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Competitive Potential of Stable Biomass in Poland Compared to the European Union in the Aspect of Sustainability

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Abstract: Biomass is the primary source of renewable energy in Poland. Its share in renewable energy production in Poland has decreased in recent years, but it still maintains a nearly 70% share. Poland has extensive forest and straw resources, such as pellets, which can be used for stable biomass production. The main objective of this research was to understand the potential of plant biomass production for energy purposes in Poland and other European Union (EU) countries in terms of sustainable development. The period of analysis covered 2000–2022. Secondary data from Statistical Poland and Eurostat were used. The primary research method was the Augmented Dickey–Fuller (ADF) test, which aimed to check the stationarity of stable biomass. Moreover, we calculated the Vector Auto-Regressive (VAR) model, which was used to develop the forecast. The indigenous production of solid biomass in 2022 decreased to 363,195 TJ, while in 2018, it was 384,914 TJ. Our prognosis confirms that biomass will increase. The prognosis based on the VAR model shows an increase from 365,395 TJ in 2023 to 379,795 (TJ) in 2032. Such countries as France, Germany, Italy, Spain, Sweden, and Finland have a bigger potential for solid biomass production from forests because of their higher area. As a result, Poland's biomass production competitiveness is varied when compared to other EU nations; it is lower for nations with a large forest share and greater for those with a low forest cover. The two main benefits of producing solid biomass are its easy storage and carbon dioxide (CO_2) neutrality. The main advantage is that solid biomass preserves biodiversity, maintains soil fertility, and improves soil quality while lowering greenhouse gas emissions and environmental pollutants. The ability to leave added value locally and generate new jobs, particularly in troubled areas, is the largest social advantage of sustained biomass production.

Keywords: biomass; renewable energy sources; competitiveness; sustainable development; European Union

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1. Introduction

Changes in the economy require new energy systems, which should be renewable, sustainable, efficient, and safe [1]. Energy sources are classified into fossil fuels, renewable sources, and nuclear energy. Economic, social, and environmental conditions should be

taken into consideration when choosing energy sources worldwide [2]. Conventional fuels are the primary sources of energy, and their supply is evaluated at a level above 80% of the world's energy requirements [3]. It is suggested that fossil fuels are responsible for 80% of greenhouse gas (GHG), causing a rise in temperature, which may lead to the death of 100 million people in the world [4].

Research on renewable energy sources presents several challenges, such as the availability of raw materials, environmental impacts, and economic and technological issues. Current energy trends strongly favor sustainable and renewable energy production. Renewable energy is assumed to solve many problems related to the climate crisis, the reduction of natural resources, and issues related to energy security. The most crucial climate crises include increasing temperature, flooding, hurricanes, droughts, warmer water, increasing humidity, tropical cyclones, stronger erosion, and other negative environmental impacts [5]. European energy strategy is based on renewable energy sources; bio-energy and biomass played a key role in contributing two thirds of the EU's 2020 target [6].

Biomass is the world's largest potential energy source. Biomass is mostly derived from plant, forest, and agricultural waste. Very little biomass is derived from animals, who contribute very little to the overall biomass potential in the world [7]. Energy is derived from biomass in the process of combustion with many different types of sources and conversion options. It can be achieved from short-rotation crops (SRC), perennial grasses, forestry, and other plant residues [8]. Forestry biomass can be wood biomass or industrial roundwood (for paper and furniture). Biomass contains cellulose, hemicellulose, lignin, and other important ingredients [9].

Energy obtained from biomass accounts for about 15% of global energy consumption, with a wide range from 2 to 3% in developed countries and about 38% in developing countries. Some regions in the world are very dependent on bio-energy, and it is the main energy source in Bhutan (86%), Nepal (97%), East Saharian Africa (81%), and Africa (39%) [10].

Renewable energy sources are necessary to develop a modern economy. However, the development of a bio-based economy requires funds. The most important policy in the EU is the Common Agricultural Policy (CAP), but this policy does not directly support the bio-based economy. The CAP could support feedstock economics and increase biomass availability by providing subsidies to farmers for biomass production [11].

Nonrenewable energy sources are the main source of greenhouse gas emissions, and they should be replaced with renewable energy. This replacement can support the required level of energy input sufficient for sustaining economic growth while reducing emission levels at a global scale [12]. Fossil fuels are the main sources of CO_2 emissions from burning, and industrial processes account for 65% of global greenhouse gas (GHG) emissions, and that is why they should be replaced by renewable energy sources [13].

Biomass is everything that exists on Earth in the form of organic matter, all biodegradable substances of plant or animal origin. Biomass contains residues from agricultural production, forestry residues, and industrial and municipal waste [14]. It is an organic substance formed in the process of accumulating solar energy [11].

Biomass is decisive as a renewable energy source. In the literature, there are no forecasts or comparisons of biomass to other sources of renewable energy in the context of its characteristics as well as advantages and disadvantages. Moreover, most elaborations describe biomass as all components. In addition, biomass competitive potential in Poland and other European Union countries has not been recognized. The context of sustainable development has also not been analyzed in depth. The authors are especially interested in forest cover because it is the main source of forest biomass in Poland. Moreover, we analyzed stable plant biomass, which is rather limited in the literature.

The following paper presents a comprehensive approach to the subject of plant biomass for energy purposes, considering both its advantages and disadvantages compared to other energy sources, in order to create a picture of the opportunities and prospects for the development of this sector in Poland and the European Union (EU). Attention is drawn to the insufficient understanding of the role of plant biomass as an alternative to fossil fuels. When analyzing the literature on renewable energy, it was noticed that relatively little is said about biomass, and its potential is often underestimated. This prompted the authors of the paper to investigate this problem more deeply and to try to fill this knowledge gap.

The main objective of the research was to understand the potential of plant-stable biomass production for energy purposes in Poland and other European Union (EU) countries in terms of sustainable development.

The detailed aims included the following:

1. Recognition of advantages and disadvantages of solid biomass production.
2. Recognition of the competitive advantages of solid biomass production.
3. Elaboration of a prognosis for solid biomass production in Poland.

The following research questions were formulated as part of the main objective:

1. What are the sustainability benefits of using biomass?
2. What are the advantages and disadvantages of biomass energy compared to other renewable energy sources?
3. What is the competitive potential of biomass compared to other renewable energy sources?

H1. *Stable biomass is Poland's most important renewable energy source because of its large resources of forests.*

H2. *The share of stable biomass will increase because of strong pressure to acquire renewable energy sources in the European Union (EU).*

The paper is organized as follows: First, we present an introduction in which we point out the research gap and sustainable development concept. Second, we present the drawbacks and strengths of biomass compared to other renewable energy sources. Then, we presented forestry as the main source of biomass in Poland and other European Union countries. At the end of the results, we present the ADF test and prognosis of biomass in Poland based on the VAR model. The final part is the conclusion.

