applied system innovation

Article

The Use of Fuzzy Modelling Based on Expert Knowledge to Determine Poland's Energy Security Index Taking into Account Political Conditions

Jarosław Joostberens [1,*], Aurelia Rybak [1,*] and Aleksandra Rybak [2]

[1] Faculty of Mining, Safety Engineering and Industrial Automation, Silesian University of Technology, 44-100 Gliwice, Poland
[2] Department of Physical Chemistry and Technology of Polymers, Faculty of Chemistry, Silesian University of Technology, 44-100 Gliwice, Poland; aleksandra.rybak@polsl.pl
* Correspondence: jaroslaw.joostberens@polsl.pl (J.J.); aurelia.rybak@polsl.pl (A.R.)

Abstract: This article presents the results of research on the energy security index in Poland. Since the development of renewable energy sources forced by the transformation of the national energy system will require an increased supply of rare earth elements, the level of demand for these metals was taken into account when determining the energy security index. Furthermore, the development of renewable energy sources in Poland will directly depend on the volume of energy demand and, as the events of previous years have shown, on political and legal conditions, especially in the case of wind energy. Since some of these factors are qualitative, it was impossible to use a quantitative method. Therefore, fuzzy sets were used. Fuzzy modelling is based on expert knowledge. Using this method, the authors created three alternative scenarios for the development of Poland's energy security index: pessimistic, optimistic, and the most probable.

Keywords: fuzzy sets; energy security model; energy transition

Citation: Joostberens, J.; Rybak, A.; Rybak, A. The Use of Fuzzy Modelling Based on Expert Knowledge to Determine Poland's Energy Security Index Taking into Account Political Conditions. *Appl. Syst. Innov.* **2024**, *7*, 82. https://doi.org/10.3390/asi7050082

Academic Editor: Christos Douligeris

Received: 27 June 2024
Revised: 22 August 2024
Accepted: 2 September 2024
Published: 5 September 2024

1. Introduction

Energy security is a concept that was first defined in the 1970s [1,2]. Its origins were oil crises, the cause of which was the excessive dependence of the economies of countries around the world on crude oil, which led to global inflation and recession. A positive result was the interest in security and energy independence. Energy security plays an important role in the development of countries, both economically and socially [3]. Access to energy also determines the country's military security, which makes the ability to measure and assess the level of energy security crucial. Determining the level of energy security will also be important during the energy transformation process [4].

The first definitions of energy security included primarily fuel prices and the continuity of supply [5]. Over time, this concept has evolved and been adapted to geopolitical changes, the environment, technological possibilities, globalization, demographic and climate changes [6]. Currently, it takes into account four main groups of factors of availability, accessibility, acceptability, and affordability, that is, the so-called 4A, which has so far been the main subject of research on energy security [7–12]. Energy security is also to be ensured by increasing energy efficiency [13]. Currently, due to changes in the composition of energy mixes and the energy policy of the European Union, renewable energy sources play an increasingly important role in the energy systems of member states. On the one hand, they are intended to be a solution to dependence on fossil fuels. Since renewable energy is available in inexhaustible amounts everywhere in the world, theoretically, renewable sources are an ideal energy carrier that will ensure the energy security of EU countries. For this reason, renewable energy sources (RES) are perceived as factors that stimulate the increase in the level of the energy security index [14–16]. However, the development of renewable energy also involves the need to have access to critical raw materials. One of the most important elements in this regard are rare earth elements (REEs). Access to them is difficult, resources are concentrated in a few places around the world, and currently, in the case of the EU, approximately 90% of the raw material is sourced from China [17–19]. All of this translates into strong fluctuations in REE prices. Therefore, access to REEs will be a key factor for the successful transformation of energy systems and their energy security. REEs are primarily used in batteries for wind turbines, but also in electric vehicles and energy storage. Neodymium, praseodymium, dysprosium, samar, yttrium, cerium, lanthanum, scandium, europium, and terbium are of great importance for the development of renewable energy sources [20,21]. Currently, the share of renewable energy sources in electricity production in the European Union is approximately 25%, but it has been estimated that to ensure EU countries' security based on renewable energy sources, it would have to increase to a minimum of 50% [22,23]. This, in turn, would result in an increase in the demand for REEs from renewable energy sources, which is currently responsible for the consumption of, for example, 30% of the world's production of neodymium [24].

Therefore, the authors concluded that REEs should be taken into account when determining the energy security index, as it is usually not a factor taken into account in energy security studies. Over the last 20 years, many energy security indicators have been determined, from those that include single measures [25] to those composed of a set of several dozen factors [26]. Many methods for determining indicators have been used, including additive [27], root mean square [28], PROMETHEE [29], DEA [30], order weighted average [31], and rhombus area [32]. Most of the indicators created are based on quantitative measures and did not take into account the impact of REEs on the level of energy security. The authors used a method that allowed for the inclusion of qualitative measures. This is the impact of the legal provisions in force in Poland on the level of energy security, which is a qualitative measure. Additionally, when determining the level of energy security, the amount of demand for primary energy was taken into account, because it is one of the most important factors shaping the level of security. So far, no attempt has been made to determine the impact of the demand for primary energy and rare earth elements on Poland's energy security, taking into account the impact of qualitative factors, such as the legal status. This is a new approach to considerations regarding the state's energy security.

To summarize, the research conducted by the authors was intended to fill the following research gap:

Determining the energy security index while taking into account qualitative factors such as the impact of the political environment and the demand for critical raw materials on the level of energy security.

