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The Role of Biogas Potential in Building the Energy Independence of the Three Seas Initiative Countries

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Abstract: Increasing biogas production in the Three Seas Initiative countries (3SI) is a good way to reduce greenhouse gas emissions and to increase energy self-sufficiency by replacing some of the fossil energy sources. An assessment of the biogas production potential carried out for the 3SI at the NUTS 1 and NUTS 2 level shows that the potential of this energy carrier was stable for the period (from 2010–2021). The results showed that it can cover from approximately 10% (Hungary, Slovakia) to more than 34% (Estonia, Slovenia) of natural gas consumption; moreover, there is strong variation in the value of potential at the regional level (NUTS 2) in most of the countries studied. The biogas production forecast was carried out with the ARIMA model using four regressors, which are GDP, biogas potential utilisation, natural gas consumption and investments in RES (renewable energy sources) infrastructure, including changes in the EU energy policy after 24 February 2022. In the most promising scenario (four regressors), the results obtained for the period from 2022–2030 predict a rapid increase in biogas production in the 3SI countries, from 32.4 ± 11.3% for the Czech Republic to 138.7 ± 27.5% for Estonia (relative to 2021). However, in the case of six countries (Bulgaria, Lithuania, Hungary, Austria, Poland and Romania) the utilisation of 50% of the potential will most likely occur in the fifth decade of the 21st century. The above results differ significantly for those obtained for three regressors, where the highest rise is predicted for Bulgaria at 33.5 ± 16.1% and the lowest for Slovenia, at only 2.8 ± 14.4% (relative to 2021).

Keywords: biogas; Three Seas Initiative countries; ARIMA

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Citation: Ślusarz, G.; Twaróg, D.; Gołębiewska, B.; Cierpiał-Wolan, M.; Gołębiewski, J.; Plutecki, P. The Role of Biogas Potential in Building the Energy Independence of the Three Seas Initiative Countries. *Energies* **2023**, *16*, 1366. https://doi.org/10.3390/en16031366

Academic Editors: Constantinos A. Balaras, Tomasz Cholewa and Umberto Berardi

Received: 10 November 2022
Revised: 20 January 2023
Accepted: 24 January 2023
Published: 28 January 2023

1. Introduction

The overarching challenge facing the world today is to combat the climate change that is taking place. This countermeasure involves an energy transition leading away from fossil energy sources and replacing them with renewable sources [1]. In addition, the situation and the economic consequences following the Russian attack on Ukraine have contributed to a shift in thinking about energy transition in individual regions of Europe towards an energy transition that is advisable from the point of view of energy security for a growing world population [2]. Renewable energy sources offer an opportunity to increase energy independence and the ability of countries without sufficient fossil fuel resources to produce energy [3].

Renewable energy sources are the fastest growing energy source worldwide [4,5], and the share of renewable energy in the energy consumption mix is increasing rapidly in Europe in particular [6]. In 2021, fossil fuels accounted for 37% of energy production sources [7] and the EEA estimates [8] that renewables accounted for 22% of energy consumed in the EU. Despite this, the increase in available renewable energy is still lower than the overall increase in global energy demand [9], and the implementation of greenhouse gas reduction recommendations regionally and locally varies widely across EU countries [10–13].

The need to become independent of Russian fossil fuels has led to the European Union having to further accelerate the green transition to become independent of fossil fuels from Russia [14,15]. Zakeri et al. [16] report that the crises (the war and the COVID-19 pandemic) initially appeared as an opportunity to move towards a low-carbon energy transition, but that efforts are now focused on short-term, seemingly faster solutions, such as seeking new fossil fuel supply routes, to increase energy security. This is confirmed by Nerlinger and Utz [17], who point out that investors' assessment of accelerating a particular mode of energy generation appears to favour coal technology over renewable energy. However, this applies to short-term measures. Analyses indicate that Europe's long-term energy security can be ensured through clean energy supply [18], and that energy transition is one of the main contributors to reducing the impact of fossil fuel energy supply disruptions on the global economy [19]. However, as Zhang [20] points out, energy supply shortages and rising prices are disrupting the intended global green energy transition. However, the Russian–Ukrainian war may accelerate the European Union's plans to increase the share of renewable energy [21], as it is indicated that renewable energy can meet two-thirds of total global energy demand [22]. Therefore, the case for a rapid transition to clean energy appears to be strong [23]. However, as reported by Sturm [24], the accelerated deployment of renewable energy and other measures to divert European economies away from Russian fuels face barriers that require new technologies (e.g., energy storage).

In Western European countries, the process of energy transition has been ongoing for more than twenty years and is characterised by great dynamism [25]. The situation is much worse in this respect in the countries of Central and Eastern Europe [26], which, in search of a way to dynamise their development and improve cohesion within the EU, have formed the Three Seas Initiative (3SI). This initiative comprises 12 Central and Eastern European countries, including Austria, Bulgaria, Croatia, the Czech Republic, Estonia, Hungary, Latvia, Lithuania, Poland, Romania, Slovakia and Slovenia, located between three seas—the Baltic, Adriatic and Black Seas [27]. It is the result of the First Summit of the Three Seas Initiative, which took place on the 23rd of August 2016 in Dubrovnik [28]. It is an intra-EU grouping, aiming to strengthen intra-regional energy corridors and reduce dependence on external energy suppliers [27], focusing on the development of economic and infrastructure cooperation [29], and is not an international organisation, which means that it has no founding agreement or statute that defines its goals and objectives [30]. It is based on a loose cooperation formula [31]. However, the range of objectives enshrined in the declaration and the expressed willingness of the states in the area to cooperate indicate the need to recognise the economic and social advantages of this arrangement. For the most part, these states are small, with relatively low economic and demographic potential [32]. As individual states, they carry little weight in the European single market. However, their potential, properly harnessed through mutual cooperation, can be an important tool for effective utilisation of their endogenous factors [33], as well as in the energy transition process.

The goals of energy transition, related to enhancing energy security and environmental protection, are undeniably important priorities and challenges in the development of modern states, an integral part of which is the development of peripheral areas [34], and such areas include the Three Seas Initiative (3SI) countries, which are the eastern periphery of the EU. The achievement of the goals of energy transition in the 3SI countries may additionally involve the acceleration of development resulting from innovative solutions accompanying such a transition. The term RES does not only mean energy obtained directly from wind or sunlight [35], although these are currently the most popular technologies [36,37]. In the energy transition process, biogas potential also plays an important role in building energy independence. Biogas has several advantages over the use of fossil fuels, such as petrol and natural gas. It can be produced continuously as it is derived from organic feedstocks [38] and there is great potential to increase its production [39]. The war in Ukraine has given biogas production a new impetus, with the European Commission proposing to increase biomethane production to 35 billion m^3 by 2030, up from 3 billion m^3 in 2020 [40]. Hence, the main objective of the research comes down to the search for an answer to the question of what biogas production potential for building energy security—energy independence—is available to the Three Seas Initiative countries. This is important in the context of ensuring energy security, which has an international dimension. Taking into account the studies of the literature and the collected research material, the following research hypotheses were formulated:

1. The Three Seas Initiative (3SI) countries show great diversity both in terms of production potential and the forecasted increase in biogas production.
2. The biogas production potential of the Three Seas Initiative (3SI) countries indicates significant opportunities to ensure energy security for these countries.

2. Materials and Methods

2.1. Biogas Potential

Biogas is produced in the process of anaerobic digestion of organic waste, in which organic substances are broken down by bacteria into simple compounds. In this process, up to 60% of the organic matter is transformed into biogas. Biogas comprises from 50– 70% methane (CH_4), from 25–45% carbon dioxide (CO_2), from 2–7% water (H_2O), from 2–5% nitrogen (N_2), from 0–2% oxygen (O_2), less than 1% hydrogen (H_2), from 0–1% ammonia (NH_3) and from 0–6000 ppm hydrogen sulphur (H_2S) [41]. Biogas can be produced from organic waste, animal manure, sewage and municipal waste. The methods for estimating biogas production potential from these sources are described below.