2. Sustainability Issues of Biomass Production

The biggest advantage of renewable energy sources in building sustainable development is their environmental friendliness. The rational use of energy and renewable energy sources, in general, are the fundamental inputs for any responsible energy policy [15]. Interest in economic changes resulting from the rapid development of industrial production has led to the neglect of research into the relationship between humans and the environment. In human history, development has created pollution. Marginal returns on investment and technologies are the subjects of debate among economists and environmental scientists [16].

The science of economics comes to the rescue, which shows how to manage the resources of the environment so that, in the long run, they generate the greatest possible benefits for humanity [16]. T. Malthus (1766–1834), in his essay on the right of the population, stated that in nature, there is a tendency for the population to exhaust all possible means of subsistence, and the provision of sufficient food for more and more people puts the struggle in a losing position in advance [17].

The processes of globalization in the second half of the 20th century led the planet to a rapid depletion of basic raw materials, including primary energy carriers. Increased interest in the accelerated depletion of resources and progressive degradation of the environment enabled the internationalization of ecological processes, including the emergence of global processes, which pose a threat to the maintenance of life processes by nature. As a result, in the 1970s, a new trend within economics was developed—environmental economics, the aim of which was to solve the most urgent problems arising at the interface of economics and the environment [16].

Sustainable development is the pursuit of improving the quality of life while maintaining economic, social, and environmental sustainability [18]. The basis for the development of the bio-economy is raw materials produced based on air, water, and soil resources, and the biological diversity of plants, animals, and microorganisms [19]. Sustainable development has led to a bio-economy in which the frontier for green and low-carbon or carbon-free economy is elaborated. The necessity to shift from fossil fuel to renewable energy sources has placed a challenge to developing a bio-based economy. Agriculture plays a key role in the economy because it delivers goods for the growing population in addition to raw materials for industries and energy [20].

Therefore, it is necessary to combine three orders, environmental, economic, and social, which together can provide effective criteria for sustainable development. It is about finding and combining the right balance between the economy, the environment, and society. The biggest environmental benefit from solid biomass production is the reduction of greenhouse gas, keeping biodiversity and preserving soil fertility. The most important economic benefit from solid biomass is the development of entrepreneurship. The biggest social benefit is the opportunity to create new jobs.

In the context of sustainable development, environmental protection is becoming a key aspect in the field of economics. Environmental issues appear already during the creation of the economic foundations of human activity and are then developed within the framework of classical and neoclassical economics, environmental and natural resources economics, and ecological economics [21]. Environmental protection is, therefore, part of a wide range of economic approaches leading to sustainable development.

Since the turn of the century, it has become increasingly clear that the economics of sustainable development cannot be limited only to limiting overexploitation and strategy development. It must develop strategies for solving other economic and socio-cultural problems that care about our future [20]. The most important environmental dimension is the protection of Earth's atmosphere from greenhouse gas emissions and pollution.

Currently, the economy is undergoing a stage of significant transformation. As its foundations change, the importance of socio-economic development with respect for the environment as the main economic and non-economic goal is growing. Economic growth is giving way to striving to achieve a sustainable economy based on the principles of nature conservation [21]. Environmental services are becoming a priority element in the emerging economy of sustainable development. In the scientific debate, no consensus has yet been reached on a uniform approach, nor has a universally recognized research methodology within economic sciences been developed [21]. Thus, environmental services continue to be an area of scientific exploration and analysis. Nevertheless, they are an indispensable part of the future of economics.

Based on the above observations, it is clear that the implementation of the idea of sustainable development in economics requires taking action in two areas. The first is to create a theoretical basis within the economics of sustainable development derived from the economics of the environment and natural resources. The second path is the development of didactics related to the economics of sustainable development. The implementation of this

concept requires qualified specialists at all levels of management: macro-, meso-, and microeconomic. The introduction of competent staff is crucial for the effective implementation of the idea of sustainable development [22].

The sustainability issue was analyzed by Lucia and Grisolia [23]. The authors found that the negative effect of greenhouse gas (GHG) on the environment should be analyzed regarding human well-being. The emissions are emitted into the atmosphere by people and human activities and by natural phenomena. The authors elaborated the Thermodynamic Human Development Index (THDI) as a bio-economic indicator, which also considers a society's technical and environmental level; moreover, it introduces the consequences of the irreversibility of the processes on the sustainability measurement.

The deep analysis should include external environmental costs and other characteristics such as human well-being and surveys among the population. Such indexes should contain information about demographic aspects and health services [24]. Moreover, much of the energy (20%) is consumed by refrigeration. This branch of industry should be considered because it has big applications in households, i.e., in refrigeration and freezers. The impact of the refrigeration sector is wide from agriculture to industry and other economic sectors [25].

3. Materials and Methods

3.1. Data Sources

The paper was written based on different sources of information. The first part is devoted to macroeconomic issues, in which the role and competitiveness of biomass against other renewable energy sources (RES) in Poland and the European Union (EU) in the years 2000–2021 were analyzed, as well as further forecasts and their development. The main source of data was Eurostat [26].

A comprehensive analysis, using various data sources, was undertaken to assess the competitiveness of biomass as a carrier of renewable energy sources (RES) in Poland against the background of the European Union (EU). In the first stage, information was collected through literature studies, a review of legal acts, and an analysis of public statistical data.

Data analysis included a Vector Auto-Regressive (VAR) model and other statistical techniques. Thanks to such a wide spectrum of research methods, it was possible to accurately determine the competitive position of biomass in relation to other renewable energy sources (RES) in the Polish and European context. The most important source of information was Statistics Poland data (Figure 1). The share of stable biomass in renewable energy sources is still high, and in 2020, it was 71.61%. However, the production of renewable energy from stable biomass increased from 190,473 TJ in 2005 to 363,195 TJ in 2022. However, it reached the biggest amount of 384,914 TJ in 2018.

Biomass and renewable energy also have drawbacks. Power variability, high investment costs, and the need to meet appropriate weather conditions are just some of them.

This review points to the need for further research and investment to make effective and efficient use of these energy sources while minimizing their drawbacks. Further technological developments and innovative approaches to the production and use of renewable energy can help meet sustainability and environmental goals.

