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Energy Resilience: A Cross-Economy Comparison

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Abstract: The goal of this paper is to use the variable returns to scale (VRS)-slacks-based measure (SBM)-data envelopment analysis (DEA) method to compare the energy resilience of different economies and areas. This study looks at the energy resilience scores of 26 economies from Europe, the Americas, and the Asia-Pacific area. It does this by looking at twelve sub-indicators in three dimensions: society, the economy, and the environment. According to the computational results, seventeen of these economies' total energy resilience achieved top-tier performance. South Korea, ranked 18th, is only second to these seventeen economies and is followed by, among others, Turkey, Luxembourg, Poland, Italy, Belgium, the Slovak Republic, the Czech Republic, and Hungary. Twelve of the twenty European economies, all three American economies, and two Asia-Pacific economies are relatively energy-resilient. There are sixteen economies in society dimensions, seventeen economies in economy dimensions, and seventeen economies in environment dimensions that are relatively energy-resilient. Sub-dimensional improvement suggestions for relatively less energy-resilient economies are provided according to empirical results. The outcome of the research provides policymakers with a benchmark for future policy planning. Due to data limitations, this study cannot benchmark all OECD economies and does not account for sub-dimensional resource inputs.

Keywords: VRS-SBM-DEA; energy resilience; IEA; disaggregate output efficiency; area analysis

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1. Introduction

Rising economies have greater energy demands and poorer rates of need satisfaction. No country, however, can satisfy human requirements while ensuring sustainable energy consumption [1]. "Resilience thinking" is a technique for managing socio-ecological systems [2] that attempts to unite (often independent and diverse) studies on the issue of catastrophic risk management. The 2030 Agenda acknowledged the significance of resilience and accorded it a significant position [3,4]. Resilience is fundamental to the international development agenda and sustainable development goals (SDGs) as a whole. Today, resilience is recognized as a key approach for addressing the many facets and dynamics of vulnerability, and, importantly, it improves the lives of vulnerable individuals [4].

Controlling energy consumption is one of the EU's most important initiatives, and it requires resilience and adaptability amid adversity [5]. It helps to generate employment, improve the economy, and safeguard the environment in a dynamic global market. In addition, energy resilience is the capacity to enhance performance via learning and adjusting to continuous change. It conforms to the present energy policy framework and the premise of this paper [6].

Energy resilience policies may achieve international development objectives known as SDGs [3,7,8], as well as long-term sustainability and health objectives. Energy resilience is anticipated to limit and contribute to adaptations that reduce energy vulnerability [9]. With the aid of energy resilience policies [4,9,10], sustainability objectives, such as increased energy availability, sustainable economic growth, and low-carbon energy consumption and production, may be accomplished.

These nations are participants in the Organization for Economic Cooperation and Development (OECD) and are distributed around the globe in Europe, the Americas, and Asia-Pacific, and their most important trading partners account for about 80% of all international trade and investment. Through its member countries and a variety of national, regional, and local partners, it facilitates change in over one hundred nations globally by leveraging their combined expertise and common ideals [11]. Twenty-five of the OECD's thirty-eight members and one key partner participated in the research.

Globally consistent, reliable, and timely data and statistics are fundamental to the establishment of successful and efficient national energy policies and are a crucial element of long-term planning for energy sector investment. The International Energy Agency (IEA) is the most reputable and complete source for these statistics and data [12]. Based on a review of the relevant literature, we combine the recently updated key IEA data with an open dataset from the International Institute for Management Development (IMD) and Reporters Without Borders (Reporters Sans Frontières, RSF) for analysis and estimation in this article.

The conventional Banker, Charnes, and Cooper (BCC)-VRS-DEA model [13] uses radial changes to treat bad outputs as inputs and favorable outputs as outputs. By requiring all inputs (outputs) to drop (rise) at the same rate, the BCC-DEA model has lower discriminative power and, hence, increases the number of fully efficient economies. VRS-SBM-DEA improves discrimination and allows energy resilience ratings to be separated.

The research question of this study is to use the VRS-SBM-DEA method to compare the energy resilience of different economies and areas along several dimensions as a valuable result and thus provide a decision-making reference for policymakers and related practitioners, which is the goal of this study.

This research evaluated the energy efficiency of the resilient system using a VRS-SBM-DEA approach. The connected decision-making units (DMUs) score provides energy efficiency programs with important information that can be used to make smart decisions.

This is the first study we know of that uses twelve sub-dimension indicators in three dimensions (including society, economics, and environment) to compare the energy resilience of 26 economies in three areas using the VRS-SBM-DEA method.