This research aimed to find answers to the following questions:

1. How will energy policy regarding renewable energy sources and critical raw materials affect energy security?
2. What is the relationship between the access to critical raw materials and energy availability?
3. What strategies should be implemented in the context of dependence on critical raw materials to improve energy security?

To determine the energy security index, when taking into account qualitative measures, fuzzy sets were used, which are described in the Methods chapter.

2. Materials and Methods

2.1. Research Methodology

Fuzzy sets make it possible to describe phenomena and regularities that can be characterized as fuzzy. In the analyzed case, these were qualitative factors, such as the impact of legal regulations on Poland's energy security. These factors are intuitively understandable, but their interpretation may be ambiguous. Due to the vague nature of this factor, a formal inference mechanism cannot be used. Since qualitative factors, such as the impact of legal regulations, will have a significant impact on shaping energy security in Poland, fuzzy sets were used to take them into account in the analysis.

Fuzzy modelling is based on expert knowledge. It may be subconscious, so it is difficult to obtain directly. The most common way to obtain it is to observe the work and reactions of an expert when handling a process. Conscious knowledge can be captured directly and formulated into an explicit record. The expert's knowledge about the process is called the mental model [33]. A diagram illustrating the process of creating a fuzzy linguistic model of a real system is shown in Figure 1.

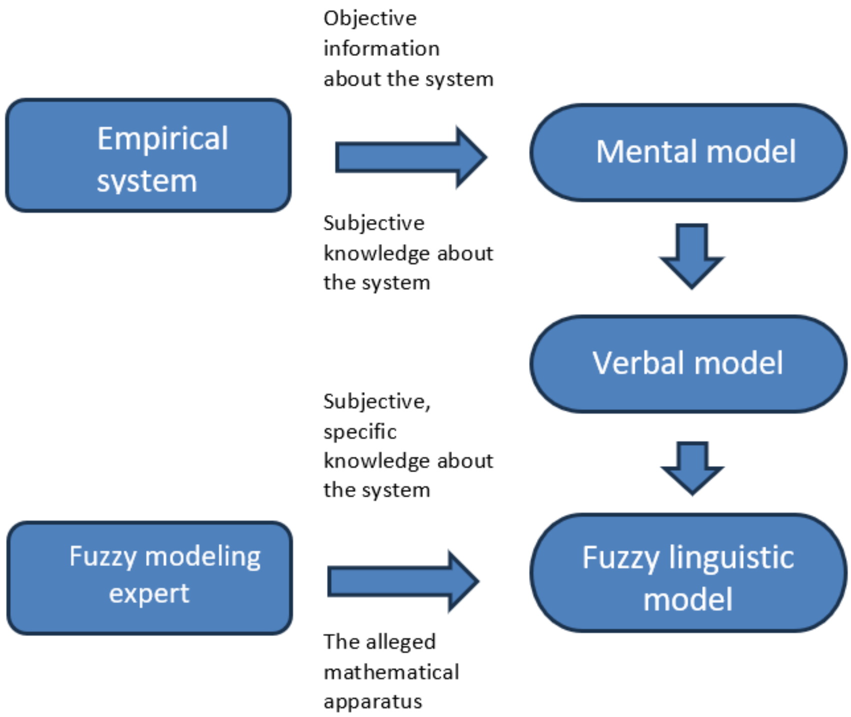

Figure 1. The process of creating a fuzzy linguistic model of an empirical system. Source: [33].

In a similar way as in the case of creating an model of an empirical process, activities can be carried out to describe (using expert knowledge) the static impact of one quantity on another quantity. In such a case, the expert's knowledge results from experience in conducting research and observing the impact of given quantities and parameters on other quantities and parameters. Conducting an interview with an expert allows to obtain their explicit knowledge. This can be achieved by using a survey and questions formulated in the form of verbal rules defining the input and output relationships of the model being sought.

To develop a fuzzy model, a survey of experts' opinions was conducted on the assessment of the impact of demand for primary energy (*ZEP*) and rare earth elements (*ZREE*) on Poland's energy security indicators in light of legislation in this area (the survey form is included in the Supplementary Material).

The experts were selected according to their knowledge of the analyzed phenomenon. They were exclusively professors. The group of experts included 60% women, and the age range of the experts was 40–65 years.

The survey included three forms containing factors used to analyze the level of the energy security index if the legal provisions in force in Poland affect security in the following ways: neutral, negative, or positive. The energy security index takes values from the set of low, medium, and high, where low means a negative assessment, high means a positive assessment, and medium means a neutral assessment. In addition, the study took into account factors such as the following:

- Primary energy—energy obtained directly from natural resources (renewable and non-renewable). The energy demand assumed in the survey may be:
- Small, for example, due to an increase in the level of energy efficiency, the use of energy-efficient machines and equipment in industry, or an increase in energy prices.

- Average, remaining at the current level.
- High—as a result of increased demand for energy caused by, for example, dynamic economic growth, natural increase, or falling energy prices.

For the primary energy demand, the following values were adopted: low—100, medium—106, and high —113 GJ/capita, marked in surveys and Tables 1–3 as M, S, and D, respectively. The values were obtained by building the ARIMA model and the confidence interval for the determined forecasts.