In this study the animal populations taken into account were bovine animals, cows, pigs, sheep, goats, poultry and horses. The amount of animal manure produced was dependent on the age and weight of the animals, among other things. Data on animal livestock during the period from 2010–2021 was taken from the Statistical Offices [42–54] of countries belonging to the Three Seas Initiative. Bearing in mind that it would not be economically viable to collect manures from free-range animals, we decided to only consider livestock kept indoors (e.g., only dairy cattle were considered from the entire cattle population). The same procedure was used for the other animal species. The animal housing system (deep litter, shallow litter or litter-free) also affected the amount of animal manure able to be collected and used in a local biogas plant [55–57]. There are four types of manure, namely solid, liquid, slurry and deep litter. A breakdown of different types of manure for bovine animals, pigs and poultry can be found in the BIO Intelligence Service [58] and in EU regulations devoted to the Best Available Techniques (BAT) Reference Document for the Intensive Rearing of Poultry or Pigs [59] and the Best Available Techniques (BAT) Reference Document for the Food, Drink and Milk Industries [60]. It was assumed that in the case of liquid manure and slurry, 1 m^3 of manure can yield 20 m^3 of biogas, whereas in the case of solid manure and deep litter, 1 m^3 of manure can yield 30 m^3 of biogas [61,62]. For each of abovementioned animal types, the amount of manure potential is calculated as follows:

$$\textit{Manure biogas potential}\ \left[\mathrm{m}^3\right] = \sum \textit{animal livestock} * \textit{manure type}[\%] * \textit{biogas yield}\ \left[\mathrm{m}^3\right] \quad (1)$$

The total biogas potential from livestock manure is the sum of the biogas obtainable from all the studied animal species maintained in different systems (deep litter, shallow litter or litter-free).

Almost the entire population is connected to the waste collection system, so municipal waste should be treated as a permanent source of biodegradable material from which up to 60% of organic matter can be converted into biogas. In the aim to obtain information about biogas potential at the regional level (NUTS 2), data on annual waste generation from animal and mixed food, vegetable, household and similar sources for 3SI countries were taken from Eurostat [63].

As for the share of biodegradable waste in municipal waste, the midpoints of intervals given by the ACR+ organisation were taken [64]. It was assumed that 1 tonne of biodegradable waste can yield 200 m^3 of biogas [65]. The total biogas potential from wastes is calculated as follows:

$$Waste\ biogas\ potential\ \left[m^3\right] = 200 * \sum waste\ mass[tonne] * share\ of\ biodegradable\ \ waste\ [\%] \quad (2)$$

Wastewater contains a lot of pollutants and is generated by many sectors, e.g., industries, households, agriculture. It is collected by wastewater treatment plants (WWTPs), where wastewater is subjected to primary, secondary and tertiary treatment. During these three steps sewage sludge is produced, from which biogas is obtained via anaerobic digestion. WWTPs are divided into industrial and municipal WWTPs. It was assumed that 1000 m^3 of wastewater can yield 100 m^3 of biogas [66]. Data on wastewater inflow to industrial and municipal WWTPs was collected from the Statistical Offices [42–54]. The biogas production potential from WWTPs is calculated via multiplication of wastewater inflow to industrial and municipal WWTPs by the yield of biogas from wastewater.

The total biogas potential is the sum of potentials from the above mentioned sources. The results of the above analysis should be understood as the technical potential that could possibly be released in the countries studied. For the needs of further analysis (where biogas potential is compared with natural gas consumption) it was assumed that the biogas average calorific value is ~23 MJ/m^3 [67]; information about natural gas calorific value was taken from the BP statistical review of world Energy 2022 [68].

2.2. Cluster Analysis

In the spatial analysis of the energy 'profile' of the Three Seas Initiative countries (3SI), hierarchical clustering methods were used to identify clusters formed by similar facilities. Hierarchical clustering methods are used to find, based on the structure of the data, clusters formed by similar objects. The effectiveness of these methods can be defined as the ability to recognise the actual structure of objects in a multidimensional space. These methods are divided into two groups:

- agglomerative—at first, each object is a one-element cluster, and then pairs of clusters are merged according to a fixed metric;
- deglomerative—at first, all objects form a single cluster, and then the clusters are subdivided into smaller and more homogeneous ones.

Hierarchical clustering methods do not require an assumption on the number of clusters or indicate an optimum number of clusters. Hence, it is necessary to use certain measures to select the optimal number of clusters. The proposed distance measures relate to variables measured on robust scales. Within each method, similar procedural steps can be distinguished. After bringing all variables to the same scale by normalising them, the distance matrix $[d_{ij}]$ between objects is determined on the basis of the chosen metric, e.g., Euclidean distance, its square or maximum, Manhattan or maximum. In the agglomerative method, initially all objects form individual clusters. In the distance matrix, the minimum distance $d_{pq} = min\ [d_{ij}]$ is found, column q is removed and the distances between cluster p and the other clusters are recalculated according to one of the linkage methods. In this study, Ward's linkage (Ward's minimum variance method) was chosen to define the distance between two groups as the sum of the squares of the distances of the objects in the two groups from the centroid of the new group that is formed by merging the two groups [69]. The procedure of combining clusters and recalculating the distances between them continues until a single cluster is formed from all objects. In the deglomeration method, the cluster with the largest dimension calculated is the maximum distance between two objects in the cluster that is selected in each iteration. The element with the largest average distance from the other objects in that cluster is then searched for, which initiates a new subgroup. The algorithm joins objects to the new subgroup that are closer to it than the subgroup of the other objects in the cluster. The visualisation of the effects of the hierarchical methods is a hierarchical tree (dendrogram). In the case of agglomerative methods, one of the primary indicators for the selection of a linkage method is the cofenetic correlation coefficient [70]. It measures the consistency of the distance between two objects and the distance between the clusters containing them when merged into a common cluster. The next step of cluster analysis is to determine the number of clusters. This choice can be made expertly and on merit using, among other things, the internal measures method: the WSS (Within Cluster Sum of Squares), which measures the compactness of clusters or the Silhouette Index, which examines the quality of clustering.

2.3. ARIMA

The widely known ARIMA (Auto Regressive Integrated Moving Average) method [71,72] was used to forecast the time series of biogas production growth. In recent years, this method has been widely used in forecasting electricity consumption or energy demand in selected economic sectors or countries [73–76]. The components of the ARIMA model are the autoregressive process of order p AR(p), the moving average accrual process of order p-MA(p) [77] and I is an integration—it determines the number of times the series differentiation operation is repeated so that the process becomes stationary. The autoregressive (AR) process can be written as follows:

$$X_t = \phi_1 X_{t-1} + \phi_2 X_{t-2} + \ldots + \phi_p X_{t-p} + \epsilon_t \tag{3}$$

where:

ϕ_{t-1}—parameters,
X_{t-i}—regressors,
ϵ_t—error.

The AR process is generated by a linear model in which the implementation of the process in the current period depends on the implementation of the series in p consecutive previous periods and the random component in the current period. For $|\phi_1| < 1$, such a process has the property that a single jump in value will have a decreasing effect on subsequent implementations of the process. Such an AR process is called stationary.

A moving average process of the order q-MA(q) is a process generated by a linear model in which the implementation of the process in the current period depends on the implementation of the random component in the current period and in q consecutive previous periods.

$$X_t = \epsilon_t + \theta_1 \epsilon_{t-1} + \theta_2 \epsilon_{t-2} + \ldots + \theta_q \epsilon_{t-q} \tag{4}$$

where:

θ_{t-1}—parameters,
ϵ_{t-i}—regressors,
ϵ_t—error.

An MA process is a process 'with memory' of past values of the random component (spikes in values). By successive substitutions, each moving average process can be represented as an infinite autoregressive process AR(∞).

For a stationary series, instead of using AR class models and MA class models separately, moving average autoregressive models, i.e., ARMA models with lag order (p, q), are used to describe the links between observations from successive periods. The data-generating process for ARMA(p, q) then has the form:

$$X_t = \phi_1 X_{t-1} + \phi_2 X_{t-2} + \ldots + \phi_p X_{t-p} + \epsilon_t + \theta_1 \epsilon_{t-1} + \theta_2 \epsilon_{t-2} + \ldots + \theta_q \epsilon_{t-q} \tag{5}$$

By adding MA components to the AR model, a large reduction in the order magnitude of the lags of the process generating the forecasts can be obtained. An ARMA process contains both AR and MA process features and an ARMA model generates a stationary process if its components are an AR stationary model and an MA inverse model. In the ARIMA model, the upcoming value of the variables is dependent upon autoregression, integration and moving average, respectively, which is denoted as ARIMA(p, d, q), where parameters (p, d, q) describe AR: p—periods to lag; I: d—the degree of differencing; MA: q—the lag of the error component. Defining the value of p, d, q plays a vital role for construction and the operation of an ARIMA model. The "predictors" on the right-hand side (5) include both the lagged values of X_t and the lagged errors. Note that the goal of the search for a useful forecasting model is not to use as many parameters as possible to describe the variability of a time series as accurately as possible. The aim of the search is to discover a model that, using a limited number of statistically significant parameters, describes the most important features of the stochastic process under study.

The confidence interval (Lo–Hi) of a forecast (dashed curves in Figure 5) is the range within which the value we forecast will fall with a certain probability. In the case of Bulgaria, in 2030, the Lo–Hi 95% of the forecast confidence interval indicates that biogas production will be at least 4368 TJ and at most 5339 TJ.