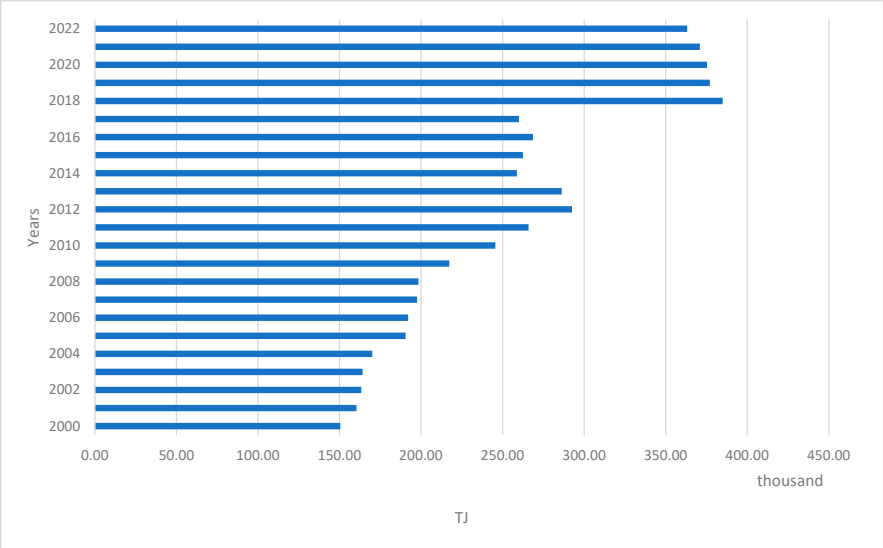

Figure 1. Production of renewable energy sources from stable biomass in Poland, 2000–2022 (TJ). Source: own elaborations based on Statistic Poland [27].

The discussion about biomass's disadvantages and advantages is very broad. Biomass also has disadvantages because its combustion produces particulate matter (PM) to the extent that biomass combustion is prohibited in some areas. During combustion, energy stored in the chemical bonds of the fuel is converted into heat and light, which propagates in the cylinder of an engine and transforms the heat into electricity [28].

Table 1 below examines various aspects of renewable energy, with a particular focus on biomass, biogas, biofuels, and other renewable energy sources (RES).

The advantages of biomass include its CO_2 neutrality, the practical availability of the raw material, and the ability to use it to produce many forms of energy, from heat to fuel. Despite some challenges, such as logistical problems or substrate price fluctuations, biomass is considered a stable, distributed energy source that does not require large technological investments.

Other renewable energy sources, such as solar and wind energy, are very clean energy sources that do not consume natural fuels and do not pollute the environment. Their advantages include their availability, the possibility of building on wasteland, and the possibility of free energy after recouping the installation costs.

Burning biomass causes pollutant gas to enter the atmosphere [29]. The emission can be harmful to health and can cause lung cancer and chronic lung and heart diseases [26,27]. Different analyses were conducted to evaluate the biomass combustion. According to Bossard et al. [30], wood pellets have the lowest ash content at 750 °C (0.54%) and the lowest humidity content (6.57%) among the experimental biomass fuels. Akinrinola et al. [31] conducted research in Nigeria and found that woods were low in potassium (K), silicon (Si), and calcium (Ca), resulting in low calculated alkali indices, resulting in a small impact of these fuels on health (Table 1).

Another group of authors pointed out biomass's advantages because it is well recognized as a renewable source of energy [32,33]. The increasing demand for energy means that biomass is a very promising source of energy [34]. Reasons for this are that biomass contains small amounts of sulfur, nitrogen and ash. Moreover, its combustion produces less harmful gases, such as nitrogen oxides (NO_x), sulfur dioxide (SO_2), and soot, compared to conventional fossil fuels. The CO_2 released from the combustion of biomass is recycled into the plant through photosynthesis [35]. It is scientifically proven that biomass is carbon neutral, and it releases only the amount of CO_2 that has been captured for the tree to

grow [7]. However, we must realize that we must wait many years for the process of growing trees, sometimes hundreds of years. Moreover, people cannot use only wood as a renewable energy source because it may cause deforestation and degradation of the countryside, and rapid emission of CO_2 and other harmful gases [36].

Table 1. Advantages and disadvantages of biomass energy compared to other RES.

Energy from Biomass, Biogas and Biofuels	Other RES
Advantages	
- Biomass and biofuel-derived biofuels are CO_2-neutral (this is the CO_2 that circulates in circulation) - production waste of the forestry and agricultural industry is managed, municipal waste is utilized - practical availability of raw materials - biomass can be used to produce many forms of energy, from heat for heating to fuel for a car - burning biomass leaves small amounts of ash - biomass is constant in contrast to the unpredictable energy of wind or sun - biomass resources can be stored and used as needed - biomass production does not require large technological investments - the least capital-intensive renewable energy source - well-known technologies for obtaining energy from biomass - dispersion of energy production	- A very clean source of energy - do not pollute the environment with exhaust fumes and dust - do not consume natural fuels - can be built on wastelands (deserts, coasts, rocks) - dispersion of energy production - free energy (especially important after the costs of building the installation have been recouped) - practical availability of energy - the possibility of producing electricity and heat (solar collectors)
Disadvantages	
- Logistical problems (very often, the substrate has to be transported to the indicated power plant) - fluctuations in substrate prices (currently, the price for substrate is very inflated) - with greater interest in the production of biomass for energy purposes, it is possible to increase food prices - combustion of biofuels, like any combustion, causes the formation of NOX, but the costs of their disposal are higher than in the case of large professional energy plants - ash from some biofuels melts at combustion temperature, plugs the grate, and must be mechanically broken up, m.in. with a breaker or disintegrator - low density of the raw material, making it difficult to transport, store, and distribute - a wide range of biomass moisture, making it difficult to prepare it for use for energy purposes - some waste is only available seasonally - chlorine corrosion in the case of bio-green mass, for example, straw, leaves, grasses - transport of biomass causes additional emissions of pollutants	- There is interference with the natural landscape - operation of the power plant determined by the weather (dependence on wind, sun, rainfall) - high investment and operating costs - they can lead to the destabilization of the country's energy system - due to the cyclical nature of the operation, they require the use of energy accumulators - variability of power over time - wind and solar farms take up much space and need uninhabited areas far from cities - appropriate weather conditions are required for their construction, related to the strength and location of the wind - daily, annual, and stochastic (random) cyclicality - relatively low-capacity utilization factor for PV approx. 11%, onshore wind turbines approx. 28%

Source: own elaboration based on [2,35,36].

3.2. Potential of Biomass in Poland Compared to Other EU Countries

Biomass has key advantages as a renewable energy source compared to other forms of RES. It stands out for its renewability, potential carbon neutrality, efficiency in processing, and versatility in the production of various forms of energy. In addition, biomass has a significant impact on waste management, reducing the amount of waste going to landfill. An important aspect is also the availability of biomass, which allows energy production to be adapted to the current demand [30]. The main sources of biomass are forest waste, waste and by-products of the forestry industry, agricultural waste, including straw and hay, harvest residues, waste and by-products of the processing industry, and other organic waste, such as sewage sludge from municipal management and animal manure [31,37].

Biomass is a renewable energy source that can be used for both electricity production and heat generation. Its competitiveness compared to other renewable energy carriers depends on various factors, such as location, availability of raw materials, technologies, costs, and energy policy. Here are some aspects that affect its competitiveness compared to other renewable energy sources.

The availability of raw materials can affect biomass's competitiveness. In places where raw materials are abundant and cheap, biomass may be more competitive [38,39].

The technologies used to convert biomass into energy are crucial to determining its competitiveness. Technologies such as combustion, gasification, fermentation, or cogeneration have different efficiencies, which can affect the cost of energy production from biomass [40].