- REEs—rare earth elements, necessary in the process of producing renewable energy technologies such as wind turbines and energy storage. They are classified as critical raw materials due to their limited availability and lack of substitution. The demand for REEs assumed in the survey may be:
- Small, e.g., due to a decline in interest in renewable energy sources such as wind energy or energy storage.
- Average, remaining at the current level.
- High, due an increased demand for REEs caused by the dynamic development of renewable energy sources or economic growth that consumes most of the REEs available on the market.
- In the case of REE demand, the following values were assumed: small demand—77,449, medium demand—214,147, and large demand—350,845 kg/MW, marked in surveys and Tables 1–3 as M, S, and D, respectively. Values (low—M, medium—S, and high—D) were obtained by building the ARIMA model and the confidence interval for the forecasts determined.

The form required the selection of the level of Poland's energy security index (SEM_f) depending on the impact of legal regulations and the demand for REEs and primary energy. The experts' task is therefore to determine the level of Poland's energy security using the SEM_f indicator expressed in qualitative form (W—high, S—medium, and N—low) for three values of demand for primary energy (*ZEP*) and rare earth elements (*ZREE*) expressed in the form qualitatively (W—high, S—medium, and N—low) for each of the three scenarios related to the legal status affecting the country's energy security in a negative, neutral, or favorable way. Poland's energy security index can reach values ranging from 0 to 1.

2.2. The Structure of the Fuzzy Model

Due to the completeness of the survey questions, the role of the fuzzy modelling expert (Figure 1) was reduced to developing the model structure and introducing a formalized mathematical notation enabling the creation of a complete fuzzy model. Based on survey research, a fuzzy model with two inputs was proposed as follows: *ZEP* and *ZREE* characterized by three fuzzy sets. Three bases of rules were proposed for the fuzzy model, depending on the legal provisions (*Pr*) affecting energy security, i.e., on the quality parameter. The legal status was marked as favorable $Pr = 1$, neutral $Pr = 0$, or unfavorable $Pr = -1$. The structure of the fuzzy model for determining Poland's energy security index is shown in Figure 2.

As can be seen in Figure 2, if, for example, legal regulations change from neutral ($Pr = 0$) to favorable ($Pr = 1$), then for the purposes of determining the sharp value of the energy security factor SEM_f in the fuzzy model, there is a transition from one (middle) rule base to another (internal) one, corresponding to a given legal status.

The fuzzy model consists of a series of blocks. The first one is Normalization. In this block, the input quantities *ZEP* and *ZREE* are converted into their normalized forms ZEP^N and $ZREE^N$ in the range $[-1, 1]$. In the model, the normalized modal values of the sets of fuzzy inputs, with the values given in Section 2.1 and qualitatively marked in the survey and Tables 1–3 as M, S, and D, define the location, i.e., the values uS^N, uP^N, and uL^N—Formula (1). They are necessary to determine the value of the function belonging to fuzzy sets of current values at the model input.

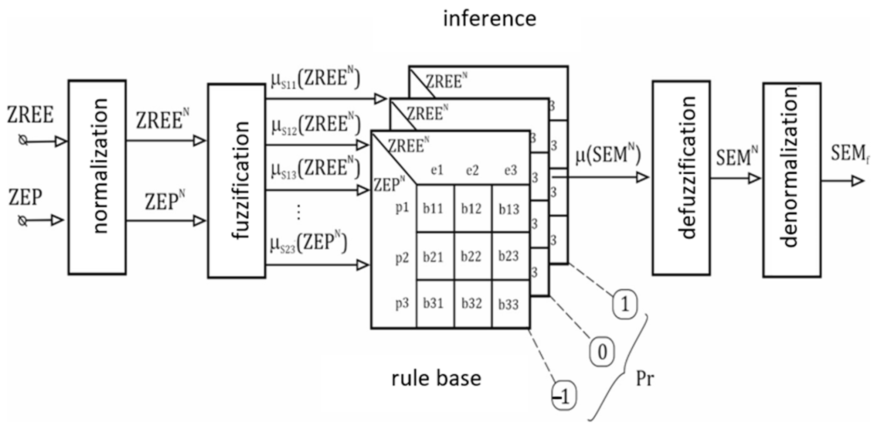

Figure 2. Structure of the fuzzy model for determining Poland's energy security index. Source: own study.

The fuzzification block assigns the degree of membership to the fuzzy sets e_i and p_j (i, j = 1, 2, 3). The input vector is then transformed into a fuzzy set characterized by the membership function [34]. Triangular functions were adopted as the function of membership in fuzzy sets of inputs, for which the value of the function of membership in fuzzy sets is determined using the following formulas:

$$\mu_{ei}\left(ZREE^N\right) = \begin{cases} 0 & for \quad ZREE^N < eL^N \\ \left(ZREE^N - eL^N\right)/\left(eS^N - eL^N\right) & for \quad eL^N \leq ZREE^N \leq eS^N \\ \left(eP^N - ZREE^N\right)/\left(eP^N - eS^N\right) & for \quad eS^N \leq ZREE^N \leq eP^N \\ 0 & for \quad ZREE^N > eP^N \end{cases}$$
$$\mu_{pj}\left(ZEP^N\right) = \begin{cases} 0 & for \quad ZEP^N < qL^N \\ \left(ZEP^N - pL^N\right)/\left(pS^N - pL^N\right) & for \quad pL^N \leq ZEP^N \leq pS^N \\ \left(pP^N - ZEP^N\right)/\left(pP^N - pS^N\right) & for \quad pS^N \leq ZEP^N \leq pP^N \\ 0 & for \quad ZEP^N > pP^N \end{cases} \quad (1)$$

where:

$ZREE^N$—normalized value of demand for REEs;

ZEP^N—normalized value of primary energy demand;

$\mu_{ui,j}(U^N)$—membership function for the i-th or j-th fuzzy input set;

uS^N—normalized modal value of the fuzzy set;

uL^N, uP^N—values of the fuzzy set of the input on the left and right sides of the normalized modal value, respectively, for which the membership is 0;

u^N—e^N or p^N;

U^N—$ZREE^N$ or ZEP^N.