3. Results

3.1. Analysis of the Energy Profile of the Three Seas Initiative

When analysing the situation of the energy sector in the Three Seas Initiative (3SI) countries, it is worth asking the question: Are these countries merely a political vision? However, do they have certain similarities in terms of the diversity of the broader energy market? To answer these questions, the similarity of the energy profiles for the European countries together with the Asian parts of Russia and Turkey were examined. To do so, Ward's agglomeration method of grouping countries with similar profiles according to Euclidean distance was used [78]. The algorithm first calculates all the Euclidean distances between the countries and puts them in the tree diagram. The dendrogram presented in Figure 1 shows the grouping of the countries according to the similarities between 24 indicators in 2021. The following indicators, which describe production and consumptions in natural units of such energy carriers as oil, gas, coal, nuclear, hydro, solar, wind, biomass, geothermal and biofuels, were selected from the BP statistical review of world Energy 2022 [68]. The above indicators were further divided by the population taken from the Eurostat database [79]. Other indicators taken under considerations were primary energy consumption per capita, CO_2 emissions from energy, renewable energy production and overall electricity generation. The choice of energy carriers was dictated by the need to know the demand side and supply side of the energy market at the level of individual consumers. For example, hard coal is mined in only five countries, while it is consumed in each of the 3SI countries.

Other indicators available in the BP database [68], such as oil, gas and coal reserves, have been omitted, as these are energy carriers that are being phased out. Reserves and extraction of rare earth elements, lithium and graphite were also not taken into account due to the fact that their extraction is not carried out in most European countries with the exception of the Russian Federation—rare earths, and Norway—graphite.

In most developed European economies, such as France, Germany, Italy, The Netherlands, Spain and the United Kingdom, we see a gradual decline in primary energy consumption per capita and in CO_2 emissions from energy in the period from 2010–2020. This shows that these countries are leading a successful energy transition, as evidenced by the gradual increase in the renewable energy share in the overall energy balance. In developing countries, the above indicators tend to remain at similar levels (with the exception of Ukraine).

It is worth noting that when using absolute values, countries such as the Russian Federation, the United Kingdom and Norway would form a separate group due to fossil fuel extraction. Furthermore, limiting oneself to indicators that take into account only the production of energy carriers and not their consumption per capita, i.e., per final consumer of energy, would not provide a complete picture of the energy market. This is all the more valuable, as biogas plants at present and in the near future will mainly be operated for the benefit of local communities, e.g., within energy clusters or cooperatives [80].

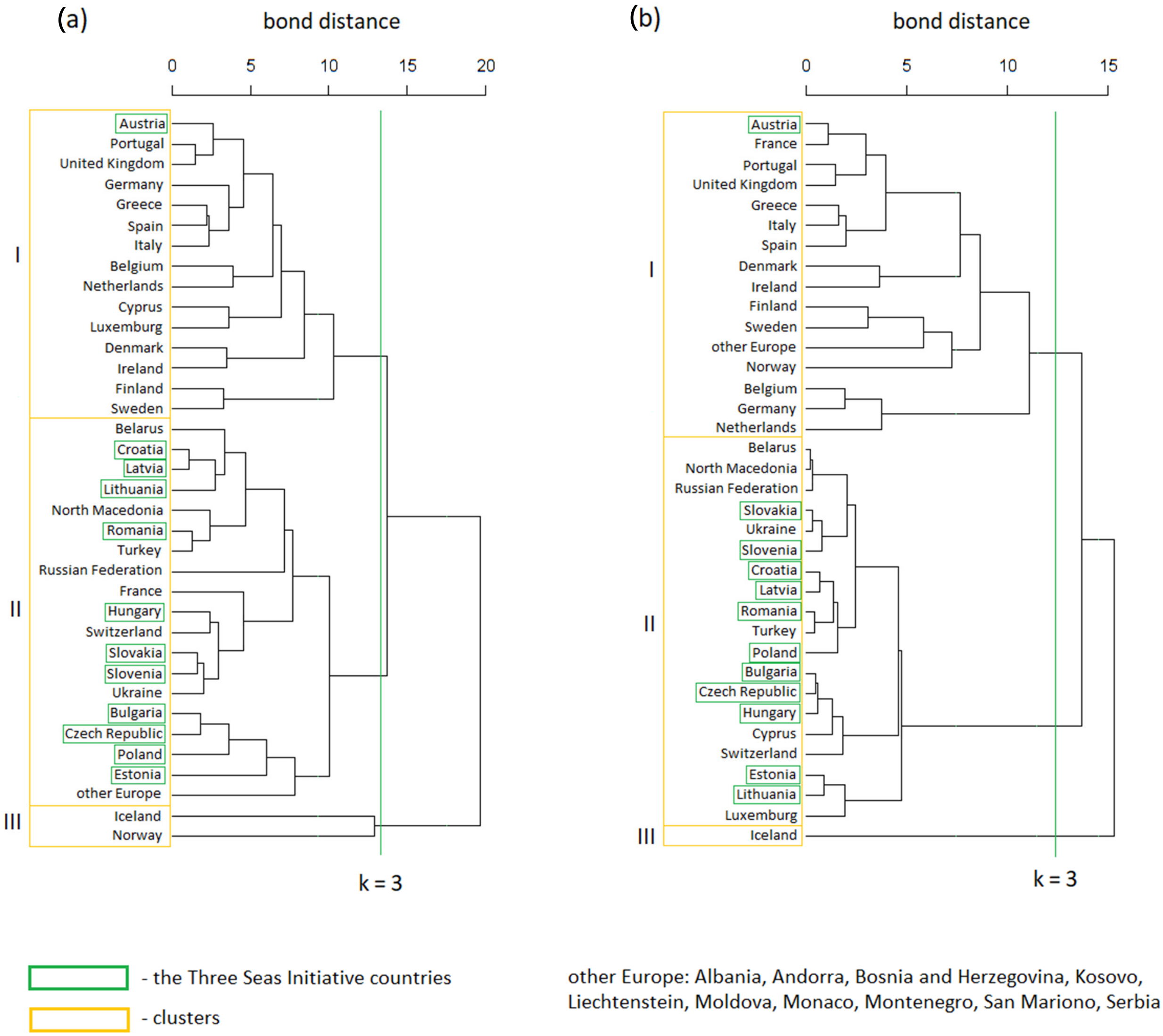

Figure 1. Dendrograms of production and consumption rates for renewable and non-renewable energy carriers (**a**) and rates describing only renewable sources (**b**).

The quality of clustering can be measured by the Silhouette Index. In the studied case, the Silhouette index indicates a division into two clusters (k = 2) as their optimal number. However, in the present case, it was decided to present the dendrograms with a division into six clusters (k = 3) in order to better represent the clustering. The Silhouette Index attains the highest value for k = 2, but in that case the first cluster will contain Iceland and Norway, whereas the second cluster will contain all the remaining countries, which has limited study value. The search for the most appropriate number of clusters was directed at finding the minimum number of clusters for which one cluster would be dominated by the 3SI countries. In the case of the analysis conducted for all indicators, the use of k = 3, 4 and 5 made it possible to identify a cluster consisting of 19 countries, 11 of which belong to the 3SI. Analysis carried out for the indicators describing renewable energy sources showed that the above division persists for k = 3, . . . , 8. Therefore, it was decided to use a division into three clusters.

In the case of the overall energy market (Figure 1a), Ward's method divides the countries surveyed into III clusters, of which the Three Seas Initiative countries (3SI) mostly belong to cluster II. With the exception of France and some smaller countries from "other Europe", cluster II is made up of countries directly bordering the countries of the 3SI.

The identification of Norway and Iceland as cluster III in Figure 1a was influenced by factors such as high GJ per capita values (well above the average value in 2021), high production and consumption of electricity from hydroelectric power per capita (an order of magnitude higher compared to other countries), and the lack of coal mining and nuclear energy production should also be mentioned. In the case of renewable energy, the identification of Iceland as cluster III in Figure 1b is a result of the high per capita production and consumption of geothermal energy (two orders of magnitude higher than the other countries), and a very high share of energy from renewable sources was also an important factor.

The 3SI countries are characterised by the highest values of indicators, among others, including GJ per capita and per capita consumption and production of most energy carriers, which can be seen in the dendrogram as the grouping of these countries in cluster II. Austria belongs to cluster I due to its high value of GJ per capita and consumption of diesel and natural gas while not producing these energy carriers. In the case of renewables, it can be seen that the most numerous cluster II is dominated by 11 of the 12 Three Seas Initiative countries (Figure 1b). This is supported by the fact that, with the exception of Austria (cluster I), they are characterised by similar values for indicators describing both production and consumption of renewable energy. The similarities shown, from the point of view of the end-user of energy, make it possible to treat the vast majority of 3SI countries as a single group, in which the entire energy sector as well as the renewable energy sector are at a similar stage of development.