However, biomass can be competitive in some cases, especially when favorable local conditions, such as the availability of raw materials or infrastructure, exist [34]. Due to its higher availability, biomass has advantages over other renewable energy sources, such as solar or wind power. This means that biomass energy can be produced regardless of weather conditions, which can affect its competitiveness.

Government support and regulations affect the competitiveness of various renewable energy sources [35,36]. In countries that promote biomass as an energy carrier, there may be incentives such as subsidies, tax breaks, or feed-in tariff schemes that affect the competitiveness of biomass compared to other renewable energy sources.

Forest area which are the main source of stable biomass are presented in Figure 2. Sweden, Finland, Spain and France have the biggest forest area in the European Union, that is why their competitive potential of stable biomass from forest is the highest.

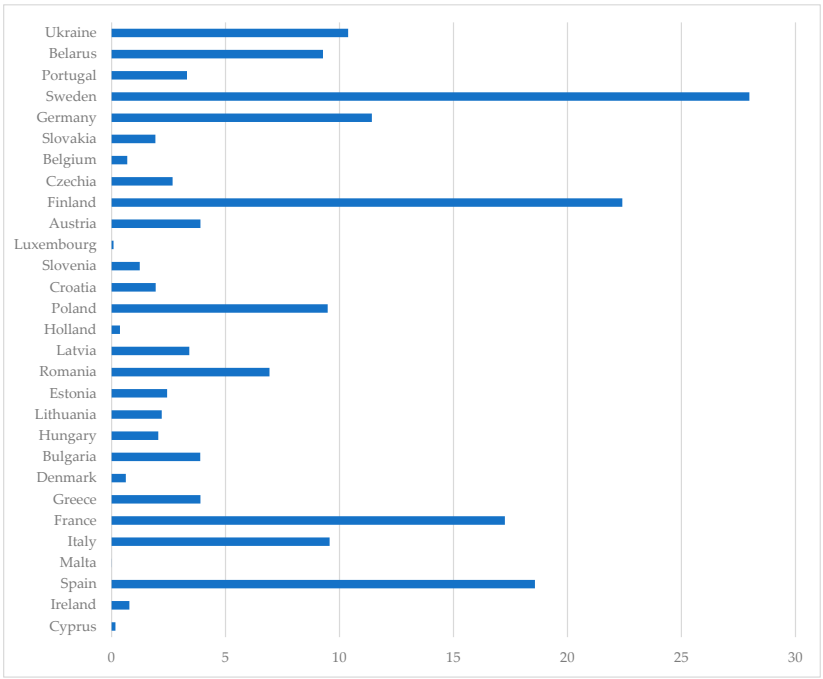

Figure 2. European countries by forest area (million hectares in 2020). Source: own study based on [41].

The analysis of Figure 3 above concerns the competitive potential of plant biomass in Poland compared to other European Union countries, based on data on the forested area. Poland, with a share of forests in the total area of the country at the level of 30%, occupies an intermediate position compared to other EU countries.

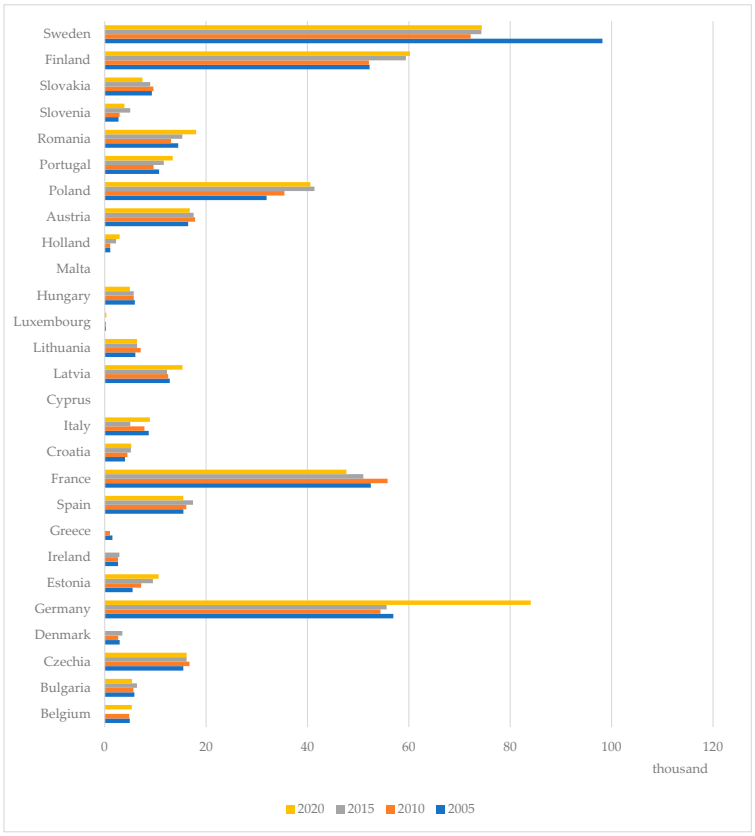

Figure 3. Amount of harvested round wood (thousand m^3). Source: own study based on [41].

Countries such as Finland, Sweden, and Estonia stand out for their high percentage of forested areas (66%, 63%, and 54%, respectively). These countries have a strong potential for biomass production due to their rich forest resources. On the other hand, countries such as Ireland, Malta, and the Netherlands have a low share of forests in the total area of the country (11%, 1.5%, and 10%, respectively), which may mean limited opportunities for large-scale biomass production.

Poland, with a share of forested areas of 30%, has moderate opportunities to develop the production of plant biomass. For this reason, Poland's competitiveness in biomass production compared to other EU countries is diverse—lower in relation to countries with a high share of forests but higher in relation to those with low forest cover. However, competitiveness depends not only on the share of forests but also on other factors such as energy policy, access to technology, and financial support for the future production of energy from biomass [29,41].

The analysis of Figure 3 below concerns the amount of harvested round timber in various European Union countries in 2005, 2010, 2015, and 2020, expressed in billions of cubic meters (billion m^3).

The data shows that in 2020, Germany harvested the largest amount of wood (84.051 billion m^3), which is a significant increase compared to 2005 (56.946 billion m^3). The next country with the largest amount of harvested wood is Sweden, which decreased the level of production (74.400 billion m^3 in 2020, compared to 98.200 billion m^3 in 2005).

In Poland, the amount of timber harvested also increased—from 31.945 billion m^3 in 2005 to 40.593 billion m^3 in 2020. This shows that Poland is also intensifying wood harvesting, which may translate into greater potential in biomass production.

At the same time, it is worth noting that in the case of some countries (e.g., France), the amount of timber harvested is decreasing (from 52.499 billion m^3 in 2005 to 47.703 billion m^3 in 2020).

Overall, at the level of the European Union as a whole (EU-28), the amount of harvested roundwood increased from 14.918 billion m^3 in 2005 to 18.467 billion m^3 in 2020, indicating the growing importance of wood as a raw material for various sectors of the economy, including biomass production (forests, forestry, and logging 2023).

