economies

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Energy Diversification and Security in the EU: Comparative Assessment in Different EU Regions

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Abstract: Various methods and tools have been developed to quantify energy supply security; however, there is no ideal framework to measure energy security, as the concept is multifaceted and context dependent. Energy supply security has always been an extremely important issue for European Union (EU) countries due to high import dependency, and recent events linked to the COVID-19 pandemic and the Russian invasion of Ukraine have made it exceptionally important to reconsider this problem to identify the crucial issues and address contemporary policy needs. This study endeavours to systematise the primary energy security indicators in terms of policy relevance and develop an energy security assessment framework to examine energy import dependency and diversification for the EU in view of recent problems. This study introduces an energy import diversification and security index which enables measurement of a country's energy security level for comparison with other countries and identifies primary areas for improvement. The proposed framework is then applied to a case study of selected EU countries to examine regional differences and identify potential improvements.

Keywords: energy import diversification; energy security; indicators: EU member states

Citation: Streimikiene, Dalia, Indre Siksnelyte-Butkiene, and Vidas Lekavicius. 2023. Energy Diversification and Security in the EU: Comparative Assessment in Different EU Regions. *Economies* 11: 83. https://doi.org/10.3390/economies11030083

Academic Editor: Lea-Rachel Kosnik

Received: 17 January 2023
Revised: 22 February 2023
Accepted: 2 March 2023
Published: 6 March 2023

1. Introduction

Modern life is entirely dependent on energy supply, and the COVID-19 pandemic and the Russia–Ukraine war have elevated the importance of energy security issues which must now be reconsidered (Chen et al. 2021). The consequences of the COVID-19 pandemic are widely discussed in the scientific literature. Overall, the changes in the energy sector during the pandemic were related to extreme fluctuations in global energy consumption and demand patterns (Krarti and Aldubyan 2021; Zhong et al. 2021), the development of renewable energy sources (Siksnelyte-Butkiene 2021) and the implementation of objectives to reduce GHG emissions (Kumar et al. 2022), among other consequences. The European Union (EU) has been dependent on imported energy sources for many years (Eurostat 2022), and a large proportion of the EU's natural gas supply comes from Russia (Eurostat 2022). The Russia–Ukraine war, which started on 24 February 2022, has amplified the necessity to strengthen the level of energy security in Europe (European Commission 2022a). Due to the constraints caused by these global events, the volume of energy trade sharply decreased, and energy transportation interruptions and limited storage capacities in EU countries placed energy security at high risk in energy-import-dependent countries.

As global product markets have experienced huge shocks in recent years, energy prices have increased significantly, causing extensive problems for countries and societies (Siksnelyte-Butkiene 2022). Energy-importing countries face high risks in the global energy market, including supply chain disruption risks. In addition, climate change mitigation commitments and the accelerated penetration rate of renewable energy put additional pressure on energy supply security due to the unreliable nature of current renewable energy sources (Istudor et al. 2021). Guaranteeing a reliable, adequate and environmentally friendly energy supply is a principal goal that presents a significant challenge for EU member states due to high dependencies on energy imports. Energy security is a context-dependent and multifaceted problem which is closely associated with national security and foreign policy. It is also a global problem linked to matters of international energy supply and energy geopolitics (Bompard et al. 2017; Rodríguez-Fernández et al. 2020; Khan and Dhakal 2022).

The extensive scientific literature analyses energy security issues, ranging from analyses of various methodological approaches for defining and measuring energy security (Helm 2002; Feygin and Satkin 2004; Jansen et al. 2004; Alhajji 2008; Gupta 2008; Axon et al. 2013; Belkin 2008; Hedenus et al. 2009; Cabalu 2010; Bollen 2008; Chester 2010; Cohen et al. 2011; Hughes 2012; Bollino and Galkin 2021) to empirical studies (Lesbirel 2004; Hellmer and Wårell 2009; Bang 2009; Devaraj et al. 2021; De Rosa et al. 2022) applying previously developed energy security indicators and proposing modifications (Kanchana and Unesaki 2015; Lefèvre 2009; Löschel et al. 2009; Wu et al. 2009; Vivoda 2010; Sovacool 2011; Song et al. 2019; Yu et al. 2022). A majority of the related research seeks to apply a general methodology to measure energy security and refine the research questions regarding energy security quantification (IEA 2007; IAEA 2005). Quantitative methods dominate studies examining energy supply security, particularly in cross-country comparisons and analyses of energy security dynamics.

Previous research regarding energy supply security does not emphasize the current state of energy supply security due to the COVID-19 pandemic and the Russia–Ukraine war, which generated considerable challenges for EU countries due to high energy import dependency and concentration. This study aims to address this gap and contribute to the analysis and assessment of energy security in the EU by considering these recent problems which disrupted natural gas and oil supplies from Russia. Based on a literature review and analysis of available energy security indicators, a measurement framework of energy import dependency and diversification is constructed and applied in a case study of selected EU member states from the main geographical regions: eastern, western, southern and northern Europe. This study presents an energy import diversification and security (EIDS) index to determine the level of energy security linked to energy import dependency and diversification. The proposed index enables the measurement of a country's energy security level for comparison with other EU countries and identifies primary areas for improvement. Three different weighting schemes are used for sensitivity analyses. The analysis covers a six-year period (2015–2020) to investigate the impact of the COVID-19 pandemic on energy supply security. The proposed index could be useful tool for further research to identify the impact of various uncertainties and geopolitical issues and events on the energy security of countries which are energy import dependent and seeking diversification.

The remainder of this paper is structured as follows. In Section 2, literature on energy supply security and energy security quantification are analysed and systematised. Section 3 presents the proposed framework for energy security assessment and details the methodology of assessment. The results of the assessment representing four different EU geographical regions are presented in Section 4. Section 5 discusses the research results and findings, summarizing conclusions and proposed policy implications.