According to the report, 17 economies have attained the optimal level of energy resilience. South Korea's energy resilience performance ranks eighteenth when compared to Japan, the United States, the United Kingdom, Ireland, Switzerland, Germany, France, Greece, Spain, Portugal, Sweden, Norway, Finland, Mexico, Brazil, Australia, and New Zealand.

The structure of this article is as follows: the second section reviews the theoretical framework and related literature on energy resilience, concentrating on the literature's important concepts and studies. Section 3 discusses the research methods, data, and dimensions for energy resilience indicators. Section 4 defines the data sources and presents the research results and empirical assessment of the building indicators. The fifth section ends with conclusions, research limitations, and future study suggestions.

2. Theoretical Framework and Literature Review

This paper starts with the three dimensions of sustainable development to construct an evaluation framework of energy resilience: society, economy, and environment [3,4,7,8,14]. For the social dimension, an economy is more energy-resilient if its social development is better by using the same energy inputs. For the economic dimension, an economy is more energy-resilient if it uses less energy to generate one unit of economic value. For the environmental dimension, an economy is more energy-resilient if it emits less into the environment by using energy.

A system's "resilience" is assessed by how fast it can recover to its starting state after a disruption and the time until a system variable's value is changed [15]. The scientific community is beginning to pay greater attention to resilience, although its definition remains flexible and unclear in disciplines such as energy. Resilience in the face of energy stress is interwoven with other significant policy challenges, including energy insecurity, poverty, and fairness. Energy resilience solutions consider potential sources of danger and emphasize safety [16].

Challenges to energy security, affordability, and fairness relate to energy resilience, making them crucial energy policy concerns. Multiple fields, including the social sciences and sustainability studies, are integrating resilience into their sustainable development strategies. Thus, Gatto et al. [17] define resilience as the capacity to enhance performance via learning and adjusting in the face of resolute change.

According to Gatto et al. [4], energy is one of the most important dimensions where resilience strategies can be used, especially in terms of utility. This is because energy is important for maintaining "the capacity to absorb, react to, and overcome economic, social, environmental, and in-institutional shocks as a result of adaptation to changing conditions." To last over time, the idea of energy resilience needs policies that consider how social, economic, and environmental problems affect each other.

Sharifi and Yamagata [2] address a variety of subjects, including how infrastructure, resources, land-use regulations, city planning, political institutions, demography, and human behaviors all contribute to the character of an area. To determine how energy-resilient metropolitan areas are, they look at the literature on the subject, come up with planning and design criteria that can be used to make these kinds of decisions, and then make guesses about how these criteria are related to likely future problems.

Tettey et al. [18] investigated the impact of various design strategies and measures on multi-story residential buildings subject to the condition of minimizing heating and cooling demand to mitigate the risk of operating energy consumption and overheating of low-energy residential buildings in future climate conditions. Droutsa et al. [19] developed empirical adjustment factors between energy consumption and actual use by assessing available data on actual building energy consumption. Vogel et al. [1] say that countries with good economic and social conditions are more likely to be able to meet demand with the least amount of energy.

The paper by Oprea et al. [20] investigates variables that contribute to the development of seven Eastern European nations (Bulgaria, Croatia, the Czech Republic, Romania, Hungary, Slovakia, and Slovenia), such as how well a region's economy holds up in hard times depends on how strong it's manufacturing, services, public administration, entrepreneurial spirit, and human capital are, as shown by its level of postsecondary education.

The rise of the green energy economy is correlated with energy efficiency, renewable energy, and ICT (information and communications technology) according to a literature assessment completed by Hu et al. [21]. Current research focuses on four primary pillars: cost-benefit evaluations, concerns about unfair competition, cybersecurity issues, and how to effectively promote energy-ICT. Although ICT requires energy, the existing empirical research demonstrates that it has overall positive benefits on issues such as energy conservation, energy efficiency improvement, pollution reduction, and economic growth. A governance framework is essential since energy-ICT improves the position of the platform operator. The global energy resilience index (GERI) is a composite indicator that consists of both main and secondary components, as established by Gatto et al. [4].

According to Giddings et al. [22], separating sustainable development into environmental problems, social concerns, and economic concerns that are only indirectly related to one another does not result in a holistic or principle-based perspective. This categorization reflects the fact that many viewpoints are used to examine and explain our lives and the environment in which we live.