Singleton functions were adopted as the output fuzzy sets. The membership functions are then expressed by the following formulas:

$$\mu_{ji}\left(SEM^N\right) = \begin{cases} 1\ dla\ SEM^N = b_{ji} \\ 0\ dla\ SEM^N \neq b_{ji} \end{cases} \quad (2)$$

$m(SEM^N)$ is calculated based on the membership degrees $\mu_{e,j}(ZREE^N)$ and $\mu_{p,j}(ZEP^N)$. This block includes a set of rule bases (for various influences of legal provisions), an inference mechanism, and a membership function of the output of the fuzzy model.

The rule base in the form of if–then rules contains qualitative knowledge about the modelled input and output relationships collected on the basis of survey research. From the point of view of the modelled relationship $SEM_f = f(ZEP, ZREE)|_{Pr}$, it is the most important part of the fuzzy model in which the knowledge of experts is formalized. In the case under consideration, a single rule has the following form:

$$\underbrace{IF\left(e^N = S_j\ AND\ p^N = S_i\right)}_{antecedent\ (premise)}\ TO\ \underbrace{\left(SEM^N = b_{ji}\right)}_{conclusion} \tag{3}$$

The proposed model uses three rule bases, each taking into account experts' opinions on the development of Poland's energy security index in the legal situation understood as negative, neutral, or positive.

In the inferential mechanism used in the model, the *PROD* operator was used to aggregate the premises, allowing the surface of the fuzzy model to be smoothed. This operator can be expressed as the following equation:

$$m_k = PROD\left(\mu_{ei}(ZREE^N), \mu_{pj}(ZWEP^N)\right) = \mu_{ei}(ZREE^N) \cdot \mu_{pj}(ZEP^N) \tag{4}$$

where m_k is the degree of fulfilment of the premise of the kth rule.

Inference was carried out using the MAX–MIN method:

$$\mu_{ji*}(SEM^N) = MIN\left(m_k, \mu_{ji}(SEM^N)\right) \tag{5}$$

Defuzzification (Figure 2) is used to determine the sharp value of the output quantity, based on the determined resulting value of the membership function, obtained by introducing the sharp values *ZEP* and *ZREE* to the inputs. The Height method was used to implement this function. Due to the fact that the model-output fuzzy sets are singletons located in a specific modal value, the output value is calculated from the following formula:

$$SEM^N = \frac{\sum_1^r b_{ji} \times \mu_{ji*}}{\sum_1^r \mu_{ji*}} \tag{6}$$

where r is the number of rules.

The last stage of the calculations is denormalization, i.e., the calculation of the absolute value of the SEM_f coefficient from the standardized range $[-1, 1]$.

Taking into account the survey results, the modal values of the output fuzzy sets for the three rule bases were determined using the following weighted average:

$$b_{ji} = \frac{\sum\limits_{q=1}^{5} B_q \times E_q}{\sum\limits_{q=1}^{5} E_q} \tag{7}$$

where:

B_q—absolute value of the energy security indicator determined by the q-th expert for the linguistic input values of *ZEP* and *ZREE* and the quality factor *Pr*;

E_q—q-th expert.

The B_q values correspond to the determination of the country's energy security index by the qth expert in a qualitative manner (W—high, S—medium, and N—low) for the linguistic input values of *ZEP* and *ZREE* and for a given qualitative factor *Pr*—Tables 1–3. The qualitative values of B_q, expressed as W, S, and N, are assigned quantitative values equal to 0, 0.5, and 1, respectively. Due to the fact that expert assessments for the qualitative input data $ZREE_j$ and ZEP_i may differ, the modal value of a given output fuzzy set b_{ji} is calculated according to Formula (7), where Eq corresponds to the existence or lack of an assessment by a given expert, and then they are normalized. In Formula (7), the E_q factor takes the value 1 if the expert expressed an opinion (W, S, N), and zero if the expert did not provide any linguistic value. As follows from Equation (7), for $ZREE_j$ and ZEP_i data, at least one expert must effectively conduct a qualitative assessment of their impact on SEM_f. The modal values of the b_{ji} output fuzzy set determined on the basis of experts' knowledge (Tables 1–3) are necessary to develop rules (3), membership functions (2), and SEM^N values.

The determined values are summarized in Tables 1–3.

Table 1. Survey results in an optimistic scenario.

No.	Primary Energy Demand (*ZEP*)	Demand for REE (*ZREE*)	1	2	3	4	5
1	M	M	W	W	W	W	W
2	M	M	W	W	W	W	W
3	M	D	W	S	S	W	S
4	S	M	W	S	S	S	S
5	S	D	S	S	S	S	S
6	D	M	S	N	S	S	N
7	D	D	S	N	S	N	N
8	S	S	S	S	S	S	S
9	D	S	S	N	S	S	N

Symbols in the tables: D, W—high, S—average, M, N—small, 1–5—expert ratings.