2. Literature Review

2.1. Energy Security Concept

The concept of energy security has evolved in the past few decades, and no universal definition of energy security or its components has emerged. Although energy security is a critical consideration of every country's energy system management and a crucial aspect of international relations (Marhold 2021), the concept remains vaguely defined and dependent on the context of the questions analysed, individual perceptions, environmental concerns and countries' political and economic factors, among other relevant factors. An uninterrupted energy supply is essential to the functioning of a country's whole economy: therefore, energy security is traditionally associated with energy supply security, which emphasizes access to energy suppliers and the scarcity of fossil fuels. In the beginning, the term was specifically used referencing oil, but after the 'oil crises' in the 1970s and 1980s, an increase in natural gas usage occurred and the concept was applied to the other energy sources as well. As energy sources are traded globally, physical shortages of energy are reflected in price fluctuations. Subsequently, definitions that only reflect physical characteristics are too narrow. Energy price is an important aspect of energy security (Kruyt et al. 2009).

In contemporary research, the concept of energy security has shifted from a traditional understanding to an interdisciplinary approach. Different concerns regarding the climate change, globalisation and individual well-being have added new dimensions, expanding the perspectives regarding what energy security is and what it is related to (Jakstas 2020). The concept of energy security is now linked with various economic, environmental, social, security and political issues. Multiple attempts to define the concept of energy security are found in the scientific literature.

For example, the Asia Pacific Energy Research Center (Asia Pacific Energy Research Centre (APERC) 2007) defines energy security as the ability to ensure the supply of energy sources in a sustainable and timely manner at an affordable price, which does not negatively affect the economic performance of a country. APERC identifies five main factors which influence energy supply security, including the availability of energy sources from domestic and external suppliers, the ability to ensure the supply required to meet energy needs, countries' energy resource and supplier diversification level, accessibility of energy resources, including energy infrastructure capacities and various geopolitical concerns regarding resource acquisition. This construct belongs to the traditional understanding and is widely applied when analysing energy security issues, which is known as the 4As approach, referencing availability, affordability, accessibility and acceptability (Cherp and Jewell 2014).

Rodriguez-Fernandez et al. (2022) stress the importance of expanding this traditional understanding of energy security to incorporate current global challenges into the construct, such as climate change and energy dependency. Sovacool et al. (2012) analyse perceptions of energy security in different regions and cultures of the world, demonstrating the presence of significant differences in perception regarding import dependency and security among countries and cultures as well as genders, political orientations, states and regions within countries. Kisel et al. (2016) introduces an energy security matrix that included political affects and indicators reflecting political stability in analysed and supplying countries, efforts to influence the policies of the other countries and the possibility of a country being affected and the corruption level in a country. Perceptions of energy supply security can also be revealed by analysing different energy security indicators.

2.2. Energy Import Dependency and Security Indicators

Previous research has developed indicators for quantifying energy supply security in terms of primary energy sources seeking to categorise the main measures of volume and price risks. Multiple approaches are applied to calculate countries' degree of energy supply security. Some scholars analyse a single aspect of energy supply security by applying simple indicators, whereas others examine several elements of energy security endeavouring to construct aggregated indicators or indices (Kruyt et al. 2009).

Several studies provide estimates of fossil resources based on single indicators. The best known one is the United States Geological Survey (USGS) which provides a reliable source of data regarding the quantity of fossil resources available around the world (USGS 2019). Some energy security indicators use reserves to production ratios (Feygin and Satkin 2004) to determine the remaining years of production at current production levels. While neither energy resource reserves nor energy production rates are fixed for countries, examining a combination of these two components enables the evaluation of dynamic quantities. In reality, as constant values are applied for both measures, if projected energy production levels are used instead of current levels, such indicators become less transparent and are not valuable for accurate strategic policy analyses.

The International Atomic Energy Agency (IAEA 2005) developed a comprehensive framework for assessing energy supply system sustainability. Single indicators of energy supply security include energy import dependency, energy prices, energy use per capita, share of oil use in the transport sector and other measures in the Energy Indicators for Sustainable Development (EISD) framework.

Portfolio theory measures financial risks to achieve trade-off between revenue and associated stock risks in investment portfolios. The approach seeks to determine the limit beyond which investment risk can overcome the benefits of returns. According to portfolio theory, every component of a portfolio is defined by revenue and risk, which are evaluated as the standard deviation of revenue per unit. The risks of price changes in energy generation technologies in energy portfolios are analysed and evaluated in research examining applications of portfolio theory to assessments of energy supply security (Awerbuch and Yang 2007; Jansen et al. 2004). The world energy import price index (Lesbirel 2004) presents a clear distinction between the systemic risk of energy imports which cannot be solved and specific risk that can be addressed.

A number of studies examining single indicators of energy security measure countries' current energy source diversification (Kruyt et al. 2009). In this strand of research, authors use energy source imports as a measure of energy security. Notably, energy supply diversification is a primary strategy used by countries to navigate energy security problems and ensure resilience to energy supply shocks. Increased resilience indicates reduced vulnerability or likelihood of domestic energy supply disruption if external energy carriers' supply is reduced or cut off. The primary indicators to assess energy supply security in terms of diversity of energy supply include the Herfindahl–Hirschman, Shannon and Gini Indices (Asia Pacific Energy Research Centre (APERC) 2007). These indices are further developed by Jansen and Seebregts (2009) to assess energy supply security, introducing more complicated indices covering several important issues of energy security. Many studies measure energy security based on energy import dependency (IAEA 2005), which is an extremely important indicator of energy supply security for determining countries' economic dependence on energy carriers that are outside of government control and can be destabilised at any time for various reasons that are independent of the energy importing country.