Aldieri et al. [23] discovered, through the application of DEA to energy policy and sustainable development factors for OECD and non-OECD nations, that knowledge spillovers from environmental advancements decrease inefficiency and enhance economic resilience [9]. Guan et al. [4] estimated carbon emission efficiency and pollution control using the constant-returns-to-scale (CRS)-SBM-DEA model.

According to the most recent review of the literature, we find a research gap in which there is still a need for studies that look at the energy resilience of 26 economies in different areas, estimate their energy resilience indicators, which we defined across multiple dimensions, and then use these estimates to calculate their disaggregate output scores by way of the VRS-SBM-DEA [23–25].

3. Research Methods, Data Sources, and Dimensions

3.1. Research Methods

This study's research topic aims to apply the VRS-SBM-DEA approach to assess the energy resilience of various economies and areas along several dimensions as a beneficial outcome and, therefore, provide a decision-making reference for policymakers and practitioners. This study assesses the literature on the topic, details the sub-dimensions (indicators) of data used by key evaluative agencies, and then organizes the whole thing into the three categories of society, economy, and environment in terms of specific connected indicators. Quantitative information is measured and computed, and worldwide economic comparisons are made.

This research aims to build and quantify the twelve primary quantitative indicators of energy resilience, establish an indicator system in which these indicators can be combined as an indicator with energy economic ramifications, and establish an indicator system in which these indicators can be combined into one indicator.

Using these metrics, it is possible to have a better understanding of the energy resilience of diverse locations. Since each condition indicator in the measurement process may have a unique purpose and diverse significance, mistakes are unavoidable if the indications are directly averaged and summed. Moreover, the situation in various economies and reports from the International Energy Agency (IEA), the World Economic Forum (WEF), the World Bank (WB), and Reporters Without Borders (Reporters Sans Frontières, RSF) indicate that a country must address social, economic, and environmental issues if it wishes to demonstrate energy resilience.

This study uses DEA to develop observational indicators to estimate the energy resilience efficiency of each economy. DEA has expanded rapidly over the last three decades, finding applications in sectors as varied as finance and economics [25]. Zhou et al. [26] gathered and analyzed over a hundred such examples as part of the DEA's efficiency study, demonstrating that the DEA technique is an effective tool for dissecting efficiency concerns [27].

To create DMUs, DEA does not presume a certain functional form, unlike parametric approaches [9,28]. Efficiency ratings are obtained using this method [29]. The efficiency resilience score can be found by comparing the energy resilience output to the DEA-determined ideal output level [6,24].

This study's basic premise is that DEA may be used to find viable energy sources, which can then be compared to the real-focus energy resilience sub-dimensions to yield the efficiency score and serve as a gauge of energy resilience performance. The DMUs score may also be used to evaluate the effectiveness of policies [9,30].

The traditional BCC (VRS) DEA model includes radial adjustments that undesirable outputs be regarded as inputs and desirable outputs be viewed as outputs. The BCC-DEA model decreases discriminatory power and increases the number of fully efficient economies by restricting that all inputs (outputs) should decrease (increase) by the same ratio [13]. However, the SBM-DEA model allows the outputs (inputs) to expand (contract) at different ratios [23], hence increasing the discriminative power and generating different disaggregate output (input) efficiency scores. To increase the discriminative power and facilitate the computation of disaggregate resilience efficiency scores, the BCC (VRS) DEA model is replaced by the VRS-SBM-DEA model in this research.

VRS-SBM-DEA was first developed as a tool for studying and evaluating energy resilience. Consequently, there is a considerable body of work using DEA to generate an energy efficiency index [31]. To use these three fundamental data components of energy resilience—social, economic, and environmental—we employ the DEA method with disaggregated output efficiency scores to examine the energy resilience score across multiple domains [24].

Assume that, in every economy o, as shown by notations y^d and y^u, respectively, both desirable and undesirable outcomes are possible. The VRS-SBM-DEA model is used to process the fractional programming problem with no inputs and both desired and undesirable outputs for an economy (Tone [32]):

$$\begin{gathered}\min \rho = \frac{1}{1+\frac{1}{n_1+n_2}\left(\sum_{r=1}^{n_1}\frac{s_r^d}{y_{ro}^d}+\sum_{r=1}^{n_2}\frac{s_r^u}{y_{ro}^u}\right)}, \\ \text{Subject to } y_o^d = Y^d\lambda - S^d, \\ y_o^b = Y^u\lambda + S^u, \\ \sum\lambda = 1 \\ \lambda \geq 0, s^d \geq 0, s^b \geq 0,\end{gathered} \tag{1}$$