3.2. Biogas Potential

The biogas production potential for the 3SI countries was calculated for the period from 2010–2021. In absolute terms, Poland remains the clear leader with a potential ranging from 6.85 billion m^3 to 7.05 billion m^3 biogas per year. In second place is Romania, with a potential estimated from 3.39 billion m^3 to 3.46 billion m^3 biogas per year (Figure 2). The high position of the two largest countries in the 3SI is not surprising, mainly due to intensive animal husbandry (natural fertilisers) and a large population compared to other countries (biodegradable waste). Estonia has the smallest potential in absolute numbers, from 0.24 billion m^3 to 0.26 billion m^3 per year, but when converted to population size, the potentials of the countries studied become more equal (from 149 m^3/person per year in the case of Slovakia to 263 m^3/person per year in Austria).

When dividing the countries in terms of potential sources, it is worth noting that in the case of the Czech Republic, Slovakia and Bulgaria, biogas from landfills builds up more than half of the biogas potential. For Estonia, Lithuania, Latvia, Austria, Poland, Romania and Slovenia, manure remains the dominant source, with more than a 50% share in biogas potential (Figure 2c). Fertiliser is the most important for Romania (over 64.2% in 2021), while it is the least important for Slovakia (over 34.7% in 2021). The third source of biogas potential, the use of wastewater treatment plant sludge, plays a minor role in each of the countries studied (7.2% in the case of Slovakia).

In this case, a scenario was examined in which all of the estimated biogas potential sources with a calorific value of 23 MJ/m^3 [67] is used to replace natural gas consumption. For this purpose, estimated biogas potential was divided by the natural gas consumption taken from the BP database [68]. Calculation was provided on the NUTS 1 and NUTS 2 levels (Figure 3). In terms of covering gas consumption by biogas potential, Slovenia and Estonia were the leaders. In their case, biogas potential could cover 36.8% and 34.0% of natural gas demand in 2021, respectively. By contrast, in Slovakia and Hungary, biogas potential would only cover 10.6% and 10.2% of natural gas consumption, respectively (Figure 3b). It is worth noting that the significance of biogas potential steadily declined over the studied period from 2010–2021. In 2010, it was able to cover an average of 19.8% of the natural gas demand in the 3SI countries, while in 2020 it was more than 17.6%. This phenomenon is mainly due to an increase in natural gas consumption among the 3SI countries and to a lesser extent to fluctuations in biogas potential (Figure 2a).

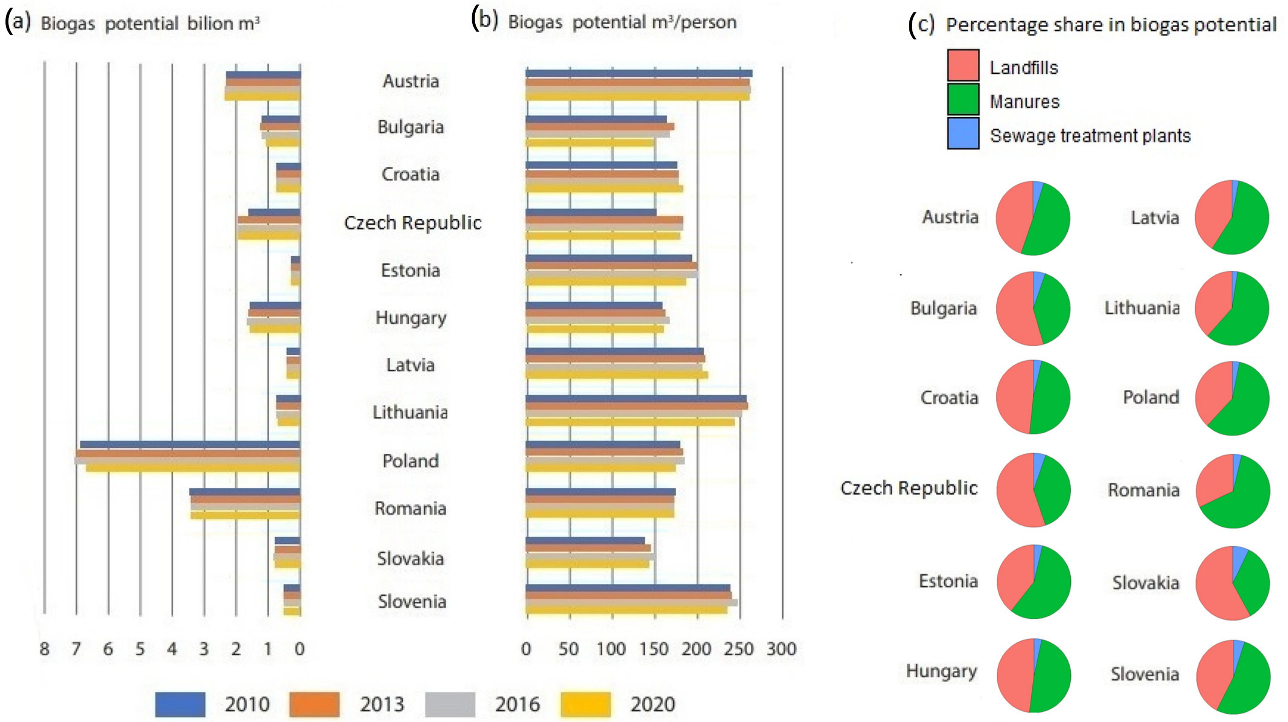

Figure 2. Biogas potential (**a**) per population (**b**) and with percentage share of individual sources at national level (**c**).

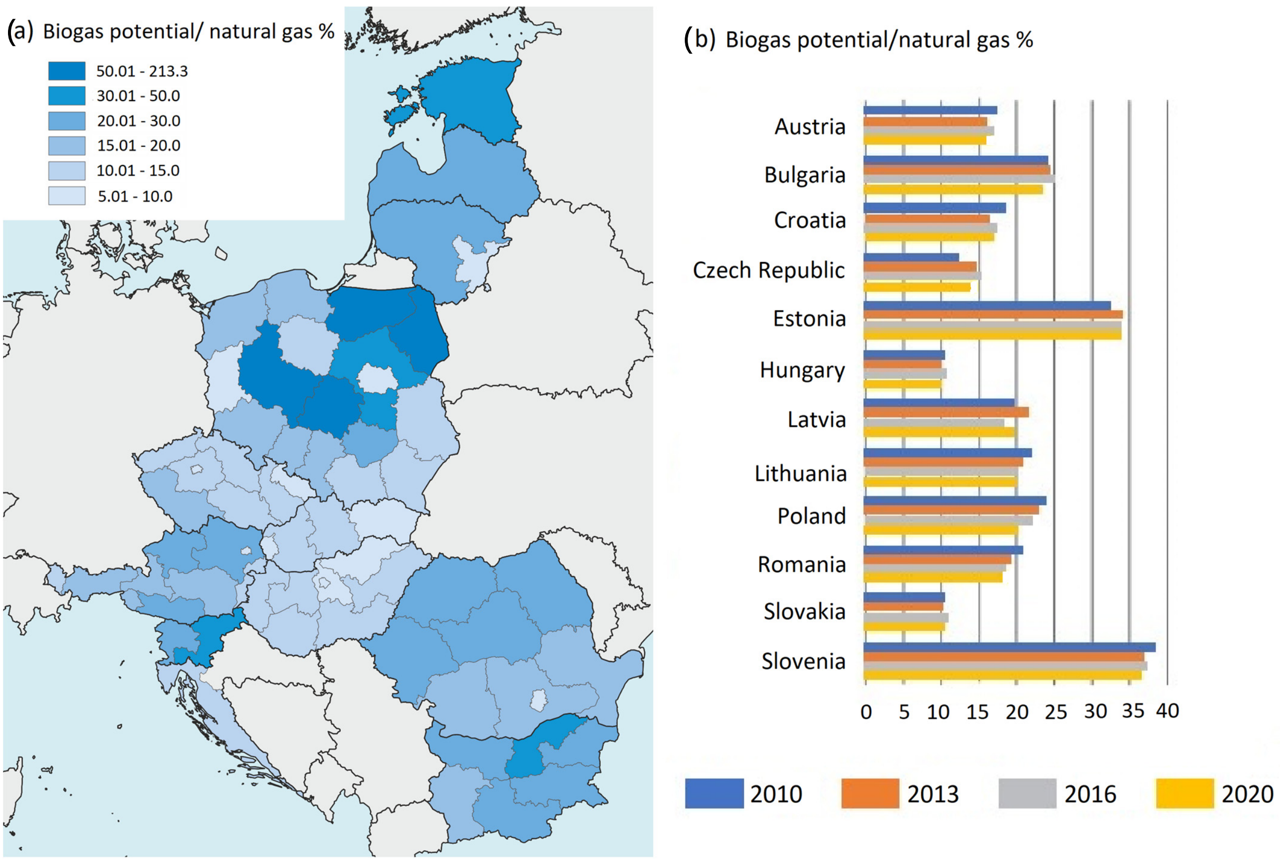

Figure 3. Biogas potential in relation to the consumption of natural gas in 2021 (**a**) and its variation in selected years (**b**).