Table 2. Survey results in a neutral scenario.

No.	Primary Energy Demand (*ZEP*)	Demand for REE (*ZREE*)	1	2	3	4	5
1	M	M	W	W	W	S	W
2	M	S	W	S	W	W	S
3	M	D	S	S	S	W	S
4	S	M	S	S	S	S	S
5	S	D	S	S	S	S	N
6	D	M	S	N	N	S	S
7	D	D	N	N	N	N	N
8	S	S	S	S	S	S	S
9	D	S	N	N	N	N	N

Table 3. Results of the survey in a pessimistic scenario.

No	Primary Energy Demand (*ZEP*)	Demand for REE (*ZREE*)	1	2	3	4	5
1	M	M	W	W	S	S	W
2	M	S	S	W	S	S	W
3	M	D	S	S	S	S	S
4	S	M	S	S	S	S	S
5	S	D	S	S	S	S	S
6	D	M	N	N	N	N	N
7	D	D	N	N	N	N	N
8	S	S	N	S	S	S	S
9	D	S	N	N	N	N	N

3. Results and Discussion

The acquired sets of points, presented in the form of 3D charts, allow to analyze all combinations of explanatory variables taken into account during the analysis and the corresponding values of the SEM_f index. This is very valuable considering the increasing level of macroenvironmental uncertainty that has emerged in the 21st century. It was caused, among others, by globalization and, in recent years, by the pandemic and the war in Ukraine. Under such conditions, scenario planning works well as a method for planning future states of the environment and analyzing phenomena. Scenarios contain information about possible alternative images of the development of the phenomenon in the future. The results of the analysis obtained through the use of fuzzy sets can be used to create scenarios for Poland's energy security. Thanks to this, the state will be able to prepare for various variants of the future development of the macroenvironment and respond in advance to possible threats that may arise there.

Using the fuzzy sets method, the authors created three alternative scenarios for the development of Poland's energy security index: pessimistic, optimistic, and the most probable. A very important factor in this case is the state's policy, e.g., towards renewable energy sources, and in particular wind energy. The 2016 Wind Act effectively limited wind energy investments. In 2023, the regulations contained therein regarding the distance from buildings were changed. However, changes and constant legislative instability can have a negative impact on the continuity of investments and investor interest. Therefore, the impact of legal regulations on Poland's energy security was treated as the main explanatory variable. Additionally, the level of primary energy and the amount of demand for REEs were used as explanatory variables. A fuzzy model determining the impact of *ZEP* and *ZREE* on Poland's energy security index, taking into account the qualitative factor in the form of legal regulations, was developed in the Matlab R2024b environment. The fuzzy model, enabling the transfer of expert knowledge into formalized mathematical notation, was used to prepare the relationship $SEM_f = f(ZEP, ZREE)\mid_{Pr}$. Taking into account the impact of legal provisions (unfavorable, neutral, and favorable) on Poland's energy security indicator, the values of this indicator were determined analytically based on the knowledge of experts. The results of these calculations are presented graphically in Figures 3–5.

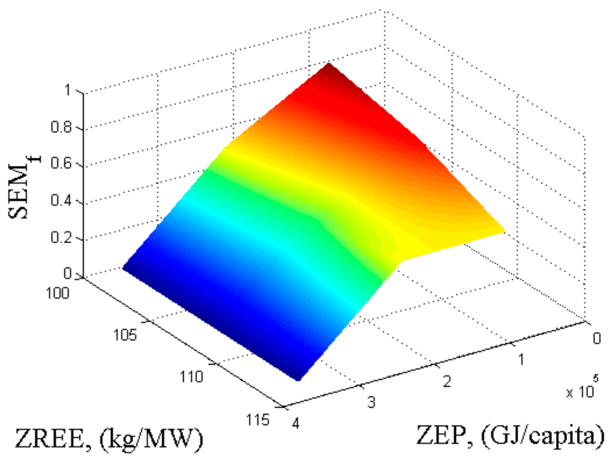

Figure 3. Dependence of the demand for primary energy (*ZEP*) and rare earth elements (*ZREE*) on the energy security index of Poland in the situation of unfavorable legal status. Source: own study. Blue—lowest indicator value, red—highest indicator value.

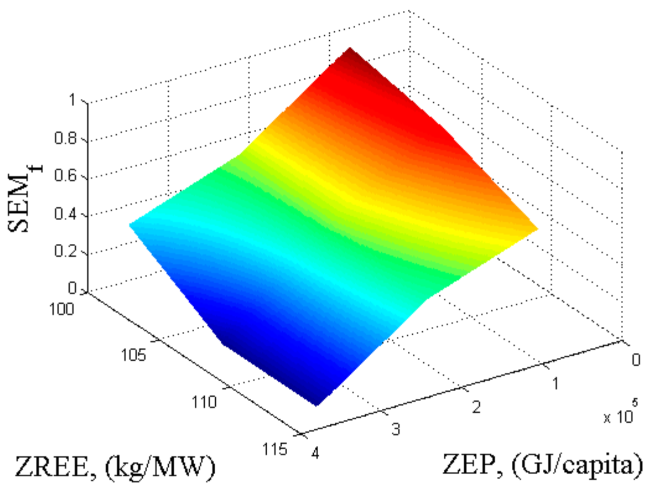

Figure 4. The relationship between the demand for primary energy (*ZEP*) and rare earth elements (*ZREE*) on Poland's energy security index in a neutral legal status. Source: own study. blue—lowest indicator value, red—highest indicator value.