where n_1 is the quantity of desirable outputs and n_2 is the quantity of undesirable outputs; Y^d and Y^u are matrices representing the desirable and undesirable outputs, with both matrices being greater than zero; S^d and S^u are matrices representing the desirable and undesirable output slacks, respectively; vector λ contains the peer weights on different weights economies with a sum of one as the convexity constraint, which makes the model to be of VRS; and ρ is the value of objective function that is between zero and one. If we solve for the above linear programming problem, we obtain a measure of an economy's technical efficiency (ρ) that accounts for both desirable and undesirable sub-dimensions. The first constraint implies that the actual desirable output is never higher than its target ($Y^d\lambda$). The second constraint says that the actual undesirable output is never lower than its target ($Y^u\lambda$). In the objective function in Equation (1), more slacks in the desirable and undesirable outputs make the efficiency score lower. Note that the DEA approach generates the weights by objective linear programming in which no subjective opinion from experts is needed.

The following is how Hu and Chang [33] compute a country's disaggregated energy resilience efficiency score:

$$\text{Actual } y^d/\text{Target } y^d \tag{2}$$

Since the actual y^d never exceeds its goal value, the disaggregated desired output efficiency score falls inside the range [0, 1]. For this metric, an efficiency value of zero suggests that the economy is extremely fragile concerning this sub-dimension, whereas an efficiency value of one means that it is a benchmark. A similar formula may be used to calculate the efficiency of an undesirable sub-dimension:

$$\text{Target } y^u/\text{Actual } y^u \tag{3}$$

The disaggregate y^u efficiency score also falls within the range [0, 1] because the actual y^u is never smaller than the target value y^u.

To assess the energy resilience of economies in different areas, Equations (2) and (3) may be used to determine the resilience scores of particular countries. This strategy has many distinct characteristics. It removes the need for a translation step between energy resilience and the numerous indicators for starters.

Second, including all indicators in the linear programming problem to establish the best production boundary might have unforeseen results, such as moving the optimal production boundary and necessitating change in additional indicators. The DEA framework represents economies with DMUs. The efficiency frontier is the set of all feasible economies that produce all important items efficiently. In addition to the overall resilience efficiency score, each economy obtains disaggregated energy resilience efficiency scores of all sub-dimensions.

3.2. Data Sources

To assess the energy resilience of the economies of interest, it may be required to consider a variety of aspects. According to our literature review above, it may be necessary to include social, economic, and environmental aspects to evaluate the government's fiscal leeway, policy tools, planning, and practical abilities. This research intends to develop these measures to compare the economic conditions of other nations. The majority of the data used in this article came from national scores in the IEA, IMD, RSF, and World Bank, which offer information about the government and organizations creating the indicators. The International Energy Agency (IEA) collects and disseminates information on public R&D, energy efficiency measures, and the Energy Efficiency Metrics database, among other critical energy-related statistics. Planning for long-term energy investments and the creation of successful and efficient national energy policies rely heavily on them [12]. Every year between May and June, the IMD publishes its "World Competitiveness Yearbook," a ranking of the world's 63 most economically powerful nations using information from more than 200 indicators and statistical analysis including coverage of economic performance, government efficiency, corporate efficiency, and infrastructure. These are generally acknowledged as vital decision-making tools in the public and commercial sectors [34].

Since 2002, Reporters Without Borders has collected data on media freedom in 180 nations and territories and published the findings annually in its world press freedom index. The reported scores for each country are used to estimate each country's and area's relative standing on global and regional indices. These country rankings were derived from a mix of qualitative analysis and responses to a questionnaire in 20 different languages submitted by experts from across the world. The rating increases as the severity of the restriction or transgression increases. Because more and more individuals are using this index, it might likely be used as an effective lobbying tool [35].

There is a requirement for survey data and uniform data quality when evaluating the energy resilience of many economies across different areas. The IEA Energy Efficiency Indicators database, the IMD World Competitiveness Yearbook, and the RFI world press freedom index were selected as the primary sources for this investigation owing to their applicability and dependability in answering the research objectives. We will incorporate information from the IEA, IMD, RSF, and World Bank in their 2020 reports.

3.3. Dimensions

Diverse perspectives of individuals and organizations generate theories of sustainable development, which in turn influence how challenges are identified, and possible solutions are suggested. There, environmental, social, and economic variables, which are often shown independently yet are interrelated, merge. They are complicated phenomena that may be investigated at many spatial scales and are not uniform entities. If we only concentrate on one of these three areas at a time, we run the danger of adopting a reductionist, technocratic viewpoint that fails to address the underlying social and economic issues that constitute the largest challenge to the status quo [22].