Although Poland is not the leader in the EU in terms of the amount of timber harvested (Germany and Sweden have higher values), the dynamic growth over the last 15 years suggests that Poland has the potential to increase its role in the biomass market. Poland also has a well-developed infrastructure of the wood and agricultural industries, which can contribute to the efficient use of harvested wood for energy purposes.

Nevertheless, Poland's competitiveness in the biomass market in the EU depends not only on the amount of wood harvested but also on factors such as investments in processing technologies, logistics, the country's energy policy, and environmental requirements and regulations at the national and EU level.

The wood from forests is mainly used for pellet production. The production of pellets increased in the EU by almost 80% in the period 2010–2018 [42,43]. The production of biomass from forests also needs to exclude so-called "hogfuel", which consists of bark or other low-quality residues, and it is estimated that up to 24% of carbon-neutral "hogfuel" is additionally needed for the pellet-production process [44]. It is proven that fibers for pellet production should be preferred over the use of fresh fibers [45]. The European Union is responsible for the production of as much as 44% of pellets in the world. In turn, biofuel consumption in EU countries is estimated at 50%. As a result, Europe remains the world's largest producer and consumer of pellets. Pellet heating is a good option for households, especially in biomass-rich rural areas.

In 2022, Poland imported 17,199 TJ of solid biofuels and exported 14,248 TJ. Poland achieved a negative trade balance of solid fuels because of a high demand. Agricultural biomass, in particular energy crops, which are divided into annual and perennial plants, as well as residues associated with agricultural production, is also important. However, straw that can be obtained from arable land and permanent grassland can also be a source of biomass [46].

Poland is considered to be an important producer of agricultural, horticultural, and animal products globally and in Europe. In Poland, which occupies 31.3 million hectares, as much as 14.6 million hectares are occupied by agricultural land, constituting about 47% of its area [41]. In recent years, the renewable energy market has developed in Poland, where biomass energy is a significant part of it. Poland is rich in raw materials, constituting a reservoir of solid biofuels, which come from agriculture, forestry, the wood industry, and related industries [29]. Currently, the energy sector is increasingly turning to renewable sources for energy production, including biomass. However, it is important that the energy sector uses fractions of this fuel that will not be used in other sectors of the economy, primarily waste and residues from the agri-food industry and forestry [47].

Biomass can be obtained in Poland in many ways, and the main sources in the entire production structure are agricultural land (accounting for 48%), forestry (25%), fruit farming (14%), and the wood industry (13%) [41,42,48].

The development of the renewable energy sector is a challenge for rural areas, where the role of agriculture in the development of the renewable energy sector does not have to be limited only to the production of energy raw materials. Farmers should also participate in the next stage of the processing of energy biomass [45].

As a result, this activity may become another direction of diversifying agricultural income, implying changes in the structure of agriculture [48]. Solid biomass must be the main source of renewable energy in EU member states and Poland.

On the other hand, the use of biomass itself should be as close as possible to the place of origin so that its transport does not cause a negative environmental effect. The products used for energy purposes are usually the following:

- low-quality wood and wood waste,
- straw, hay, and other agricultural waste,
- sewage sludge,
- animal excrement,
- vegetable oils and animal fats,
- organic waste (seaweed grown specifically for such purposes),
- branches from orchard cuttings,
- other waste from plant and vegetable production,
- plantations of energy crops,
- trees and branches from the felling and sanitary felling of forests [48].

Biomass in the energy-processing process must be stable in terms of chemical properties (calorific value) and physical properties (moisture). It must also have the appropriate fraction, material homogeneity, and be free of impurities (sand, soil). The high availability of biomass types causes many logistical, technical, technological, and economic problems at the stage of acquisition and use [48].

3.3. Methods

To test the degree of integration of the variables, the Dickey–Fuller test (unit root test) can be used. However, we used the ADF test (Augmented Dickey–Fuller test), where

$$xt = (t - 1, \ldots T) \tag{1}$$

The methods used allowed for the realization of the main objective and specific objectives of the research, at the same time contributing to a comprehensive approach to the undertaken issues, both in the empirical and theoretical dimensions. In the processing of the research material in the form of quantitative data, the process is described by the following formula [49]:

$$xt = u + \rho xt - 1 + \varepsilon t \tag{2}$$

where x0 = 0, u is a constant, and {εt} is a sequence of independent normal random variables with zero mean and variance σ2 (i.e., εt~i.i.d (0, σ2)).

We also used the Vector Auto-Regressive (VAR) model, which is widely used in econometric analysis [50]. These models analyze the uncertainty in the underlying distribution [50,51]. They are also used for data interdependences and test hypotheses [52]. This model analyzes the quantile of distribution [46]. The applications for these models are wide, e.g., to evaluate the performance of risk-takers, regulatory requirements, and financial analysis in banks [53–55]. This tool is used for volatility forecasts in the financial industry [56,57].

The form is as follows:

$$Zt = \sum_{i=1}^{k} AiZt - 1 + \varepsilon t, t = 1, 2, \ldots n \tag{3}$$

where Zt is the vector of observations of the current values of all n model variables, Ai is the matrix of auto-regressive operators of individual processes in which no zero elements are assumed a priori εt is the vector of residual processes for which it is assumed that individual components are simultaneously correlated with each other, but do not contain autocorrelation, and k is the order of the VAR model.

First, we assessed in the papers the literature review and pointed out the research gap. We presented the advantages and disadvantages of biomass. Moreover, we characterized the competitive potential using literature sources. The authors of the paper presented the ADF test to measure the stationarity of the data and the VAR model to prepare the prognosis. The section on forecasts for biomass and energy production from renewable energy sources (RES) in Poland is based on a detailed analysis of data from 2000 to 2022. Both descriptive statistics and advanced econometric analysis methods were used to evaluate the results of the study using the GRETL software.2024d.

4. Results

4.1. Global Production of Bio-Energy and Share of RES in Gross Final Energy Consumption in 2022

Global production of bio-energy has increased. For example, the production of bio-energy was 30,118.87 TJ in 1990 to 52,901.62 TJ in 2022. The global production of bio-energy increased by 76% from 1990 to 2022. These changes reflect the effect of the need to increase renewable energy worldwide (Figure 4).