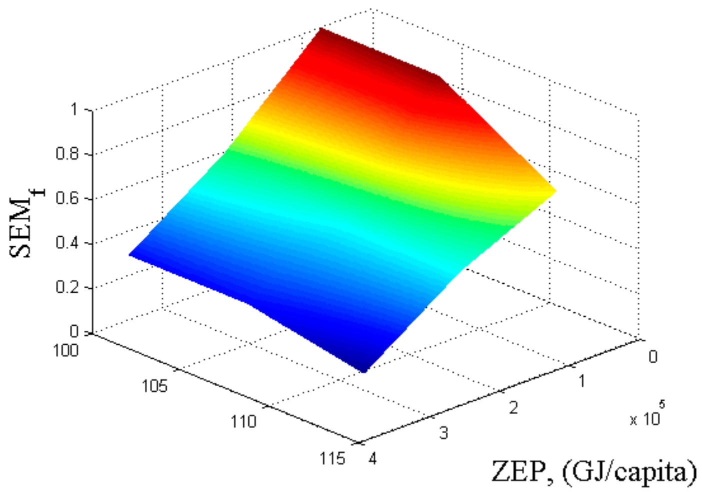

Figure 5. Dependence of the demand for primary energy (*ZEP*) and rare earth elements (*ZREE*) on the energy security index of Poland in the situation of favorable legal status. Source: own study. blue—lowest indicator value, red—highest indicator value.

3.1. Pessimistic Scenario

It should be noted that in the case of unfavorable legal conditions in the environment, the SEM_f indicator has a maximum value of 80% and a minimum value of 0% (Figure 3). Energy security is at risk when the demand for primary energy is high, regardless of changes in the level of demand for REEs. The maximum value is achieved with minimum REEs and primary energy demand. Energy security will therefore be at risk in the event of a high demand for energy, which the state will not be able to cover with the energy carriers available in the energy mix. The course of the function parallel to the REEs axis indicates that this phenomenon will be independent of the share of RESs in the mix. This situation may occur if coal is withdrawn from the energy mix.

3.2. The Most Likely Scenario

For neutral conditions of the political environment, the SEM_f indicator reaches a maximum value of 90% at the minimum values of demand for REEs and primary energy, and a minimum value of 0% at the highest level of demand for REEs and primary energy (Figure 4). Therefore, security will reach its highest level when the demand for energy is limited. Such a situation may occur, for example, in the event of an economic slowdown, an increase in energy productivity, or the introduction of a new energy carrier into the energy mix, e.g., nuclear energy.

3.3. Optimistic Scenario

In positive conditions of the political environment, the SEM_f indicator reaches the highest value—up to 100%—and the lowest value of 20% (Figure 5). This situation may occur in the case of the dynamic development of renewable energy sources due to a favorable energy policy, as indicated by the high level of demand for rare earth elements. Due to this, even in conditions of high demand for primary energy, the SEM_f indicator does not reach 0%.

The political factor was also taken into account in the research presented in the literature [26,35,36]. The results confirmed that political factors have a major impact on the level of energy security. However, only the energy security index value was calculated. The authors created alternative scenarios for Poland's energy security index: pessimistic, optimistic, and the most probable, depending on the conditions of the political environment, instead of relying on measurements obtained by quantitative and statistical methods [37–39], which are currently dominant in the literature. This is especially important in a rapidly changing, turbulent market and political environment.

4. Conclusions

Safety indicators, many examples of which are described in the literature, usually include primarily measures related to accessibility, availability, acceptability, and affordability (4A). However, most of them do not cover the impact of REE demand on safety. Various methods were also used to determine the metrics, such as z-score, min–max, and taxonomic methods. The measure proposed by the authors is based on fuzzy sets. This method makes it possible to take into account the qualitative factor (legal factors) and the impact of the demand for REEs on the level of Poland's energy security index during the analysis. Fuzzy sets not only provide an answer to the size of the *SEM* index, but also make it possible to build three scenarios of energy security depending on the selected explanatory variables. Such scenarios can be extremely valuable during the process of planning a country's energy strategy. The fuzzy model can be used to determine scenarios of the impact of changes in demand for primary energy and rare earth elements on Poland's energy security in the situation of changing legal regulations in this area. Scenarios can be excellent guidelines for decision makers in determining the country's energy strategy. The universality of the proposed solution allows for the assessment of energy security on a smaller scale, relating to a specific organization, e.g., a plant or a company. In the future, it is planned to further expand the fuzzy model to include other factors that affect the energy security of the organization or Poland, including those resulting from cyberattacks on critical infrastructure.

The conducted research allowed us to find answers to the research questions:

1. What is the relationship between access to critical raw materials and energy availability? The basic strategic document shaping the energy system in Poland is the Polish Energy Policy until 2040. In addition to PEP2040, the National Energy and Climate Plan for 2021–2030 also has an impact on the energy system. Both documents place great emphasis on the development of renewable energy. The policy states that by 2040, the share of renewable energy sources in electricity production should be 50%. This production will be based mainly on wind and solar energy. It is assumed that in addition to onshore wind farms, offshore wind farms will also be built in Poland, and by 2040 they will reach an installed capacity of 11 GW. Both documents contain information on access to critical raw materials, but in the authors' opinion, they are negligible, especially considering the importance of critical raw materials in the development of renewable energy sources. In the presented research, the authors focused on REEs, without which it will be impossible to carry out an energy transformation based on wind energy. REEs are also of great importance for the development of electromobility and energy storage, without which the development of photovoltaics in the future may be unjustified.
2. How will energy policy regarding renewable energy sources and critical raw materials affect energy security?