However, much more research endeavours to construct energy security indicators that cover various issues of energy security and single indicators of energy security. Jansen et al. (2004) present an index based on a modified Shannon index which considers the diversity of fuels and suppliers in the proportion of imports for each energy carrier, also assigning a political stability component for each supplier. The International Energy Agency (IEA 2007) and Lefèvre (2009) propose two important energy security indicators regarding the physical availability and price risks of energy import concentration. The IEA (2007) presents two specific indices for energy security assessment. The first index examines energy supply volume interruptions (ESIVolume), and the second assesses energy price change risks (ESIPrice). The volume–risk index measures the proportion of oil-indexed, pipeline-bound gas imports in a country's primary energy supply. The price risk index examines market concentration which is computed by applying a political stability-weighted Herfindahl–Hirschman index for all energy supply carriers using concentration measures for each energy carrier market weighted by the proportion of the primary energy supply associated with the price risk of that market (Cohen et al. 2011). Lefèvre (2009) applies these energy security measures to investigate the energy supply security in France and the UK.

The energy security measures used by the Asia Pacific Energy Research Centre include energy supply diversity and import dependence (Asia Pacific Energy Research Centre (APERC) 2007). Seebregts et al. (2007) propose a supply–demand (S/D) index based on expert assessments of all possible energy security issues that could arise, such as energy supply and demand, energy conversion, transportation and distribution. The S/D index developed by Seebregts et al. (2007) is estimated as the weighted average of sub-indices for supply and demand, transportation and distribution, conversion and primary energy supply. The usual indicators are integrated into this index, including share of imports, reserve factors and storage capacities, among others. The weights are defined by an expert panel and are quite problematic in terms of robustness and transparency.

Bollen (2008) proposes a 'willingness to pay' function for examining energy supply security, introducing it into the MERGE model to determine the proportion of gross domestic product (GDP) a country is willing to spend to lower energy supply security risks, which is presumed to be higher for elevated energy supply security. Notably, this measure only calculates oil and natural gas as the primary sources of potential energy supply security risks, limiting its application as a comprehensive indicator of energy supply security.

Gupta (2008) proposes an aggregated index of oil supply vulnerability, including the ratio of oil import value to GDP value, oil consumption per unit of GDP, GDP per capita, the share of oil in total energy supply, the ratio of domestic oil reserves to oil consumption level and exposure to geopolitical oil supply and market liquidity risks. The weighting for the aggregation of the indicators is based on a component analysis approach which is robust and transparent; however, the main criticism is that aggregation which could provide useful information for policy analysis is hidden in the index.

Table 1 presents the main indicators of energy supply security from the literature review with assessments based on measures' appropriateness for policy analysis and relevant strategic decision-making.

Table 1. Measures and indicators of energy supply security.

Indicator	Input Data Required	Source	Appropriateness for Decision-Making
	Single indicators		
Oil and other energy source estimates	Quantity and likelihood the occurrence of oil and other fossil energy resources in the energy markets	(USGS 2019)	Qualitative
Energy resource reserve to energy production ratio	Energy resource and production estimates	(Feygin and Satkin 2004)	Qualitative
Energy diversity measures	The proportion of energy carriers or energy import in total primary energy supply (TPES) or the proportion of energy suppliers in of energy carriers' imports	(IEA 2007; Cohen et al. 2011)	Yes
Energy market concentration measures	The proportion of energy producers in the market	(Hellmer and Wårell 2009; Kanchana and Unesaki 2015; De Rosa et al. 2022)	Yes
Energy import dependence measures	Import quotes or the proportion of energy imports in TPES	(Alhajji 2008; Vivoda 2009, 2010)	Yes
Net energy import dependency index (NEID)	Energy carriers' import quotes and proportion of energy carriers in TPES	(Asia Pacific Energy Research Centre (APERC) 2007)	Yes
Political stability indicators and weights	The UN Human Development Index (HDI) is supplemented by various ratings of political risks provided by the World Bank and other international organisations	(IAEA 2005)	Qualitative
Energy price	Prices of oil, natural gas, coal and other energy resources and their dynamics	(IAEA 2005)	Yes
Mean variance portfolio	The proportion of energy carriers in TPES, energy costs per energy carrier and short-term variance in specific energy carriers' energy cost	(Lesbirel 2004; Awerbuch and Yang 2007; Wu et al. 2009; Bollino and Galkin 2021)	Limited
Non-carbon fuel share	Share of non-fossil resources in TPES	(Asia Pacific Energy Research Centre (APERC) 2007)	Yes
Energy market liquidity	The energy carriers available on the market and satisfying energy import needs	(IAEA 2005)	Yes

Table 1. *Cont.*

Indicator	Input Data Required	Source	Appropriateness for Decision-Making
Energy (or specific fuel) intensity indicators	The proportion of energy or specific fuel consumption to GDP	(IAEA 2005)	Yes
Energy use per capita	Energy or specific fuel consumption ratio to population	(IAEA 2005)	Limited
Portion of oil use in the transport sector	The proportion of oil used in transport consumption	(IAEA 2005)	Limited
Share of transport fuel in total energy (oil) consumption	The proportion of transport sector fuel consumption in total energy (oil) consumption	(IAEA 2005)	Limited
Aggregated indices			
Shannon index-based aggregations	The proportion of energy sources in TPES: import quotes, shares of energy suppliers in imports	(Jansen et al. 2004)	No
ESI	The proportion of energy producers in the energy market (based on net energy exports), including the political risk ratings per energy producers	(IEA 2007)	No
Supply–Demand (S/D) Index	The proportion of energy carriers in TPES, the proportion of energy carriers in imports and the proportion of energy suppliers in imports, including the duration of contracts, energy intensity, conversion and transport data	(Seebregts et al. 2007)	No
MERGE	Energy import quotes; energy carrier proportions in TPE, including energy intensity data	Bollen (2008)	No
OVI	Energy import quotes, including GDP, oil price, TPES and the proportion of oil suppliers in imports	(Gupta 2008)	No

Source: Produced by authors based on (IAEA 2005; Kruyt et al. 2009; Vivoda 2009; Yu et al. 2022; De Rosa et al. 2022; European Commission 2022b).

All analysed indicators allow an ordinal ranking of alternative energy supply options for countries. Furthermore, using a wide range of energy security indicators that address important energy supply security concerns allows us to define the current circumstances of EU energy security and its development. Some energy security indicators are better fit for policy analysis, some can provide only qualitative assessments and others are not useful for local policy analysis and evaluating and monitoring the effects of policies.

