 of forest biomass that could be used for energy purposes. The amount of post-production biomass from sawmills decreased from approximately 8.7 million m^3 in 2018 to around 7.6 million m^3 in 2020, which accounted for approximately 190% of the harvested forest biomass. In the years 2018–2020, the supply of forest biomass gradually decreased, falling by 8% annually. This trend may lead to an increase in the demand for imported biomass from abroad and necessitate the search for other sources of biomass (agriculture and recycling of wood products) [70]. In relative terms, poorer European countries (e.g. Romania, Bulgaria) show higher rates of consumption of renewable energy in households than wealthier Western countries (e.g., Luxembourg, Belgium, Netherlands). However, these poorer countries primarily rely on solid biofuels (wood), while solar technologies and biogas are more common in wealthier parts of Europe [55].

The prediction of roundwood supply, considering several input variables, yielded good results. The use of ANN RBF and MLP in forecasting fuel wood production has yielded favorable results, particularly in relation to MLP. The problem is the lack of comparable results, statistics, and reports on estimating and forecasting the potential of forest biomass, the level of forest biomass extraction, and its utilization for bioenergy production in Europe and beyond. Although the prospects of biomass utilization for energy purposes have been extensively studied, the results and estimates vary significantly depending on the research. Estimates of bioenergy potentials mainly differ due to variations in research scope, methods and approaches used, as well as assumptions regarding market development. Studies have primarily focused on the theoretical or technical potential of bioenergy, paying insufficient attention to the economic potential and the influence of policy [31]. Wieruszewski and Mydlarz [53] also indicate significant differences in estimates of bioenergy potential due to the lack of consistent methodology and assumptions among authors. Díaz-Yáñez et al. [54] emphasize that, when interpreting studies on energy potentials of forests, one should consider the large differences between studies regarding potentials derived from different geographical areas, methodological assumptions, limitations, research scenarios, and biomass categories [71]. Understanding the differences between estimates can facilitate investment planning and policymaking. Hänninen et al. [31] identified factors and assumptions influencing estimates of bioenergy potential in forests. They point out limitations in estimates resulting from the lack of consideration for market factors such as prices and international trade. The main producers of woody biomass are countries with the largest territories and forest resources, although tree plantations are gaining increasing importance. In Europe, five leading producer countries should be distinguished (France, Sweden, Germany, Finland, and Poland), which account for 58% of solid biomass energy production [54]. In 2010, Mantau et al. [72] analyzed the potential supply of woody biomass and the demand for wood. Differences between European regions were confirmed in terms of perspectives on wood supply potential and future wood demand. In northern countries (Estonia, Finland, Lithuania, Latvia, Sweden), potential demand in a low mobilization scenario slightly exceeds the resource potential until 2030. In a high mobilization scenario, potential supply remains higher than potential demand between 2010 and 2030. This is mainly because this scenario assumes few limitations and allows for high utilization of residues and stump removal in northern Europe. In western EU countries, such as Austria, Belgium, Germany, Denmark, France, Ireland, Luxembourg, the Netherlands, and the United Kingdom, potential demand is higher than potential supply, even at a high mobilization level. On the other hand, supply conditions in eastern countries (Bulgaria, Czech Republic, Hungary, Poland, Romania, Slovenia, Slovakia) largely remain stable in a medium mobilization scenario until 2020. Verkerk et al. [30] demonstrated that the highest total potential of forest biomass per unit of land can be found in northern Europe (southern Finland and Sweden, Estonia, and Latvia), Central Europe (Austria, Czech Republic, and southern Germany), Slovenia, southwestern France, and Portugal. However, a significant portion of these potentials is already being utilized for material and energy production, and further biomass extraction possibilities in these areas are limited. As noted by Dafnomilis et al. [73], a significant portion of woody biomass is imported to northwestern Europe due to insufficient domestic supply or higher production costs in the country. According to the authors, forecasts may underestimate or overestimate biomass potential depending on the data sources and whether the models consider policy developments in this area.