A much stronger variation in biogas potential in natural units is evident at the regional level (NUTS 2), changing from a value of ~0.06 billion m^3 biogas per year for the Austrian Burgenland region to a value of ~0.98 billion m^3 for the Greater Poland region (Poland). Such a wide range of potential values also translates into a large regional variation within the countries studied. In the case of Austria, the potential of the Niederösterreich region (~0.53 billion m^3) is on average 8.85 times higher than that of the Burgenland region (~0.06 billion m^3). A slightly smaller difference at NUTS 2 level can be seen in Poland, where the average potential of the Greater Poland region (~0.98 billion m^3) is 6.95 times higher than that of the Lubuskie region (~0.14 billion m^3). In this respect, Slovenia, where the difference between the two regions is only ~1.65, remains the least regionally diverse country. For the above assessment, it should be borne in mind that for Estonia and Latvia, the NUTS 2 regions are the same as NUTS 1 [81].

At the NUTS 2 level, the Podlaskie region (Poland) remains the leader in terms of coverage of natural gas demand by biogas potential. In 2021, biogas potential could cover natural gas consumption by more than 213% (Figure 3a). Such a favourable result comes from low natural gas consumption (~7.2 PJ) compared to other Polish regions, which is mainly due to the low degree of gasification in this region (the lowest length of active gas network in Poland per 100 km^2) [82] and high biogas potential (~0.67 billion m^3 or 15.4 PJ). In the case of the Podlaskie region, it is built up by over 88%, which is the highest percentage among the regions studied. The Warmińsko-Mazurskie region (Poland) ranked second, where biogas potential could cover more than 82% of annual natural gas consumption in 2021. This region's potential is also built mainly on animal manure (over 74%). With the exception of the above-mentioned areas, only two more regions in Poland (Łódzkie and Wielkopolskie) have biogas potential that could cover more than 50% of natural gas consumption.

Significant biogas potential, capable of covering from 25% to 50% of natural gas consumption, is found in only 10 regions (5 Bulgarian, 2 Polish, 2 Slovenian and Estonia), whereas as many as 42 regions (9 Polish, 8 Austrian, 7 Romanian, 6 Czech, 5 Hungarian, 2 Croatian and Slovak, 1 Lithuanian, Bulgarian and Latvia) have a biogas potential that could cover from 10% to 25% of natural gas consumption. In contrast, the group of regions with the lowest potential for biogas production, not exceeding 10% of gas consumption, mainly includes regions with the capital of the countries. The lowest biogas potential characterises the Budapest region (Hungary), only 5.7% in 2021. It is worth noting that in the study period (2010–2021), a decrease in the importance of biogas production potential in relation to natural gas consumption was recorded in 39 of the 68 NUTS 2 regions studied, in most cases it was the result of an increase in natural gas consumption.

In Slovenia, biogas potential could cover 36.8% of natural gas demand in 2021 due to the low consumption of natural gas per capita (14.69 GJ/person) and the fact that this energy carrier only accounts for 11.21% of total energy consumption. In the case of Estonia, which has no nuclear power plants, natural gas consumption accounts for only 7.38% of total energy consumption, with other fossil fuels accounting for more than 78.38% of energy consumption (Table 1). The largest share of natural gas in energy consumption is found in Hungary (38.12%), while per capita this represents more than 37.56 GJ per year. Such high values translate into low biogas potential (10.6%) relative to natural gas consumption. A similar situation exists in Slovakia, where biogas potential covers (10.2%) natural gas consumption, while natural gas covers 26.55% of total energy consumption.

Table 1. Consumption of energy carriers in 2020 calculated with the help of the BP database [68].

Country	Fossil Fuels Consumption [PJ]	Nuclear Consumption PJ	RES Consumption [PJ]	Primary Consumption [PJ]	RES/Primary Consumption [%]	Nuclear/Primary Consumption [%]	Gas/Primary Consumption [%]	Gas/Population [GJ/Person]
Austria	889.76	0.0	533.48	1423.24	37.48	0.0	21.57	34.49
Bulgaria	465.30	150.84	74.62	690.76	10.80	21.84	15.22	15.13
Croatia	243.42	0.0	82.80	326.22	25.38	0.0	32.41	26.05
Czech Republic	1196.91	272.57	106.49	1575.97	6.76	17.30	19.33	28.49
Estonia	179.97	0.0	29.88	209.85	14,24	0.0	7.38	11.65
Hungary	760.23	145.66	56.66	962.55	5.89	15.13	38.12	37.56
Latvia	108.20	0.0	36.29	144.49	25.11	0.0	26.74	20.25
Lithuania	221.40	0.0	25.56	246.96	10.35	0.0	34.41	30.41
Poland	3765.81	0.0	274.59	4040.39	6.80	0.0	18.77	19.98
Romania	973.77	104.03	233.75	1311.54	17.82	7.93	30.91	20.97
Slovakia	436.33	140.12	68.24	644.69	10.58	21.73	26.55	31.36
Slovenia	163.68	57.64	53.38	274.70	19.43	20.98	11.21	14.69

Fossil fuels consumption—oil, gas and coal consumption. RES consumption—Hydro, Solar, Wind, Geo biomass and other renewable sources consumptions.

In natural units, the Czech Republic remains the leader in biogas production among the 3SI countries (24,500 TJ in 2021). Poland, with annual production of 13,051 TJ in 2021, is ranked second [83]. The biogas produced in the 3SI countries is mainly used for the production of electricity and heat in cogeneration facilities, while biomethane plants that can feed into the local gas grid are still rare [84,85]. However, when comparing biogas production to natural gas consumption, it can be seen that biogas plays the greatest role in the Czech Republic and Latvia, where it would be able to cover more than 8.1% and 7.1% of natural gas demand in 2020, respectively (Figure 4a). It is worth noting that the utilisation rate of biogas production potential also reaches high values in the Czech Republic ~54.9% and Latvia ~35.6% in 2020 (Figure 4b). In the case of Poland, biogas production would be able to cover just over 1.7% of natural gas consumption, which also translates into a low utilisation rate of production potential (only 7.9% in 2020). Romania remains the country where biogas production plays the smallest role (only ~0.2% compared to natural gas consumption in 2020), with a very low production potential utilisation rate of ~1.1%.

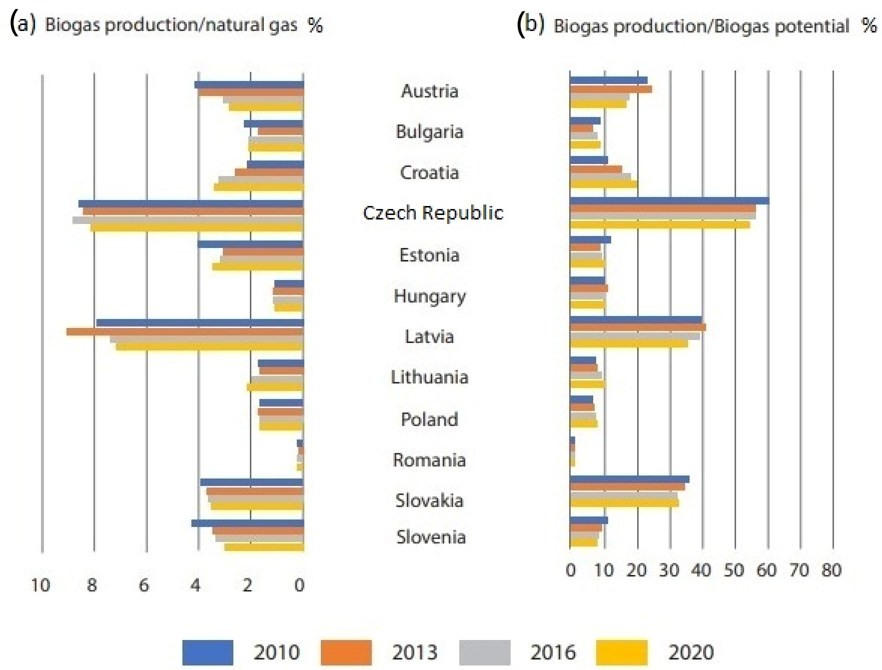

Figure 4. Biogas production against natural gas consumption (**a**) and biogas potential (**b**).