The most significant conclusion from this analysis is that there is no ideal indicator for measuring energy security, as the adequacy and relevance of energy security indicators strongly depends on the context and time of application.

3. Methodology

3.1. Framework for Assessing Energy Security Linked to Energy Import Dependency and Diversity

A framework for assessing energy security in relation to energy import dependency and diversity in the EU is developed based on analysis of available data from the EUROSTAT database (Eurostat 2022) and a set of indicators to monitor the progress towards Energy Union objectives (European Commission 2022b). To convert the set of energy security indicators into more manageable number of indicators, multi-criteria decision tools (Stirling 2009; Devaraj et al. 2021) can be applied to rank EU member states based on a cumulative index of energy security. The purpose of a set of indicators is to determine whether specific policies and strategies advance energy security. The proposed tool can be applied to forecast possible outcomes of potential and implemented policies and measures.

The developed set of indicators should include all relevant issues of energy security and leverage available quantitative and empirical data. This is essential for changes to be straightforwardly compared among countries over time. If appropriate, composites of the more important metrics created using a transparent weighting method should be used. Transparency is the key concept for all stages of the development and implementation of any system's set of indicators and metrics. Another important requirement is that the set of indicators must avoid replication and unnecessary complexity. In addition, it is essential to remember that the construction of indicator frameworks presenting a set of metrics that are not designed for a specific purpose is merely a set of statistics.

The main energy security indicators associated with energy import dependency and diversification are selected for the case study. The indicator framework that is constructed for the assessment of energy security in selected EU member states is based on the primary problems identified during the recent COVID-19 pandemic and Russia–Ukraine war global shocks, as these crises have significant impacts on energy supply security risk in the EU due to high energy import dependency on a single energy supplier and/or high concentration ratios.

Table 2 presents the energy security indicator framework for EU member states. The indicators are also selected considering data availability and comparability to ensure straightforward application of the proposed framework for future studies and monitor the progress achieved.

As presented in the energy security indicators framework in Table 2, the first group of energy security indicators cover energy import dependency (overall and for the most significant energy carriers) and indicators of energy supply security associated with energy infrastructure, including the N-1 rule and electricity interconnectivity indicators. The N-1 criteria for gas infrastructure measures the adequacy of countries' natural gas supply infrastructure by testing the resilience of natural gas supply systems. The indicator is defined in the Annex II of the Regulation (EU) 2017/1938 concerning measures to safeguard gas supply security and is available for all EU member states. Electricity interconnectivity indicators measure countries' share of electricity import interconnection capacity and total power generation capacity, which is calculated as the ratio of synchronous import interconnection capacity and total generation capacity at 19:00 around 10 January each year.

The second group of energy security indicators identifies the concentration of internal energy (power and natural gas) markets in the country. The measures cover market concentration indices and cumulative shares of power generation and natural gas supply by main entities. Cumulative market shares of power generating capacity and power generation of main entities are indicators of the combined power generation market share and the combined market share of generating capacities of the main power generation companies with shares of more than 5 % of national power generation. The cumulative market share of the main natural gas retailers indicates the combined natural gas market share of the main importers with market shares of 5 % or more. The market share of the largest electricity producer and the largest gas production and import company determine how strongly energy generation and supply are dependent on a single supplier.

In summary, the framework for assessment of energy security in EU member states includes three groups of indicators covering three main issues of energy security that are relevant to the current context of energy import dependency, energy import concentration/diversification and internal energy supply market concentration.

Table 2. Energy security indicators for EU countries associated with energy import dependency and diversity.

Indicator Group	Indicator	Abbreviation	Description	Target	Source
			Energy import dependency indicators		
Import dependency	Net energy import dependency—Total Net import dependency—Natural gas Net import dependency—Crude oil and natural liquid gas Net import dependency—Hard coal	I-1 I-2 I-3 I-4	Net import dependency (total and by main energy carriers) indicates the percentage of energy that a country imports or the extent to which an economy relies on energy imports to meet its energy needs; %.	min	Eurostat (2022)
Gas infrastructure	N-1 rule for gas infrastructure	I-5	The N-1 rule for gas infrastructure indicator reveals the capability of available natural gas infrastructure to meet overall natural gas demand in case of an interruption in the single largest natural gas infrastructure during days of extremely high demand like extremely cold temperatures; % of total demand that can be satisfied if the largest item of gas supply infrastructure is disrupted.	max	European Commission (2022b)
Electricity infrastructure	Electricity interconnection capacity	I-6	Electricity interconnectivity level is the ratio between the interconnection capacity of a power import specific country and its overall power generation capacity; % of installed capacity.	max	European Commission (2022b)
			Market concentration/diversification indicators		
Market concentration and diversification in the electricity sector	Market share of the largest electricity producer Cumulative market share of main electricity generation entities Cumulative market share of the main electricity generation entities' capacity	M-1 M-2 M-3	The market share of the largest electricity producer demonstrates the concentration of electricity generation; %. The cumulative market share in electricity generation is the combined power generation market share of power generating companies with shares of more than 5 % of overall power generation in the country; %. The cumulative market share in electricity generation capacity is the combined share of total power generation capacity of power generating companies with shares of more than 5% of overall power generation in the country; %.	min	Eurostat (2022)
Market concentration and diversification in the gas sector	Market share of the largest gas production and import company Cumulative market share of the main entities providing natural gas in the country	M-4 M-5	The market share of the largest gas production and import company shows how much the country's gas sector depends on a single gas supplier; %. The cumulative market share of the main entities providing natural gas in the country shows the combined natural gas market share of the main natural gas importers with natural gas market shares of 5 % or more; %.	min	Eurostat (2022)

Source: Produced by the authors.

3.2. Methods and Data

The EU is conventionally separated into eastern, southern, western and northern regions based on geographical locations. The countries in these regions have similar physical geographies and socio-economic development circumstances, including cultural traits; therefore, one representative country of a similar size in terms of area and population number is selected from each region for our case study assessing energy supply security. The four representative countries are the Czech Republic (10.7 M), representing eastern Europe; Greece (10.7 M), representing southern Europe; Belgium (11.6 M), representing western Europe; and Sweden (10.4 M), representing northern Europe.