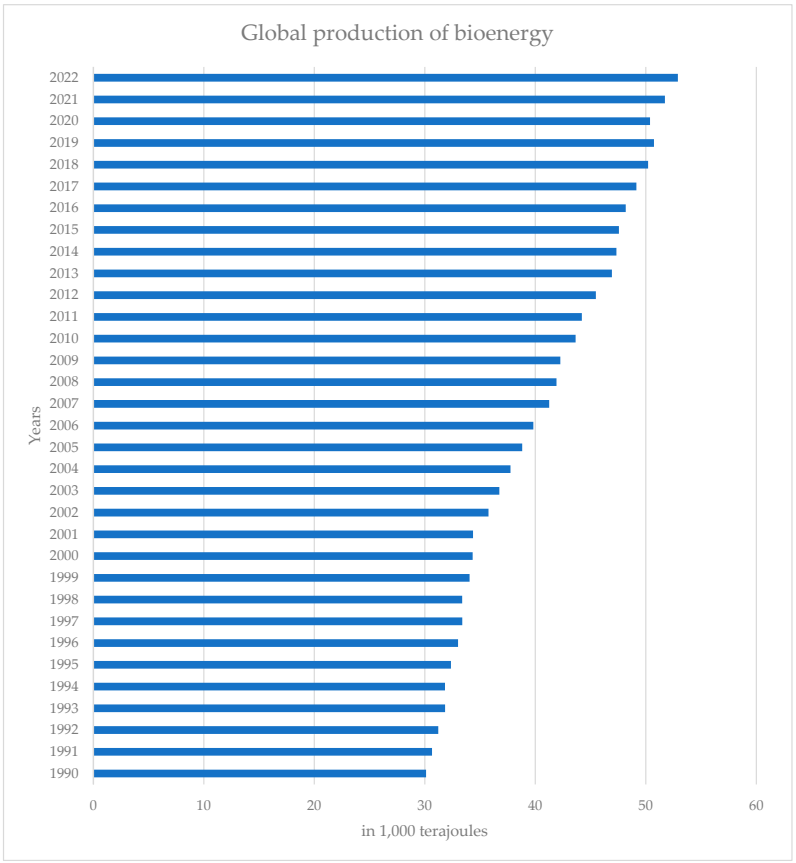

Figure 4. Total production of bio-energy worldwide from 1990 to 2022 (in 1000 terajoules). Source: own elaborations based on https://www.statista.com/statistics/1497660/global-production-of-bio-energy, accessed on 15 November 2024 [58].

The total production of bio-energy is diversified by sources. Fuelwood constitutes 31,010.44 (1000 terajoules), other vegetal material and residues 10,205.52, bagasse 3963.38, biogasoline 2253.98, biodiesel 2166.83, charcoal 1920.85, black liquor 1842.89, biogases 1093.28, animal waste 329.76, and other liquor biofuels 35.54 (Figure 5). Fuelwood is considered to be the most important renewable energy source worldwide. Global wood resources are still big and can be used for renewable energy production.

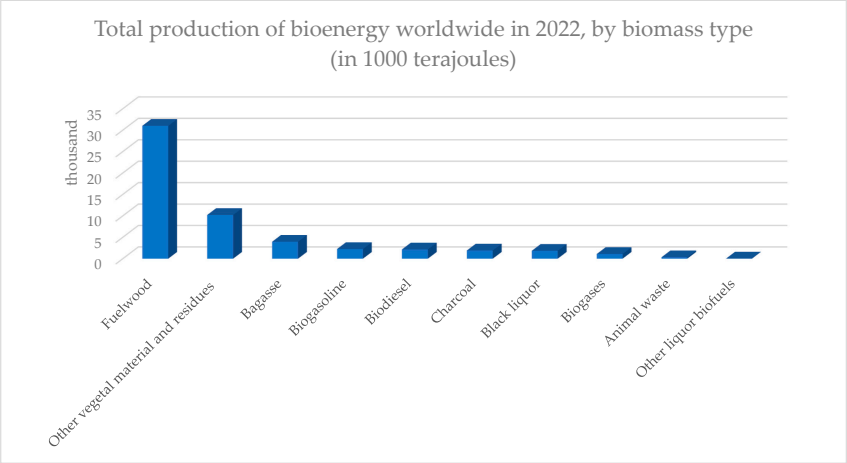

Figure 5. Total production of bio-energy worldwide in 2022 by biomass type. Source: own elaborations based on https://www.statista.com/statistics/1497660/global-production-of-bio-energy, accessed on 15 November 2024 [58].

Biomass also includes processed forms, including pellets and briquettes. Poland ranks seventh in terms of gross availability of energy from solid biofuels in the European Union (EU) (approx. 6.2 Mtoe) [46]. Most EU countries have achieved the required level for renewable energy sources (Figure 3). The biggest share of renewable energy sources in 2022 was Sweden (66%), Finland (47%), Latvia (43%), and Denmark (41%). Poland achieved more than 15% in renewable energy sources, which means solid biomass helped to achieve the level. The smallest share was achieved by Ireland (13%) and Belgium (14%) in 2022 (Figure 6).

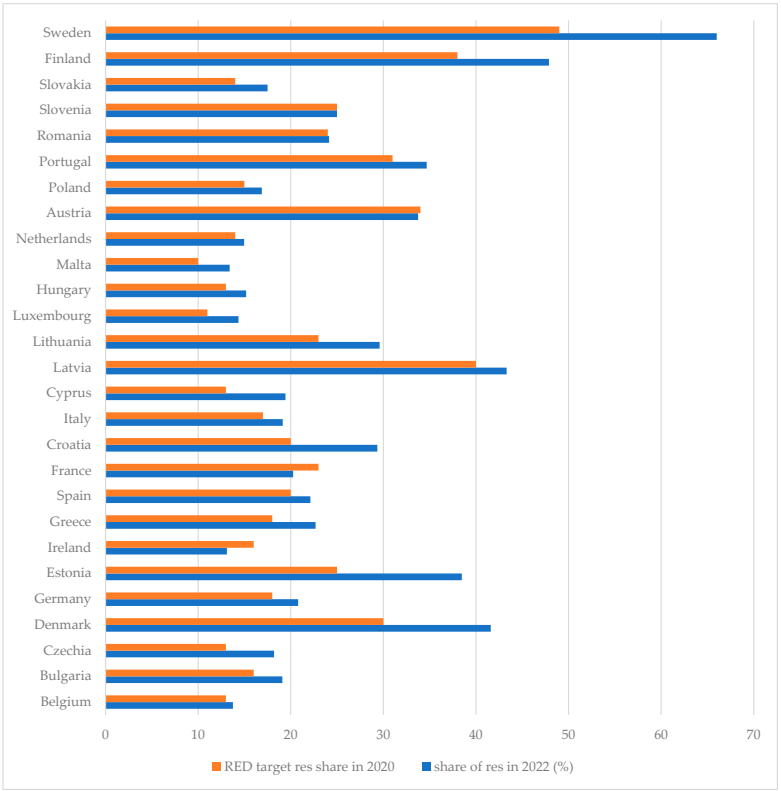

Figure 6. Share of RES in gross final energy consumption in 2022 in the European Union (EU) (%). Source: own elaborations based on Statistics | Eurostat (europa.eu https://commission.europa.eu/about/departments-and-executive-agencies/eurostat-european-statistics_en, accessed on 30 July 2024) [59].

In 2022, solid biomass had about 70% of the renewable energy sources in Poland. Other sources were photovoltaics, wind energy, and liquid fuels. Geothermal energy and heat pumps have the smallest share of renewable energy sources.