Sulaiman et al. [74] conducted an analysis of the impact of wood biomass energy consumption on CO_2 emissions in 27 European Union (EU) member states from 1990 to 2017. Using the panel dynamic ordinary least-squares (DOLS) method, the results revealed that CO_2 emissions decrease with increasing wood biomass energy consumption. The study recommends that EU member states increase the share of wood biomass energy used to reduce CO_2 emissions. Similarly, the findings of Bilgili et al. [75] indicate that per capita energy consumption from biomass reduces per capita CO_2 emissions and increases per capita GDP. The consumption of biomass energy can be an effective policy tool for sustainable development, and therefore, biomass production technologies and consumption need to be promoted in other countries, including the USA. Researchers emphasize the need to minimize the worsening impact of biomass utilization on climate change. Therefore, the cascading use of wood is gaining increasing importance. One of the critical and challenging issues associated with commercial and large-scale biofuel production is the efficient design and optimization of biomass supply chain networks [76]. Cambero et al. [77] highlight the requirement for systematic design of the entire supply chain network, which considers all stages ranging from the production of forest and wood residues to the final utilization of all bioproducts, to ensure the optimization of economic and environmental benefits. For example, a recent economic analysis demonstrated that, at current market prices, it is more cost-effective to produce fuel wood than wood chips. Wood-derived fuel has a smaller environmental impact compared to heating oil, but still has a greater impact than natural gas [24]. Mayfield et al. [78] notes that the forestry industry, energy industry, academic environments, construction personnel, and rural communities should collaborate to support research, policy issues, and educational programs that enhance the efficiency of current forest biomass utilization operations. In practice, forest bioenergy faces challenges related to fluctuating social support and the increasing availability of cheaper wind and solar energy. Galik et al. [79], in their social research in the USA, demonstrated that forest bioenergy lacks a natural constituency that is willing or able to represent it in political debates. The changing and unequal support for forest bioenergy hinders durable political solutions, resulting in limited operational and land use planning opportunities. Mola-Yudego et al. [80] note that the strategy for managing woody biomass resources should have a local rather than a general character. This is particularly relevant during the energy transition stages of EU countries towards renewable energy sources. Each country, and even each region, should develop independent political strategies for biomass production to effectively utilize their own potential in wood-based bioenergy.

5. Conclusions

In most European countries, the production of roundwood per unit of forest area has been increasing since 1992, especially in the Czech Republic, Germany, Estonia, Denmark, and the UK. A decreasing trend in roundwood extraction has been observed in France, Spain, Greece, and Cyprus. Regarding the consumption of woody biomass (both primary and pellets) per capita, the highest values were found in Estonia (5 m^3/capita), Finland (4.66 m^3/capita), and Sweden (approximately 3 m^3/capita). The lowest indicators, except for Malta, were observed in Cyprus, Greece, Spain (approximately 0.14 m^3/capita), and England (0.17 m^3/capita). On the other hand, the highest consumption per unit of country area was found in Austria (180 m^2/km^2) and Estonia (158 m^3/km^2), while the lowest is in Cyprus (2.2 m^3/km^2), Greece (10.1 m^3/km^2), and Norway (11.7 m^3/km^2).

Woody biomass still holds a significant position among renewable energy sources in Europe. The significance of biomass as an important and strategic resource in EU countries is likely to continue growing. This was evident during the energy crisis (caused by the war in Ukraine) in many European countries in 2022 and the resulting issues with access to traditional but crucial sources of energy, such as natural gas and coal.

The clusters identified using the Ward agglomeration method based on the production and consumption of woody biomass primary (fuel wood) and secondary (pellets) were found to be heterogeneous. Tests to identify the factors influencing the differentiation of objects (including roundwood production, growing stock density, forest area, share of solid biomass energy, and share of renewable energy sources used for heating and cooling) did not show statistically significant differences between clusters in terms of forest biomass production. Regarding biomass consumption, the analysis only revealed significant differences in terms of the share of fuel wood in roundwood production. The diversity of identified clusters may result from other unaccounted external variables, such as the country's location and that natural–geographic conditions that determine access to different sources of energy, including hydropower, wind power, and solar energy. Economic, political, technological, ecological, and social factors also play significant roles.

The management of biomass for energy purposes, beyond studying its physicochemical properties, should include analyses of resource availability and the prediction of supply of primary and secondary woody biomass. Forecasting the production/supply of primary and secondary woody biomass for energy purposes is crucial for investors due to potential plans for investment/technology localization and the cost optimization of bioenergy production. Supply forecasts for roundwood generally yields satisfactory results, and the inclusion of exogenous variables influences the quality of the models to varying degrees. The results obtained in this study were subject to errors that varied depending on the country. The lowest values were obtained for Norway (MAE = 22.01, RMSE = 27.47), while the highest values were observed for Estonia (MAE = 133.52, RMSE = 168.26). The utilization of neural networks to predict roundwood supply can be practically employed and hold significance for market participants.

There is a need for further research in this area, particularly for the purpose of developing a rational EU policy and providing special treatment to member countries in the process of transforming their energy systems towards renewable energy. It appears that countries during energy transition towards renewable energy and with significant wood resources, after considering the needs of the forest industry, should freely utilize wood for bioenergy during the transitional period. Therefore, it is necessary to develop national strategies for the cascading use of wood, including for bioenergy purposes.

The availability of reliable and standardized source data on the level of production and consumption of woody biomass in European countries for energy purposes, particularly industrial residues and post-consumer wood, has been limitation on research. It is necessary to improve the process of data collection and reporting in this area at the EU level. It is worthwhile to continue research on the significance and potential of primary and secondary woody biomass production for energy purposes in European countries in order to develop good practices for the sustainable utilization of forest biomass at national and regional levels. Knowledge in this area can reduce costs and improve management processes for the benefit of forest ecosystems, societies, and the climate.

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