3.3. Biogas Production Forecasts

Biogas production projections from 2022–2030 were developed with the ARIMA (0,0,0) model using three regressors: biogas potential utilisation, natural gas consumption and investment in RES infrastructure. In this model, the last regressor was based on the EU countries' expenditure in the period from 2010–2021 and their continued development for the current decade before 24 February 2022 [86–89]. In Figure 5, the results obtained are highlighted by green curves. In order to better demonstrate how the conflict in Ukraine might affect biogas production, a second modelling exercise was also carried out. The second scenario was based on four regressors: GDP, biogas potential utilisation, natural gas consumption and investment in RES infrastructure. In this model, RES investments took into account the increase in spending on energy security and energy transition that occurred in the European market since 2020, before or after 24 February 2022 [90,91]. The RES sector expenditure for each country up to 2030 is shown below:

Bulgaria—needed over EUR 33 billion for advancing the Green Deal objectives [92].
Croatia—intends to spend EUR 22.5 billion on 12 activities for energy transition for the period from 2021–2030 [93].

Czech Republic—reaching the RES target set in the NECP by 2030 will require an investment of CZK 327.5 billion [92].
Poland—the value of investment outlays until 2030 was estimated in PEP2040 at EUR 53 billion, additionally taking into account the changing market environment, these outlays may still increase to EUR 135 billion [94].
Hungary—The estimated total investment needs based on this NECP amount to roughly EUR 44.5 billion (by 2030) [92].
Latvia—The NECP allocates approximately EUR 550 million for increasing the share of RES in district heating and connecting new clients to more efficient networks; EUR 60 million will fund projects in low temperature heating systems and waste heat recovery; EUR 225 million will be spent on modernising heating systems, combining RES uptake and efficiency measures; EUR 267 million will support the modernisation of local and individual heating systems [92].
Romania—the NECP need financial support amounting to EUR 22.6 billion to achieve the climate target [92].
Slovenia—estimates that between 2021 and 2030 approximately EUR 19.2 billion are needed for energy-related investments. When transport infrastructure and sustainable mobility are also taken into consideration, the necessary total investment amounts to EUR 28 billion [95].
Estonia—the implementation of NECP 2030 in the energy sector amounts to EUR 347 million, EUR 589 million in transport, EUR 1.046 billion for the renovation of building stock and EUR 278.5 million in agriculture [96].
Lithuania—the implementation of the PPM scenario will cost about EUR 14 billion [97].
Austria—overall investments for the entire period up to 2030 in the expansion of electricity generated from renewable energy is estimated at EUR 20~27 billion [98].
Slovakia—National Action Plan for Renewable Energy, Government Resolution 677/2010 EUR 1.483 billion per year [99].

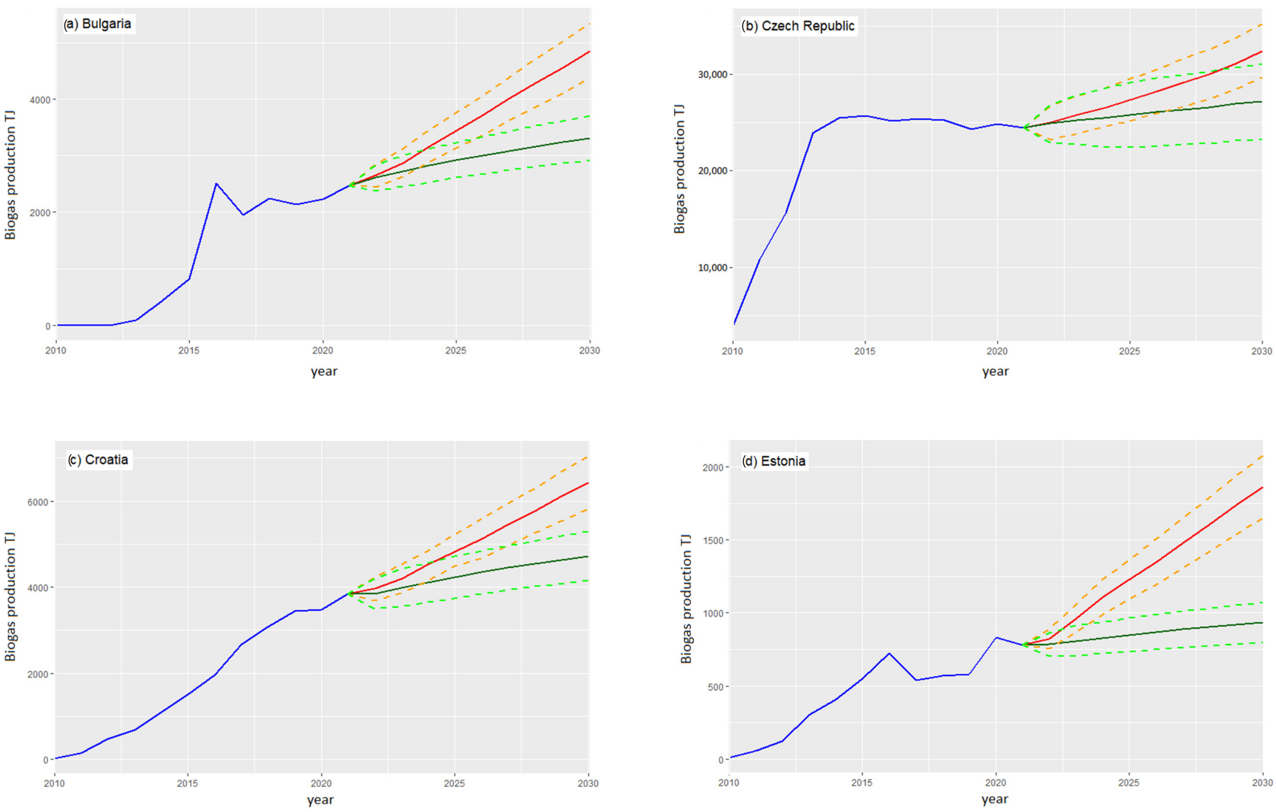

Figure 5. *Cont.*

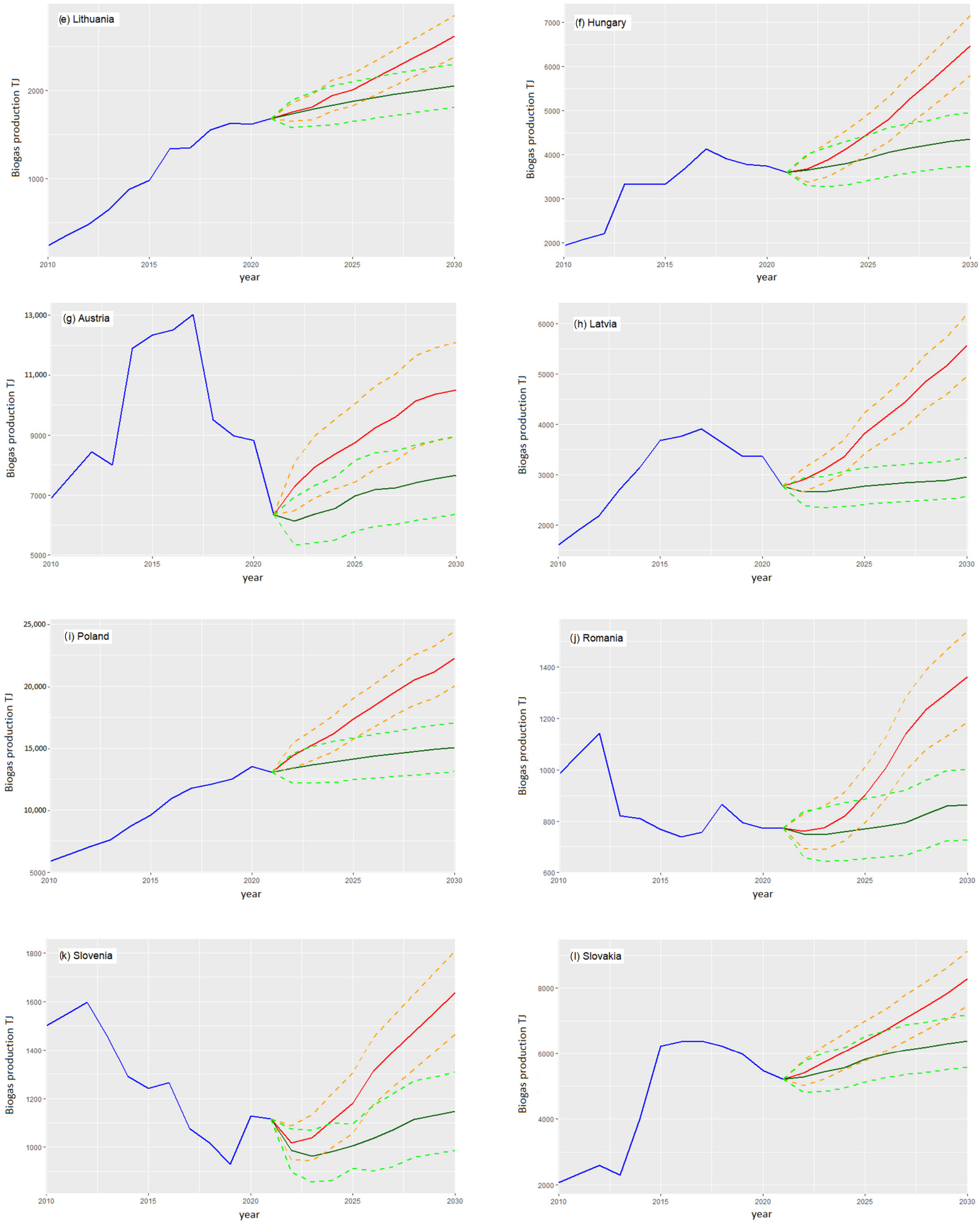

Figure 5. Biogas production forecast based on three regressors (green curves) and on four regressors (red curves) with the confidence interval Lo–Hi 95% (dashed curves). Biogas production to date (dark blue curves).