   As shown by the presented research results, in conditions of high demand for REEs and energy ultimately coming from renewable energy sources, the energy security index may, in extreme cases, have the lowest value of 0%. Such a scenario concerns neutral conditions of the political environment, assuming that the development of RESs and ensuring access to REEs will not be stimulated by the state, but that it will not block the development of RESs, as, e.g., in the case of wind energy (Wind Act of 16 July 2016). The lowest level of energy security in the range of 80–0% would be achieved under unfavorable legislative conditions. If, in addition, the demand for energy and REEs is significant, the energy security index may drop to 0.
3. What strategies should be implemented in the context of dependence on critical raw materials to improve energy security?

It is necessary to develop an additional policy to ensure access to critical raw materials. Importing REEs from a single source is a huge threat; if China limits the supply, there will be a shortage of raw materials on world markets, without which the creation of renewable energy technologies will be impossible. Decision makers should take care to indicate alternative import directions or sources of REEs. A new supply chain for these raw materials should be built. In the case of Poland, this may be fly ash generated in the process of coal combustion. It is necessary to develop an REE management strategy that will take into account economic as well as ecological aspects. It will also be necessary to provide support for the research and development of technologies for obtaining REEs from energy waste, which is consistent with the principles of a circular economy.

One of the limitations of the presented research is that the obtained results lack reference to another country or benchmark. The authors plan to expand their research with additional factors. The indicator will also be determined for other EU countries so that it will be possible to compare Poland with them and create a ranking of countries.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/asi7050082/s1.

Author Contributions: Conceptualization, J.J. and A.R. (Aurelia Rybak); methodology, J.J. and A.R. (Aurelia Rybak); software J.J. and A.R. (Aurelia Rybak); formal analysis, J.J. and A.R. (Aurelia Rybak); writing—original draft preparation, A.R. (Aleksandra Rybak), A.R. (Aurelia Rybak) and J.J.; validation, J.J. and A.R. (Aurelia Rybak); visualization, J.J., A.R. (Aleksandra Rybak) and A.R. (Aurelia Rybak); investigation, A.R. (Aurelia Rybak) and J.J.; funding acquisition, J.J. and A.R. (Aurelia Rybak); methodology J.J. All authors have read and agreed to the published version of the manuscript.

Funding: This work was elaborated and partially financed in the framework of the statutory research BK 06/010/BK_23/0060.

Data Availability Statement: The data presented in this study are available upon request from the corresponding author. The data are not publicly available due to their extremely large size.

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

References

1. Lubell, H. Security of Supply and Energy Policy in Western Europe. *World Politics* **1961**, *13*, 400–422. [CrossRef]
2. Colglazier, E.W., Jr.; Deese, D.A. Energy and Security in the 1980s. *Annu. Rev. Energy* **1983**, *8*, 415–444. [CrossRef]
3. Dospinescu, O.; Dospinescu, N. A profitability regression model of Romanian stock exchange's energy companies. In Proceedings of the 17th International Conference on Informatics in Economy Education, Research & Business Technologies, Iasi, Romania, 17–20 May 2018; pp. 17–20.
4. Neofytou, H.; Nikas, A.; Doukas, H. Sustainable energy transition readiness: A multicriteria assessment index. *Renew. Sustain. Energy Rev.* **2020**, *131*, 109988. [CrossRef]
5. Yergin, D. Energy Security in the 1990s. *Foreign Aff.* **1988**, *67*, 110–132. [CrossRef]
6. Cherp, A.; Jewell, J. The Three Perspectives on Energy Security: Intellectual History, Disciplinary Roots and the Potential for Integration. *Curr. Opin. Environ. Sustain.* **2011**, *3*, 202–212. [CrossRef]
7. Goldthau, A. Governing Global Energy: Existing Approaches and Discourses. *Curr. Opinion. Environ. Sustain.* **2011**, *3*, 213–217. [CrossRef]
8. Asia Pacific Energy Research Center (APERC). A Quest for Energy Security in the 21st Century. 2007. Available online: https://aperc.or.jp/file/2010/9/26/APERC_2007_A_Quest_for_Energy_Security.pdf (accessed on 19 June 2024).
9. Deese, D.A. Energy: Economics, Politics, and Security. *Int. Secur.* **1979**, *4*, 140–165. [CrossRef]
10. International Energy Agency (IEA). Energy Security. *IEA Energy Technology Systems Analysis Programme, Paris*. 2014. Available online: https://iea-etsap.org/#:~:text=About%20IEA-ETSAP,and%20one%20private%20sector%20sponsor (accessed on 19 June 2024).
11. World Energy Council (WEC). *Energy for Tomorrow's World—Acting Now*; World Energy Council: London, UK, 2000.
12. Hancock, K.J.; Vivoda, V. International Political Economy: A Field Born of the OPEC Crisis Returns to Its Energy Roots. *Energy Res. Soc. Sci.* **2014**, *1*, 206–216. [CrossRef]
13. Bertoldi, P.; Mosconi, R. Do energy efficiency policies save energy? A new approach based on energy policy indicators (in the EU Member States). *Energy Policy* **2020**, *139*, 111320.
14. Trifonov, I.; Trukhan, D.; Koshlich, Y.; Prasolov, V.; Slusarczyk, B. Influence of the Share of Renewable Energy Sources on the Level of Energy Security in EECCA Countries. *Energies* **2021**, *14*, 903. [CrossRef]
15. Brahim, S.P. Renewable Energy and Energy Security in the Philippines. *Energy Procedia* **2014**, *52*, 480–486. [CrossRef]
16. Wang, B.; Wang, Q.; Wei, Y.M.; Li, Z.P. Role of Renewable Energy in China's Energy Security and Climate Change Mitigation: An index decomposition analysis. *Renew. Sustain. Energy Rev.* **2018**, *90*, 187–194. [CrossRef]
17. Humphries, M. *Rare Earth Elements: The Global Supply Chain*; Diane Publishing: Collingdale, PA, USA, 2010.