4.2. ADF Test of Stable Biomass Production in Poland

The Augmented Dickey–Fuller test was performed to see if the process being analyzed is stable over time, i.e., stationary. The test included 23 observations and aimed to determine whether the process had a unit root, which would mean non-stationarity (Table 2).

Table 2. ADF test.

Specification	Intercept Test	Test with Intercept and Linear Trend
Estimated value (a-1)	0.10315	−11.2914
Test tuac statistic	0.8386	−2.1593
p-value	0.9947	0.5119
autocorrelation of first-order residuals	0.146	−0.331

Intercept Test (No Trend): This test assumed that the process "solid biomass" can have no stationarity. The model estimated using this test indicates that the value of the test result is −0.10315, with a *p*-value of 0.9947. This means that it cannot be ruled out that the process is not stationary.

Intercept and linear trend test: In this model, a linear trend has been added to the analysis. The test score was −11.2914, and the *p*-value was 0.5119, indicating that the process is likely non-stationary.

In both cases, the test showed that the "solid biomass" process can be non-stationary, meaning that its properties can change over time.

After differentiation, the process of "solid biomass" appears to be non-stationary, especially when considering a model with a linear trend. However, residual autocorrelation values indicate that the model may not be perfect, which is worth considering in further analysis.

4.3. Forecast of Stable Biomass Production in Poland Using the VAR Model

After a period of growth, Poland's energy production from solid biomass shows a downward trend in forecasts for the coming years, which may indicate changes in the structure or efficiency of renewable source use. The uncertainty of these forecasts increases in the longer term, marked by widening confidence intervals.

Wood-stable biomass can be used for pellet production, which accounts for 1.3 million metric tons in Poland [47,48]. This fuel is mainly used by residential consumers, commercial stakeholders, and for heat sales. That is why the authors of the paper intend to check the future prognosis of stable biomass.

The authors of the paper used the Vector Auto-Regressive (VAR) model (Table 3). The *p*-value of the model is 0.000, which suggests that the model was a proper choice for the data. We tested the model with the Portmanteau test: LB(5) = 3.82717, df = 4 [0, 4299]. The R2 for the model was 0.86209, which suggests a good adjustment of the model.

Table 3. VAR model of stable biomass production in Poland.

	AIC	**BIC**	**HQC**	**Constant**				**Model for Biomass**			
				Coefficient	**Std. Error**	**t-Student**	***p*-Value**	**Coefficient**	**Std. Error**	**t-Student**	***p*-Value**
Const	**23.483**	**23.582**	**23.506**	**25,714.8**	**21,639.8**	**1.188**	**0.2486**	**0.93525**	**0.0836**	**11.18**	**0.000**
Arithmetic mean of the dependent variable	Sum of square rest	R-squared determination coefficient	F	Autocorrelation of rests	Standard deviation of dependent variable	Standard deviation error3	Corrected R-square	*p*-value for F test	Durbin–Watson statistics		
257,506.4	1.700	0.86209	125.0257	−0.0923	76,533.3	29,123.1	0.855198	0.000	2.1763		

Source: own elaboration.

During the analysis, the VAR model was verified positively and can be used for prognosis elaborations. The data proved the lack of autocorrelation of random components and proved the normal distribution.

Figure 7 presents the prognosis elaborated on the VAR model, including stable biomass. The stable biomass production will increase in Poland. This can be achieved by a fast increase in the production of almost all renewable energy sources, including photovoltaics and wind production. Global warming and improving the state of the economy will increase the demand for stable biomass in Poland and other countries of the European Union (EU) [60]. However, based on the VAR model, the increase in stable biomass production is smaller, from 365,395 TJ in 2023 to 379,795 (TJ) in 2032. We can observe that the forecast interval depends on the average forecast error, which is increasing.

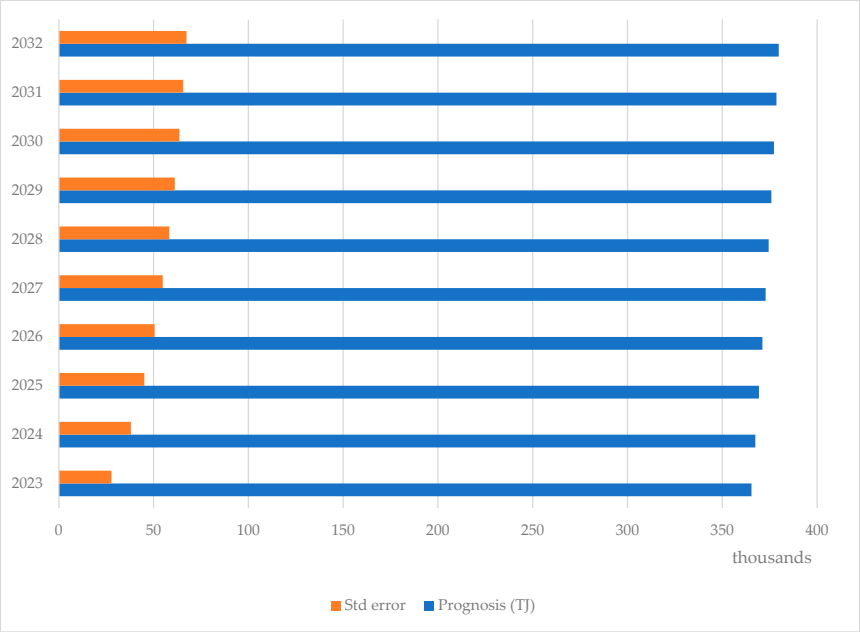

Figure 7. Prognosis of stable biomass production in Poland based on VAR model. Source: own elaboration.

5. Discussion

The VAR model has its limitations. Using each economic model is questionable because we do not know to what extent the model reaches the current and future situation in the market. Using econometric models, we want to explain and check the future situation, but we realize that it can be changed by different factors. First, it is projected on yearly data. Only such data are available. Yearly data are good, but weekly and monthly data would be more suitable because we could check the seasonality during the year and which part of the year sees particular changes.

The stable biomass production in 2022 was 363,195 (TJ), and in 2023 it was 365,395 (TJ). It means that the production of energy from biomass will increase. We realize that the demand for energy will increase, but it will be filled up by photovoltaic energy and wind energy and, in some countries, by nuclear energy. Households, especially in rural areas, will use biomass the most.

Renewable energy sources are the foundation of a sustainable future. Biomass energy uses organic matter such as wood waste or straw. Biogas energy exploits gas from landfill, sewage treatment plants, or livestock farms. Hydropower is based on the power of water in hydroelectric power plants, wind energy on the power of wind, and solar energy on sunlight in photovoltaic micro-installations. Geothermal energy uses the heat of the Earth. All these renewable energy sources are important for the development of the energy

sector in Poland. Among the renewable energy sources in the EU-28, the most important source is wood and other solid biofuels, which accounted for 41.2% of primary energy production from renewable sources in 2021. Wind power is the second largest share in the renewable energy mix with 13.6%, followed by hydropower with 12.3%. Biogas accounts for 7.5% of the share of energy production from renewable sources, liquid biofuels 6.5%, and solar energy 6.1%. Ambient heat energy (captured by heat pumps) accounted for 6.2%, geothermal energy 2.8%, and the share of renewable waste increased to 3.8% [61].