Most of the data posted was made public in 2020 or 2021; these were strategies covering the years from 2021–2030 and adopted for implementation or proceeding just before 24 February 2022. However, due to the high value of the amounts and the scale of the projects presented there, it was decided to consider the aforementioned studies as current financial plans. For the purpose of modelling, the above amounts were divided into equal values spent until 2030. In Figure 5, the results obtained are highlighted by red curves. All calculations were carried out using R-Studio.

The results seen in Figure 5 marked by red and green curves show a strong variation among the countries studied in terms of projected growth in biogas production. The confidence interval (Lo–Hi) of a forecast (dashed curves) is the range within which the value we forecast will lie with a probability of 95%.

Of the countries studied, the largest percentage increase in production between 2022 and 2030 is projected for Estonia at 138.7% in 2030 compared to 2021 (Figure 5d—red curve). This is primarily due to one of the fastest projected GDP growth rates among the 3SI countries [100] and a low utilisation rate of biogas production potential (~10% in 2020, Figure 4b). A very strong percentage increase in biogas production is also forecasted for Latvia (101.3% in 2030 compared to 2021). However, in the case of Latvia, the period from 2022–2026 will be mainly managed to rebuild 2017 production levels (Figure 5h—red curve). High production growth (~96.1%) is also projected for Bulgaria. For the countries with the highest biogas production potential, Poland and Romania, the projected growth will be 70.3% and 76.6%. However, in the case of Romania, the period from 2022–2027 will be dedicated to rebuilding the 2012 production level (Figure 5j—red curve). The lowest growth in biogas production (~32.4%) is projected for the Czech Republic. This is a result of one of the smallest (among the 3SI countries) projected GDP growth rates [100] and a high degree (~55%) of biogas production potential utilisation (Figure 5b—red curve).

According to the development paths prepared by Austria Federal Environment Agency, a combined production of biomethane, synthetic methane and biogas should attain ~13,000 TJ by 2030, which is a close value to that of 2017 biogas production. In the case of Austria, the prepared forecast (Figure 5g) predicts an increase in biogas production to 10,510 TJ in 2030, whereas Austria's Federal Environment Agency predicts reaching such a value in 2028 [98]. Thus, taking into account the confidence interval (Lo–Hi) from 8934 TJ to 12,087 TJ, and the MAPE value (17.17%), the model's prediction of ~10,510 TJ in 2030 can be considered a more conservative estimate. In Slovenia, biogas production has decreased due to the financial collapse of larger biogas plants. In recent years, interest in biogas production has been slowly increasing. This is also supported by the new Act on promoting the use of renewable energy sources [101]. An analysis released by the Slovenia Ministry of Infrastructure shows that combined electricity and heat production from biogas in CHP units could rise from 270 GWh (972 TJ) in 2020 to over 338 GWh (1216.8 TJ) by 2030 [102]. However, the above estimations do not take into account electricity production alone and the biomethane market share. In this light, the forecast shown in Figure 5k (red curve), which predicts an increase in biogas production to ~1636 TJ in 2030, with the confidence interval (Lo–Hi) from 1464 TJ to 1808 TJ and the MAPE value (6.22%), can be considered as overestimated results. Results obtained for three regressors (green curve in Figure 5k) seem to be better aligned with the government predictions. Due to its geographical position, rugged terrain, numerous protected areas and relatively small farms, Slovenia is specific in terms of agriculture, similar to Romania and Austria. In 2018, the annual production of energy from renewable resources in Romania was approximately 6550 ktoe (274,235 TJ), with biogas representing only 865 TJ. For the year 2030, an optimal scenario shows an increase in energy from biomass (including biogas) from 42 TWh (151,200 TJ) to 51 TWh (183,600 TJ) [103]. Firewood accounts for more than 95% of the biomass used in Romania, with the remaining 5% coming from agricultural waste, energy crops, liquid biofuels and also biogas. Thus, the aforementioned increase in biomass consumption should also result in an increase in biogas production. In the case of the Czech Republic, the report prepared as part of the TRACER project predicts a biogas yield of 31,100 TJ in 2030 [104], which coincides with the forecast shown in Figure 5b (32,437 TJ in 2030).

Table 2 summarises the most important results of the forecasts shown in Figure 5 (obtained for four regressors). In addition, based on the ARIMAX model, the dates for achieving 50% and 100% utilisation of the biogas potential are also estimated. The projected increase in biogas production for the period from 2022–2030 looks promising (Figure 5—red curves); however, it should be noted that in the case of Romania, Austria, Slovenia and Latvia, the first years of the projected growth will be devoted to rebuilding the production levels of previous years. Furthermore, the extended forecast in Table 1 shows that, in the case of six countries, the utilisation of 50% of the potential will most likely occur in the fifth decade of the 21st century. In the case of Romania (second-largest biogas production potential among the 3SI countries), reaching 50% of its utilisation rate is projected for the 22nd century. Even the new EU energy policy, gradually being built after 24 February 2022, seems far from sufficient in this light. Forecasts obtained using three regressors predict a much smaller increase in biogas production in each of the countries studied. By comparing the two tested models, it appears that the largest difference occurs in the case of Estonia (nearly 1.9 times the difference for the forecast from 2030), while the smallest (~1.2) is for the Czech Republic. The quality of the two studied models was estimated with the help of the Akaike information criterion (AIC) and its modification for small sample size AICc. The measure of the goodness of fit for the models was estimated with the help of the log-likelihood. Obtained results are presented in Table 3.

Table 2. Biogas production forecast based on four regressors.

Country	Percentage Change in Biogas Production in 2030 vs.		Expected Date of Use	
	2021 Production Values	Highest Production Value of the Period 2010–2021	50% Biogas Potential	100% Biogas Potential
Bulgaria	96.1	93.3	~2060 yr.	after 2100 yr.
Czech Republic	32.4	26.3	2013 yr.	~2035 yr.
Estonia	138.7	123.8	~2038 yr.	~2060 yr.
Croatia	67.2	67.2	~2036 yr.	~2060 yr.
Latvia	101.3	42.5	~2028 yr.	~2043 yr.
Lithuania	55.3	55.3	~2070 yr.	after 2100 yr.
Hungary	79.8	56.4	~2060 yr.	after 2100 yr.
Austria	65.7	−19.28	~2055 yr.	after 2100 yr.
Poland	70.3	64.7	~2070 yr.	after 2100 yr.
Romania	76.6	19.3	after 2100 yr.	after 2100 yr.
Slovenia	46.7	2.5	~2024 yr.	~2040 yr.
Slovakia	59.3	29.9	~2032 yr.	~2060 yr.

Results obtained for the Czech Republic and Austria present the highest log-likelihood values. This means that the studied models offer a lower fit to the data than in the case of the other countries; the high value of the AICs and AICs support these findings. In the case of the Czech Republic, this may be due to the fact that the biogas sector has shown stable production of ~24,000 TJ since 2013; in addition, the biogas industry is utilising a potential of more than 55%, which may translate into greater limitations in projected growth than in other countries. The biogas industry in Austria has been experiencing a sharp decline in production since 2017, causing a number of problems in forecasting. The best goodness of fit is observed in the case of Slovakia, a country utilising its own potential of more than 30% (Figure 4b). It is worth mentioning that MAPE (mean absolute percentage error) for seven models shows very good forecasting ability (less than 10%), good properties for three models (between 10% and 20%) and reasonable forecasting ability for two models.

Table 3. The quality of ARIMA (0,0,0) models.