The proposed energy import diversification and security (EIDS) index enables measurement of the level of energy security associated with countries' energy import dependency and diversification in the country and comparison of the results with other EU countries to monitor the progress achieved over the research period and identify the main areas for improvement. The model to compute the EIDS is as follows:

$$EIDS = \sum_{j}^{n} \beta \times X_k$$

where β is the weight of indicator, and X_k is the selected energy security indicator corresponding to the country.

Before calculating the EIDS index, all indicators are transformed to a 0–1 scale, where the value of 0 is the best possible result for indicators which need to be minimised, and the value of 1 is the best possible result for indicators which need to be maximised. The proposed EIDS index captures countries' sensitivity, with a lower index indicating higher vulnerability and low energy security.

The index is calculated using three different weighting schemes. In Scheme-1 (S-1), all the indicators have equal weights, while in Scheme-2 (S-2), equal weights are among indicator groups. Scheme-3 (S-3) divides the weights between energy import dependency and market concentration/diversification indicators, giving each category a half weight. In summary, for S-1, each indicator is equal; for S-2, each indicator group is equal; and for S-3, each category is equal, and the weights for each indicator are equal. Details of weighting schemes are presented in Table 3.

Table 3. Details of weighting schemes.

	Import Dependency				**Gas Infrastructure**	**Electricity Infrastructure**	**Market Concentration and Diversification in the Electricity Sector**			**Market Concentration and Diversification in the Gas Sector**	
	I-1	**I-2**	**I-3**	**I-4**	**I-5**	**I-6**	**M-1**	**M-2**	**M-3**	**M-4**	**M-5**
S-1	1/11	1/11	1/11	1/11	1/11	1/11	1/11	1/11	1/11	1/11	1/11
S-2	1/5				1/5	1/5	1/5			1/5	
S-3	1/2						1/2				

Source: Produced by the authors.

The correlation coefficients among different weighting schemes are also calculated to verify the appropriateness of the weighting coefficients used in the proposed index.

A six-year period (2015–2020) is analysed to determine the tendencies in previous years and identify how the COVID-19 pandemic affected energy supply security. The data used in the assessment are presented in Appendix A. The correlation coefficients among the indices in different weighting schemes are calculated to analyse the direction between the years under analysis to determine deviations in the data set for each year under study.

4. Results

The proposed EIDS index is calculated for the four selected EU member states which represent different regions of the EU and have similar characteristics in terms of territory and population size. The results indicate that regardless of which weighting scheme is applied, the countries can be ranked regarding the strength of energy security according to the indicators selected as follows: Czech Republic, Belgium, Greece and Sweden. This ranking remains unchanged during the period analysed and is not affected by the different weighting schemes. Table 4 presents the EIDS index for the selected countries for S-1, Table 5 presents S-2 and Table 6 presents S-3 from 2015 to 2020.

Table 4. EIDS index in selected countries, S-1, 2015–2020.

S-1	2015	2016	2017	2018	2019	2020
Belgium	0.4417	0.4700	0.4965	0.4826	0.4847	0.4748
Czech Republic	0.5932	0.7310	0.6546	0.6307	0.5576	0.6699
Greece	0.2225	0.2048	0.2013	0.2355	0.3056	0.2887
Sweden	0.1920	0.1799	0.2119	0.2039	0.2146	0.2042

Source: Produced by the authors.

Table 5. EIDS index in selected countries, S-2, 2015–2020.

S-2	2015	2016	2017	2018	2019	2020
Belgium	0.7015	0.7599	0.7935	0.7800	0.7763	0.7935
Czech Republic	0.8061	1.0671	1.0060	0.9825	0.8506	1.0060
Greece	0.3202	0.3072	0.2519	0.2905	0.4061	0.2519
Sweden	0.1832	0.1771	0.1984	0.1751	0.1828	0.1984

Source: Produced by the authors.

Table 6. EIDS index in selected countries, S-3, 2015–2020.

S-3	2015	2016	2017	2018	2019	2020
Belgium	0.4400	0.4648	0.4928	0.4828	0.4836	0.4730
Czech Republic	0.5745	0.7091	0.6306	0.6051	0.5410	0.6500
Greece	0.2196	0.2008	0.2069	0.2389	0.3131	0.2999
Sweden	0.1936	0.1831	0.2152	0.2077	0.2200	0.2110

Source: Produced by the authors.

To simplify the results analysis, the dynamic of the EIDS index is presented in Figure 1, revealing that the despite the different importance of the indicators selected, the patterns of the EIDS dynamic remain almost the same.

The EIDS assessment reveals significant differences among the countries under analysis in terms of energy import diversification and security. As leading country, the Czech Republic is distinguished as having capabilities of available natural gas infrastructure, low overall energy import dependency, low import dependency of hard coal, comparatively high gas market competition and comparatively high electricity interconnection, which rose from 17% to 27.45% during the period under analysis. The Czech Republic is distinguished by a high capacity of underground natural gas storage and the N-1 rule of the gas infrastructure indicator reaches 373% in almost all years under analysis. The overall energy import dependency rate fluctuates between 32% in 2015 to 41% in 2019. Competitiveness in the gas market is demonstrated by the low share of the largest gas production and import company (26% in 2020) and low rate of cumulative market share of the main entities bringing gas into the country, at 56% in 2020.

Belgium also stands out with capability in available natural gas infrastructure and comparatively sound gas market indicators. The N-1 rule of the gas infrastructure indicator is extremely high, reaching 246–279% in the period under analysis, and the market share of the largest gas production and import company reaching 26.20–35.30%. However, the total energy dependency rate is extremely high, varying from 84% to 97% in the years under analysis. The country's energy system is fully dependent on imported natural gas, crude oil and hard coal.