Biomass production is also a source for biogas production, which is also developing. Farms, municipalities, and forests are very important sources of material for biogas production [62].

Biomass production, which is an important part of renewable energy sources, fosters progress towards sustainable development and requires the pursuit of economic and environmental objectives. It can also improve eco-efficiency as a tool derived from the concept of sustainability [63]. The replacement of fossil fuels by renewable energy sources depends on the prices of bio-energy and the level of subsidization. The way to increase the renewable energy sources and production of biofuels is the competitiveness of agricultural raw materials in the food chain. This process causes an increase in prices of energy, food, and land. Therefore, the best way is to produce energy on a farm using its manure, for example, for biogas. Additionally, the use of one's own biomass for energy purposes on a farm can also be more effective because of the small logistics. This significantly decreases the transaction costs of the whole process [64]. Biomass plays an important role in Poland in the process of fossil-fuel usage decrease and the utilization of local forests. The share of forest in Poland is about 30%, which suggests a great potential for the production of biomass, such as pellets. Straw is also an important source of biomass in Poland; however, there is a demand for it in animal production [63].

Poland has a big potential for solid biomass production because of the share of forest exceeding 30%. However, such countries as France, Germany, Italy, Spain, Sweden, and Finland have a bigger potential for solid biomass production from forests because of their higher areas. That is why the production of stable biomass can be increased using residues in the production of energy crops in agricultural production systems, which are of great importance. The availability of land for the cultivation of energy crops depends on the total amount of available agricultural land and the demand for land for food and feed production [62].

The use of biomass and other renewable energy sources is described in the EU energy policy. The revised Renewable Energy Directive (RED II) estimated 32% of renewable energy sources for 2030 [65]. Moreover, according to the complementing Efficiency Directive, biomass should be used efficiently in electricity and heat [64]. In addition, wood should be used in a variety of products, and its use should be in synergy with other products [65,66].

The meaning of renewable energy sources (RES), including biomass, is important. These sources can reduce greenhouse gas emissions, improve energy security, and create new jobs [67]. Renewable energy sources are used in electricity production, in heat production, and as fuels. Most important is the share of renewable energy sources in electricity production. Wind energy produces about 44% of electricity from renewable energy sources. Second place is taken by solid biomass (36%) and third by hydropower (14%) [68].

6. Conclusions

Biomass offers additional benefits, such as the ability to store energy and the ability to be used in a variety of methods and forms, making it an attractive option for the renewable energy sector. The prospects for the development of this technology are promising, provided that research on the optimization of its production continues and favorable political

and economic conditions are created. These aspects will be crucial for the full realization of biomass's potential as a major player among renewable energy sources. However, the competitiveness and adoption rate of biomass production are influenced by various factors, including initial investment costs, production challenges, and price volatility in the raw material market [69,70].

Attention is drawn to the need for policy measures that reduce the initial investment costs, provide adequate financial support, and help to cope with the challenges of growing and using biomass, especially waste biomass. It is also recommended to intensify activities in the field of promotion of awareness and education about the benefits of biomass production and the use of renewable energy sources among farmers. It is suggested that greater awareness, supported by appropriate financial support, could significantly increase the adoption and competitiveness of biomass and other renewable energy sources.

More and more energy and electricity are used for refrigeration and air conditioning [71,72]. This energy is particularly used during summer when the need for refrigeration and air conditioning is very high. During this season, the most important source may be photovoltaics.

The most important source for stable biomass production and reproduction is forests. Poland is an important forest owner in the EU. For this reason, Poland's competitive potential in biomass production compared to other EU countries is diverse—lower in relation to countries with a high share of forests but higher in relation to those with low forest cover.

The most important advantages of solid biomass production are that it is CO_2-neutral and the production of waste from the forestry and agricultural industry is managed. Moreover, biomass can be used for the production of many forms of energy, such as heat for heating to fuel for a car, and its burning leaves small amounts of ash. In addition, biomass is constant compared to the unpredictable energy of wind or sun. Biomass resources can be stored and used as needed.

The most important disadvantages of solid biomass production are logistical problems, fluctuations in substrate prices, and the greater interest in the production of biomass for energy purposes. It is possible to increase food prices.

Analysis of the VAR model for the production of renewable energy sources from stable biomass in Poland from 2000 to 2022 showed strong autoregression, indicating the impact of past energy production values on current energy production levels. Key statistics such as the high coefficient of determination R2 confirm the models' ability to explain the data's variability.

We verified two hypotheses. The first hypothesis—H1: Stable biomass is Poland's most important renewable energy source because of the large resources of forests—was verified positively. Germany was the largest producer of wood in 2020. In second place was Sweden. Poland is also intensifying wood harvesting, which may translate into greater potential in biomass production.

The second hypothesis—H2: The share of stable biomass will increase because of strong pressure on acquiring renewable energy sources in the European Union (EU)—was verified positively. There is strong pressure to acquire renewable energy sources in the European Union (EU).

The prediction, based on the VAR model, shows that the increase of stable biomass production will be from 365,395 TJ in 2023 to 379,795 (TJ) in 2032. These results show a big increase. However, we realize that VAR models and prognoses have some limitations. The model based on yearly data does not include seasonal trends. Moreover, the model shows a big error and a 95% chunk. This means that while predicting biomass production, the data shows bigger errors, and the prognosis may be different.

Based on the literature, the VAR model has disadvantages, e.g., underestimation of the risk. Each model has a maximum loss to a certain degree of confidence. The VAR models helped us to evaluate the stable biomass time rank and to check the stationarity [73].

Estimates indicate a diversified development of the solid biomass sector in Poland, with small fluctuations in production and a growing forecast error. This means that although some stabilization of production can be expected, it will be important to monitor market and technological changes affecting the RES sector.

In conclusion, the presented analysis provides an in-depth look at the production of biomass and energy from stable biomass in Poland based on robust statistical and econometric methods. This enables a better understanding of trends and potential changes in the sector, which is crucial for planning and implementing RES development strategies.

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Conflicts of Interest: The authors declare no conflicts of interest.

Nomenclature

ADF test	Augmented Dickey–Fuller test
ARiMA model	Auto-Regressive Moving Average model
Ca	Calcium
CAP	Common Agricultural Policy
CO_2	Carbon dioxide
EU	European Union
GARCH	Generalized Auto-Regressive Conditional Heteroskedasticity
GHG	Greenhouse gas
K	Potassium
NO_x	Nitrogen oxides
PM	Particle Matter
RED	Renewable Energy Directive
RES	Renewable Energy Sources
Si	Silicon
SO_2	Sulfur dioxide
TJ	Terajoule

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