Country	4 Regressors					3 Regressors				
	AIC	AICc	Log Likelihood	σ^2	MAPE	AIC	AICc	Log Likelihood	σ^2	MAPE
Bulgaria	164.19	174.19	−77.09	3.894	20.08	170.97	173.97	−82.48	4.014	22.98
Czech Republic	225.24	235.24	−107.62	5.927	14.05	225.12	230.84	−108.56	6.002	17.37
Croatia	150.48	156.19	−71.24	3.692	27.28	148.61	151.61	−71.31	3.709	29.02
Estonia	143.98	153.98	−66.99	3.634	16.69	131.83	138.5	−61.91	3.654	18.11
Lithuania	139.46	149.46	−64.73	3.601	5.57	150.36	156.07	−71.18	3.694	6.12
Hungary	172.78	182.78	−81.39	3.774	5.24	154.55	161.21	−73.27	3.834	5.99
Austria	220.93	226.64	−106.46	5.864	17.17	191.48	194.9	−92.74	5.991	18.53
Latvia	171.66	177.37	−81.83	3.851	5.83	170.07	173.07	−82.04	3.899	6.21
Poland	181.19	191.19	−85.6	3.874	2.87	202.09	212.09	−96.04	3.976	3.09
Romania	144.61	154.61	−67.3	3.604	5.61	143.34	149.05	−67.67	3.684	6.05
Slovenia	150.05	155.76	−71.02	3.834	6.22	122.54	139.34	−55.27	3.947	6.89
Slovakia	82.89	98.09	−36.45	1.362	8.89	97.37	103.08	−39.68	1.971	9.79

4. Analysis

The use of biogas potential plays an important role in enhancing energy security. This aspect is of particular importance for countries with relatively low economic potential (which include most of the Three Seas Initiative countries). There are very few studies in the scientific literature on the energy transition of the 3SI countries. Among the 3SI countries, renewable energy development is receiving rather moderate attention. It is worth mentioning that only 11 of the 82 Priority Projects currently underway are in the renewable energy sector, diversification of supply or expansion of energy storage facilities [105]. Therefore, the results obtained at the regional level (NUTS2) concerning biogas potential and biogas production forecasts can be helpful in building a biogas market development strategy. The development dynamics of the biogas sector varies between countries or regions [62], and there are also diverse barriers to the development of this sector [106]. However, despite the fact that each country has its own development factors, the experiences and solutions applied in one country may be useful for others.

By observing biogas production and the projected growth until 2030, it can be seen that in this respect, the 3SI countries show some similarities. Figure 6 shows a dendrogram obtained using Ward's agglomeration method. It shows the results of the clustering based on the similarities between the indicators of biogas production against natural gas consumption, biogas potential against natural gas consumption, biogas production against biogas potential, and the projected increase in production value of the period from 2022–2030. In this case, the clustering quality measure Silhouette Index indicates a division into two clusters (k = 2) as the optimal number, but a division into four clusters (k = 4) was used to better represent the clustering.

The first most numerous cluster includes countries characterised by average percentages of biogas production growth in the period from 2022–2030. This cluster also gathers countries of the highest biogas potential (Poland, Romania, Hungary and Austria) and the lowest percentage of its utilisation (Poland and Romania) (Figure 4b). The separation of Slovenia and Estonia as separate clusters II and III was influenced by the high values of the indicator describing biogas potential in relation to natural gas consumption and the low values of biogas potential utilisation (below 10%). It is worth noting that Estonia showed the highest percentage increase in biogas production in 2030 compared to 2021

(138.7%), while for Slovenia it was only 46.7%. On the other hand, presence in cluster IV was determined by a high degree of biogas potential utilisation (more than 55% for the Czech Republic and around 40% for Latvia) and a high value of biogas production relative to natural gas consumption. The priority of energy development in Europe to accelerate carbon neutrality is the need for all countries to solve the problem. Without the dissemination of knowledge in this area and the appropriate use of renewable resources, it will not be easy to develop alternative energy sources to accelerate the climate transition. The current international situation is forcing European countries to invest in such a way as not to be dependent on external suppliers (energy security) and to meet the objectives of preventing a climate crisis. One good solution would be to use biogas, for example.

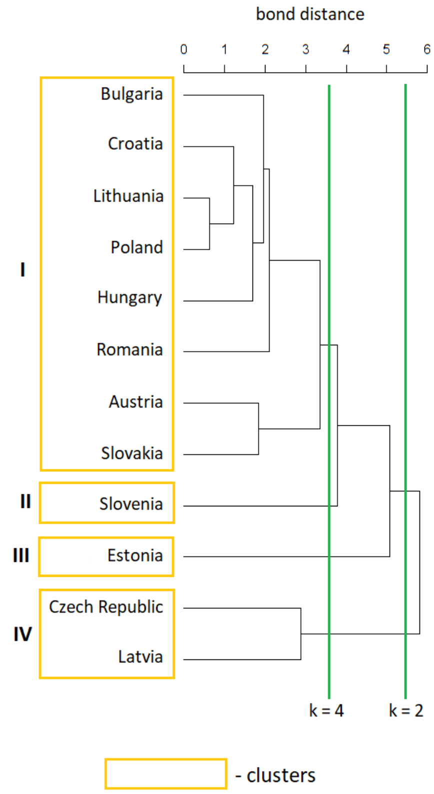

Figure 6. Dendrograms of indicators describing the biogas market in 2021.

5. Conclusions

At present, most of the biogas produced is used to produce electricity and heat, but it should be noted that these forms of energy can be successfully produced using other methods. Therefore, bearing in mind that natural gas is an important component of many production processes (e.g., production of mineral fertilisers), it is necessary to consider using the potential of biogas to cover the demand for this energy carrier. Biogas production and its increase in the following years in the 3SI countries would be a good way to reduce the dependency on natural gas imports. In this regard, the 3SI countries show a wide variation, from 10.2% for Hungary to 36.8% for Slovenia, in covering natural gas consumption by biogas potential (Figure 3). Projected production growth in 2030 from 32.4% for the Czech Republic to 138.7% for Estonia makes biogas investments very promising from an energy security perspective. Thus, the first and second hypotheses can be considered positively verified. The results of the cluster analysis presented in Section 3.1 showed that from the point of view of the end-user of energy, Europe can be divided into at least three clusters (k = 3). One cluster in both studied scenarios (with RES and without RES) is dominated by the 3SI countries, which partially supports the idea of cooperation in the energy market [27]. The analysis carried out with the help of forecast results (Figure 5) shows that the biogas market in the 3SI countries can be divided into four clusters (Figure 6). The most numerous cluster brings together countries with the greatest potential and problems in the development of the biogas industry (Romania and Poland); this sector should be focused on to increase cooperation. In Poland, the main barriers to the development of renewable energy are limited opportunities for entrepreneurs to finance investments, legal regulations for support, administrative and procedural difficulties, as well as problems with the operation of transmission networks [107]. Poland's power and gas grid requires significant investments. Constraints to RES development in Romania are related to investment costs, underdeveloped infrastructure, some discontinuities in legislation and implementation of environmental policies, and bureaucracy [108]. In the case of Hungary and Poland, it is worth mentioning the dispute with the European Commission over raising funds from the National Recovery Plan. The possible absence of these funds will certainly contribute to stalling the energy transition in these countries. Autoregressive models implicitly assume that the future will resemble the past but can be inaccurate under certain market conditions, such as crises or periods of rapid production change, which happened in the case of Austria, Latvia, Romania and Slovenia. The above mentioned problems are significant unknowns in any forecast (the decisions of politicians and lawmakers are difficult to predict). In this light, forecasts made for Poland, Hungary and Romania, assuming an increase in production in 2030 of more than 70% over 2021, should be treated with more caution than for the other countries. Another major issue causing a forecasting problem is the revival of biogas production in such countries as Austria, Latvia, Romania and Slovenia. The biggest problem for the countries surveyed remains the long time it takes to exploit a high level of biogas potential. For the two countries with the highest potential, Poland and Romania, utilisation of 50% of the potential is projected for the fifth decade of the 21st century. A similar situation is observed for Bulgaria, Lithuania, Hungary and Austria (Table 1). In this case, even the EU energy policy promoting a rapid transition to a green economy and increasing the resilience of the EU energy system seems difficult to implement. In addition, as Balakrishnan et al. [109] point out, there are many barriers to renewable energy development. The most important one is the reluctance of the private sector to invest due to the significant investment and late return on capital.

Author Contributions: Conceptualisation, G.Ś. and D.T.; methodology, M.C.-W., D.T. and P.P.; software, P.P. and D.T.; validation, P.P. and D.T.; formal analysis, B.G., D.T., M.C.-W. and G.Ś.; investigation, J.G., M.C.-W., D.T. and P.P.; resources, P.P., M.C.-W. and D.T.; data curation, P.P. and D.T.; writing—original draft preparation, G.Ś., B.G., J.G., D.T. and M.C.-W.; writing—review and editing, B.G. and J.G.; visualisation, G.Ś. and D.T.; supervision, G.Ś.; project administration, G.Ś., B.G. and J.G.; funding acquisition, G.Ś. and B.G. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

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

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