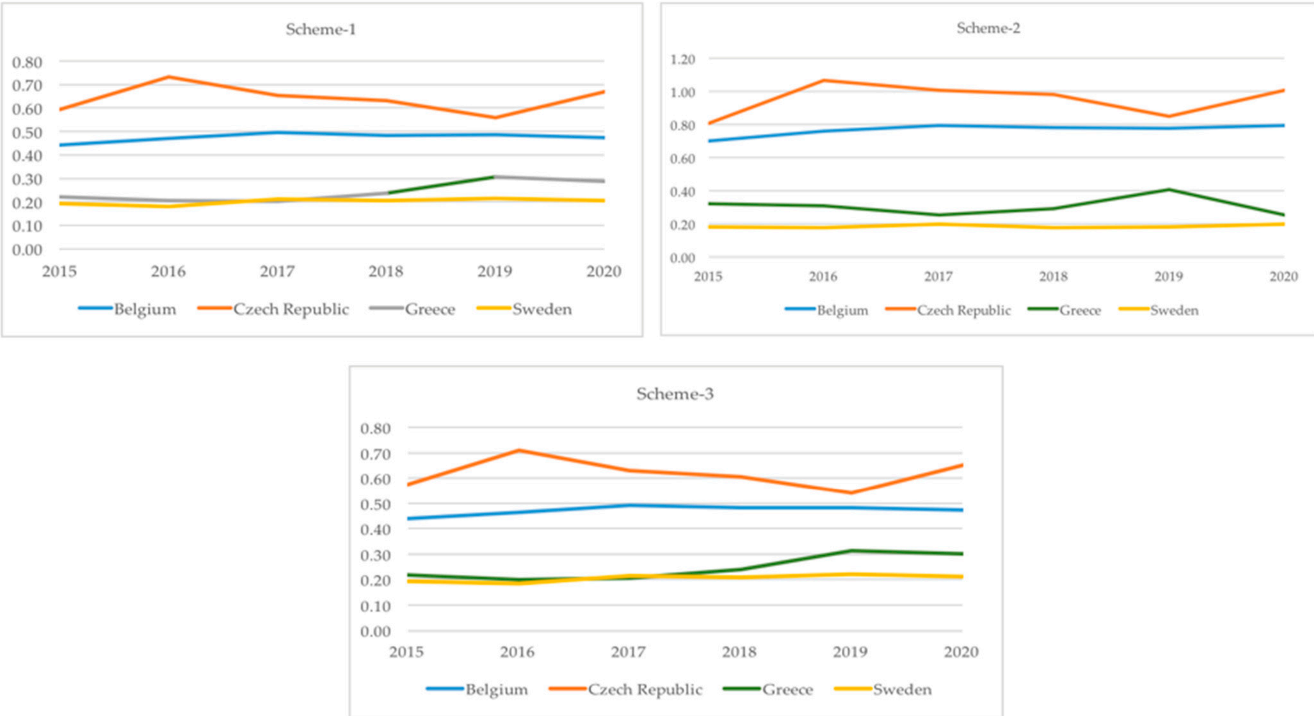

Figure 1. The dynamic of the EIDS index in different weighting schemes, 2015–2020. Source: Produced by the authors.

Notably low values in the EIDS index are obtained in Greece in all periods under analysis. Greece has high rates of energy import dependency, which varies from 76% in 2015 to 88% in 2020. The country is fully dependent on imported natural gas, crude oil and hard coal. In addition, the electricity interconnection level is very low, reaching only 10% of the installed capacity; however, the capability of available natural gas infrastructure is full coverage of the overall natural gas demand in case of an interruption of the single largest natural gas infrastructure. Notably, the shares of the largest electricity producer and the largest gas producer and import company are comparatively low, but the cumulative market share of the main entities bringing gas into the country reaches 94%.

The lowest results are observed in Sweden. The results are primarily affected by indicators related to the gas sector. First, the capability of available natural gas infrastructure covers only 2.5% of overall natural gas demand in case of an interruption of the single largest natural gas infrastructure. The country's gas sector is monopolised. In addition, Sweden is also fully dependent on crude oil and hard coal. Despite this, some other indicators, such as overall energy dependency, the level of electricity interconnection and electricity market competitiveness, are remarkably high. For example, overall energy dependency is only 35% in 2020, electricity interconnection reaches about 25% of all installed capacity and the share of the largest electricity producer is 38% in 2020.

The correlation coefficients among different weighting schemes are calculated to verify the suitability of the proposed weighting coefficients in the proposed EIDS index (Table 7).

The correlation coefficients among different weighting schemes demonstrate that the final results of the assessment do not differ despite varying levels of significance among the criteria selected. In some cases, the correlation is almost 1. The most different weighting is determined for S-2; however, the correlation coefficients among different schemes shows that these variations do not influence the final results of the assessment and all applied weighting schemes are appropriate for measuring the EIDS index.

Table 7. Correlation coefficients among the results of different weighting schemes.

	2015		2016		2017		2018		2019		2020	
	S-2	**S-3**	**S-2**	**S-3**	**S-2**	**S-3**	**S-2**	**S-3**	**S-2**	**S-3**	**S-2**	**S-3**
S-1	0.975	1.000	0.990	1.000	0.994	1.000	0.995	0.999	0.994	0.999	0.978	1.000
S-2		0.979		0.990		0.996		0.997		0.998		0.977

Source: Produced by the authors.

Correlation coefficients are used to evaluate the degree of association between two variables or data sets. Correlation coefficients were calculated to identify the direction of the linear relationship of the index between years and determine whether the pandemic had an impact on the EIDS index in the countries under study. Correlation coefficients between years and in different weighting schemes are presented in Table 8.

Table 8. Correlation coefficients between years.

Years Compared	S-1	S-2	S-3
2015–2016	0.99543	0.98475	0.99398
2016–2017	0.98980	0.99284	0.98904
2017–2018	0.99655	0.99771	0.99656
2018–2019	0.97946	0.97885	0.97683
2019–2020	**0.97742**	**0.96480**	**0.97376**

Source: Produced by the authors.