18. Hurst, C. China's Ace in the Hole: Rare Earth Elements. *J. Force Q.* **2010**, *59*, 121–132.
19. Proposal for a Regulation of the European Parliament and of the Council Establishing a Framework for Ensuring a Secure and Sustainable Supply of Critical Raw Materials and Amending Regulations (EU) 168/2013, (EU) 2018/858, 2018/1724 and (EU) 2019/1020. Available online: https://eur-lex.europa.eu/resource.html?uri=cellar:903d35cc-c4a2-11ed-a05c-01aa75ed71a1.0011.02/DOC_1&format=PDF (accessed on 19 June 2024).
20. Gielen, D.; Lyons, M. *Critical Materials for the Energy Transition: Rare Earth Elements*; International Renewable Energy Agency: Abu Dhabi, United Arab Emirates, 2022.
21. International Renewable Energy Agency (IRENA). Critical Materials for the Energy Transition: Rare Earth Elements. 2022. Available online: https://www.irena.org/Events/2022/May/Critical-Materials-for-the-Energy-Transition-Rare-Earth-Elements (accessed on 10 May 2022).
22. Sadorsky, P. Do Urbanization and Industrialization Affect Energy Intensity in Developing Countries? *Energy Econ.* **2013**, *37*, 52–59. [CrossRef]
23. Cergibozan, R. Renewable Energy Sources as a Solution for Energy Security Risk: Empirical Evidence from OECD Countries. *Renew. Energy* **2022**, *183*, 617–626. [CrossRef]
24. Circilarise. Available online: https://www.circularise.com/ (accessed on 19 June 2024).
25. Frondel, M.; Schmidt, C.M. Measuring energy security—A conceptual note. *Ruhr Econ. Pap.* **2008**, *52*, 1–19. [CrossRef]
26. Augutis, J.; Krikstolaitis, R.; Martisauskas, L.; Peciulyte, S. Energy security level assessment technology. *Appl. Energy* **2012**, *97*, 143–149. [CrossRef]
27. Ang, B.W.; Choong, W.L.; Ng, T.S. A framework for evaluating Singapore's energy security. *Appl. Energy* **2015**, *148*, 314–325. [CrossRef]
28. Geng, J.B.; Ji, Q. Multi-perspective analysis of China's energy supply security. *Energy* **2014**, *64*, 541–550. [CrossRef]
29. Antanasijević, D.; Pocajt, V.; Ristić, M.; Perić-Grujić, A. A differential multi-criteria analysis for the assessment of sustainability performance of European countries: Beyond country ranking. *J. Clean. Prod.* **2017**, *165*, 213–220. [CrossRef]
30. Ramanathan, R. An analysis of energy consumption and carbon dioxide emissions in countries of the Middle East and North Africa. *Energy* **2005**, *30*, 2831–2842. [CrossRef]
31. Badea, A.C.; Tarantola, S.; Bolado, R. Composite indicators for security of energy supply using ordered weighted averaging. *Reliab. Eng. Syst. Saf.* **2011**, *96*, 651–662. [CrossRef]
32. Yao, L.; Chang, Y. Energy security in China: A quantitative analysis and policy implications. *Energy Policy* **2014**, *67*, 595–604. [CrossRef]
33. Piegat, A. *Fuzzy Modeling and Control*; Akademicka Publishing House EXIT: Warsaw, Poland, 2003.
34. Driankov, D.; Hellendoorn, H.; Reinfrank, M. *Introduction to Fuzzy Control*; WNT: Warsaw, Poland, 1993.
35. Wang, Q.; Zhou, K. A framework for evaluating global national energy security. *Appl. Energy* **2017**, *188*, 19–31. [CrossRef]
36. Filipović, S.; Radovanović, M.; Golušin, V. Macroeconomic and political aspects of energy security–Exploratory data analysis. *Renew. Sustain. Energy Rev.* **2018**, *97*, 428–435. [CrossRef]
37. Bompard, E.; Carpignano, A.; Erriquez, M.; Grosso, D.; Pession, M.; Profumo, F. National energy security assessment in a geopolitical perspective. *Energy* **2017**, *130*, 144–154. [CrossRef]
38. Vasić, B.; Pekić, I.; Šimić, G. Energy security of the European Union and corruption in Central Asia as the main challenges for the European sustainable energy future. *Energy Sustain. Soc.* **2023**, *13*, 31. [CrossRef]
39. Gawusu, S.; Ahmed, A. Analyzing variability in urban energy poverty: A stochastic modeling and Monte Carlo simulation approach. *Energy* **2024**, *304*, 132194. [CrossRef]