Although the correlation coefficients are considerably high in all years, indicating particularly strong correlation, certain deviations in the EIDS index suggesting deviations in the indicators are observed specifically in 2020. In summary, it can be said that the level of energy security increased significantly in the Czech Republic in 2020 and decreased slightly in the other countries. The Czech Republic maintains high natural gas security supply through its high capacity of underground natural gas storage. In 2020, the indicator showing the capability of Greece's available natural gas infrastructure to cover overall natural gas demand in case of an interruption of the single largest natural gas infrastructure (N-1 rule for gas) increased from 300% to 370%. However, this increase followed a decrease in 2019. In addition, a significant decrease in the cumulative market share of main entities bringing gas into the country is observed, which decreased significantly from 89% to 56% and is the lowest among the countries under analysis. The natural gas import dependency rate decreased 24% (from 110% to 86%) in Greece as well. These important changes regarding achievements in the gas sector were followed by an increase in the EIDS index in 2020.

5. Discussion

EU countries imported more than 40%, 27% and 46% of the total consumed natural gas, oil and coal from Russia in 2021. In the same year, 62% of total EU imports from Russia are related to energy carriers, reaching 99 billion EUR. In 2011, almost 80% of EU imports from Russia were energy-related (Eurostat 2022). Although the energy import dependency on Russia has declined in EU member states, the problem remains.

The results of this study assessing energy import dependency and supply security in selected EU member states in different EU geographical regions align with other studies examining energy security. The Czech Republic was the best performing country during the entire period investigated, followed by Belgium. Greece and Sweden were the worst performing according to the proposed EIDS index due to Sweden's high energy import dependency on natural gas, extremely low indicator for the N-1 rule for gas infrastructure and a high market concentration index in the gas sector, although the country has low total energy import dependency and considerably high electricity interconnection capacity.

Other studies (De Rosa et al. 2022) also confirm that countries in the western European region have higher energy security than southern Europe, primarily due to more developed infrastructure and a richer energy mix. Krikštolaitis et al. (2022) analyse the energy security of the main energy consumers in the EU, finding that countries in western Europe, such as Germany and France, perform significantly better than southern European countries (i.e., Italy and Spain) in terms of energy security assurance. A set of 22 indicators for estimating the energy security level is applied, including such indicators such as the share of renewable energy in gross final electricity consumption, various concentration indices, energy dependence rate, political risk and share of energy expenses per household in the total household expenses. The main factors attributed to these differences are the rich energy mix in Germany and the substantial presence of nuclear power in France. In our case study, Greece was ranked significantly lower in the EIDS index in comparison to Belgium, to a lower N-1 rule for gas infrastructure indicator and extremely low electricity interconnection capacity, showing less developed energy infrastructure in the country.

The Czech Republic was also found to be among the top performers in 2020 according to the World Energy Trilemma index (World Energy Council 2020), which covers energy security, and is ranked as the eighth country in the world based on energy security, leaving the other countries analysed (Greece, Belgium and Sweden) far behind in terms of energy security. Energy security in the World Energy Trilemma index measures countries' ability to meet current and future energy demand and to withstand and respond to system shocks minimising supply disruptions. This dimension examines effectiveness in the management of domestic and external energy sources, along with the reliability and resilience of energy infrastructure.

Elbassoussy (2019) analyses EU energy security challenges and mitigation strategies, finding that new EU member states, including the Czech Republic, Slovakia and the Baltic States are distinguished by lower energy import dependency in comparison to Western and Southern European countries.

While EU production of renewables has grown substantially in recent years, gas production has declined, leading to higher dependence on natural gas imports. The increase in energy prices and high volatility require reduction in energy import dependency, one of the main objectives of which is to enhance EU emergency preparedness and resilience to gas disruptions.

It is essential to stress that the countries analysed also have different socio-economic contexts for energy security dependence based on natural resource endowments and market integration. The rapid penetration of renewable energy sources has a positive impact on decreasing energy import dependency; however, due to the high volatility of renewable energy production, greater interconnectivity with neighbouring grids and increased energy storage capacities could improve system resilience and bolster supply security.

6. Conclusions

The problem of energy security is one of the most important concerns in the energy policies of many countries in the world. The significant increase in energy studies, proposed indices and assessments tools reveals the multifaceted nature of the problem and connections with many other issues, such as energy poverty, resource efficiency, environmental policy and geopolitics. The review of energy security indicators demonstrates that indicators have clearly become more complex, with a broader focus, moving from simple energy market issues to environmental, technological and social issues, aiming to provide guidance for future research and policymaking.

This study examines the most important challenges to EU countries' energy security in the post-COVID-19 era for meaningful policy responses in the face of the Russia–Ukraine war, including high energy import dependency and high supply concentration of energy sources from non-EU countries. A framework of the energy security indicators that are relevant to addressing the current challenges of energy security in the EU is proposed in this study. Based on the indicators selected, the EIDS index is developed to measure the level of energy security and diversification at a country scale. Three different weighting schemes are also proposed to investigate the significance of the selected indicators. To perform a comparative assessment, four EU countries representing the main geographical regions with similar physical geography or cultural traits based on physical geographical demand and populations are chosen for a case study to assess energy supply security in the EU.

The results reveal high diversity in the of energy supply security between EU regions due to different contexts related to energy resource endowments, available energy infrastructure and market integration levels. The study shows that the Czech Republic (eastern Europe) was the best performing country, according to the level of energy security and diversification, followed by Belgium (western Europe). The worst performing region, based on the results for Greece, was southern Europe, followed by the northern Europe country of Sweden. The primary rationale for such ranking included Sweden's high energy import dependency on natural gas, oil and coal, extremely low score for the N-1 rule for gas infrastructure and high market concentration index in the gas sector, although the country has low total energy import dependency and quite high electricity interconnection capacity.

The rapid penetration of renewable energy sources has a positive impact on decreasing energy import dependency; however, due to the high volatility of renewable energy production, greater interconnectivity with neighbouring grids and increased energy storage capacities could improve energy system resilience and bolster energy supply security for all EU countries.

To determine the impact of the COVID-19 pandemic on the energy security in the countries under study, the correlation coefficients of the results between years were calculated, finding that despite the fact that the correlation coefficients are very high in all years, with extremely strong correlation, the largest deviations are observed in 2020. However, these deviations are primarily related to individual countries, and further studies analysing a longer pandemic period are needed to comprehensively evaluate the pandemic's impact on energy security. The proposed indicator framework and the EIDS index can be useful tools for identifying the impact of various economic instabilities on energy security levels in EU countries.

The research also has limitations. The study does not assess the country's energy policies developed to meet energy security and other energy goals. It is assumed that all EU countries have similar policies guided by common EU energy policy; however, further research, including more comprehensive assessments of countries' capacities to meet energy security goals based on in-depth policy analysis could expand this exploration. In addition, the proposed EIDS index does not consider the share of energy resources in the final energy mix; therefore, to properly compare countries with one another applying the EIDS index, it is essential to select countries with a similar energy composition mix. This condition is not required when evaluating data from one country to examine individual dynamics.

Author Contributions: The contribution of all authors is equal. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the grant S-REP-22-4 from the Research Council of Lithuania.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: The authors express gratitude to the reviewers, who contributed to the improvement of the paper.

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

Appendix A

Table A1. Energy security indicators for the assessment, 2015. Source: European Commission (2022b) and Eurostat (2022).

Country	I-1	I-2	I-3	I-4	I-5	I-6	M-1	M-2	M-3	M-4	M-5
Belgium	93.27	99.32	100.04	96.28	246.70	17.00 *	48.48	58.37	65.71	32.60	83.80 *
Czech Republic	32.09	95.09	98.45	−8.57	268.30	17.00 *	67.70	49.46	62.01	51.04	85.52 *
Greece	76.31	99.88	101.49	91.46	108.80	11.00 *	70.72	67.03	75.72	92.48	100.00 *
Sweden	31.23	100.00	103.64	99.57	14.00	26.00 *	40.60	80.40	73.40	100.00	100.00 *

* Because of data unavailability, data from the previous year are provided.

Table A2. Energy security indicators for the assessment, 2016. Source: European Commission (2022b) and Eurostat (2022).

Country	I-1	I-2	I-3	I-4	I-5	I-6	M-1	M-2	M-3	M-4	M-5
Belgium	84.84	100.56	99.69	93.89	279.00	13.00	62.55	50.48	71.09	30.30	81.60
Czech Republic	32.80	95.71	97.69	−3.78	373.50	19.00	68.40	49.57	59.77	22.75	65.49
Greece	78.21	99.22	100.57	93.69	108.80	10.00	72.00	73.23	86.61	95.00	95.00
Sweden	34.66	100.00	99.96	116.85	15.00	25.00	42.00	77.30	71.40	100.00	100.00

Table A3. Energy security indicators for the assessment, 2017. Source: European Commission (2022b) and Eurostat (2022).

Country	I-1	I-2	I-3	I-4	I-5	I-6	M-1	M-2	M-3	M-4	M-5
Belgium	85.25	98.45	100.09	94.25	279.00	18.95	60.66	50.50	70.03	26.20	66.40
Czech Republic	37.16	101.86	99.06	17.82	373.50	19.30	67.13	60.70	67.60	33.46	87.90
Greece	77.52	100.51	97.87	109.27	62.00	10.60	58.65	62.16	74.93	75.87	94.40
Sweden	27.92	102.07	98.03	105.27	15.00	25.61	42.40	60.00	71.80	100.00	100.00 *

* Because of data unavailability, data from the previous year are provided.

Table A4. Energy security indicators for the assessment, 2018. Source: European Commission (2022b) and Eurostat (2022).

Country	I-1	I-2	I-3	I-4	I-5	I-6	M-1	M-2	M-3	M-4	M-5
Belgium	97.05	100.61	99.98	105.67	273.00	18.95 *	51.51	51.00	63.97	31.80	59.50
Czech Republic	36.88	96.84	98.59	28.38	373.50	19.30 *	68.40	60.26	68.01	46.46	95.18
Greece	77.16	100.66	99.20	87.42	75.00	10.60 *	58.18	57.98	74.53	71.47	99.91
Sweden	30.09	102.14	99.30	97.09	2.50	25.61 *	43.60	58.70	72.90	100.00	100.00 *

* Because of data unavailability, data from the previous year are provided.

Table A5. Energy security indicators for the assessment, 2019. Source: European Commission (2022b) and Eurostat (2022).

Country	I-1	I-2	I-3	I-4	I-5	I-6	M-1	M-2	M-3	M-4	M-5
Belgium	88.93	101.86	99.99	102.71	273.00	18.27	55.20	48.00	62.00	31.40	68.00
Czech Republic	40.82	109.75	98.61	41.70	299.70	25.40	69.00	54.00	77.00	31.84	89.00
Greece	82.03	98.99	98.10	104.98	112.40	9.80	49.37	56.00	62.00	40.63	94.00
Sweden	31.29	101.83	99.97	98.08	2.50	25.15	41.37	52.00	67.00	100.00	100.00

Table A6. Energy security indicators for the assessment, 2020. Source: European Commission (2022b) and Eurostat (2022).

Country	I-1	I-2	I-3	I-4	I-5	I-6	M-1	M-2	M-3	M-4	M-5
Belgium	87.73	99.15	100.51	104.18	273.00 *	14.21	53.02	48.00	62.00	35.30	75.00
Czech Republic	38.90	86.04	101.75	52.00	372.60	27.45	71.10	54.00	77.00	26.41	56.00
Greece	87.89	100.69	101.96	114.59	101.40	9.91	40.83	56.00	62.00	35.85	93.87
Sweden	35.42	101.59	106.15	101.55	2.50 *	24.24	38.40	52.00	67.00	100.00	100.00

* Because of data unavailability, data from the previous year are provided.

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