The application of composite indicator tools can effectively describe energy resilience. The idea of energy resilience is multifaceted and interwoven into the three dimensions of sustainability (society, economy, and environment) [4,22]. Therefore, this research further categorizes twelve sub-dimensions of energy resilience into three distinct dimensions: society (four sub-dimensions), economy (five sub-dimensions), and environment (three sub-dimensions) and then provides distinct reports for the analysis results for each dimension.

The GERI covered the sub-pillars of utility transparency and monitoring, carbon tracking, counterparty risk, and building energy codes [4], which were related to the dimensions of economic infrastructure and the energy security environment. Sharifi et al. [2] say that infrastructure and governance related to energy resilience can be used to measure energy resilience. They also look at how these criteria relate to any bad things that might happen.

This study chooses indicators from the three dimensions. The social indicators are collected from IMD and Reporters Sans Frontières open data, whereas the economic and environmental indicators are collected from IEA open data [36], as mentioned in detail below.

3.3.1. Society

Previous research has shown that, when analyzing the elements that contribute to the resilience of an area or economy, sociocultural issues often play a crucial role. That is, a higher degree of inclusive social participation can help enhance the energy resilience of an economy. Cooke [37] contends that regional resilience needs a set of policy tools and metrics. Schwab [38] says that national planning and crisis response capacities should include techniques for balancing public health and economic policies. Fritzsch [39] contends that post-crisis economies will recover more rapidly in the presence of robust rule of law and extensive rules and regulations; Oprea et al. [20] remark that public administration will be an important component in deciding resilience. There is a correlation between the openness of government policy, efficiency of policy implementation, and credibility of the news media. The majority of governments are devoted to developing pro-people and pro-business economic policies and initiatives. The Swiss Re Institute accounted for fiscal easing while compiling its economic resilience index (E-RI). In conclusion, concerning the sub-quotient of economic resilience at the societal level, this research will focus on the four elements listed below:

- Transparency
- Control of bribery and corruption
- Democracy index
- Lack of press freedom: the higher the score, the more serious the problem

3.3.2. Economy

The majority of efforts are devoted to supporting economic activities and development. Therefore, an economy has a higher degree of energy resilience if it can have a lower energy input for the same economic output. Human life, social institutions, and the economy are all rooted in and reliant on the natural world, including energy inputs [22]. Efficient energy utilization is a key dimension to sustaining economic operations [40]. For instance, due to its complexity, the resilience of Europe's energy system is threatened by several aspects. It was developed through the combination of national markets and infrastructures that already existed [5].

Demand fulfillment and energy demands are both driven by economic considerations; nations with more favorable economic conditions are more likely to be able to meet requests while using less energy [1]. Energy-ICT has a positive impact on energy conservation, energy efficiency, emissions reduction, and economic growth according to Hu et al. [21]. This article will use an energy consumption or carbon emissions indicator from IEA-accessible data as the inverse sub-energy resilience dimension. According to the documentation for the Energy Efficiency Indicators Database, the important index should be defined item by item before the associated important index is defined.

The total final energy use (PJ) represents overall energy use, including all the related energy goods [41].

Per capita energy intensity (GJ/cap) is derived by dividing the total population by total energy use [41].

Total final emissions ($MtCO_2$) represent total CO_2 emissions from all reported energy fuel uses, excluding emissions from non-energy fuel uses, biofuels, and waste, and include emissions redistributed from power and heat generation [41].

Per capita carbon intensity (tCO_2/cap) is derived by dividing the total population by tons of CO_2.

DMU population: the total population is calculated based on the de facto population definition, which includes all inhabitants regardless of immigration status or citizenship. Estimates as of the year's midpoint are shown [42].

For fair comparing consideration, we use total final energy using number divided by DMU population to obtain the average total number as follows:

per capita residential final energy use (PJ) = total residential final energy use (PJ)/population

per capita services final energy use (PJ) = total services final energy use (PJ)/population

per capita manufacturing final energy use (PJ) = total manufacturing final energy use (PJ)/population

This paper will focus on five sub-dimensions as follows:

- Per capita residential final energy use (PJ)
- Average total services/total final energy use
- Average manufacturing [ISIC 10–18; 20–32]/total final energy use (PJ)
- Per capita residential energy intensity (index 2000)
- Per capita services energy intensity (index 2000)

3.3.3. Environment

Sustainable development involves recognizing and adhering to global environmental responsibilities, not just those belonging to our local surroundings [22,43]. On a local, regional, or global scale, operating methods must not damage environmental quality in any manner. The emission rate from facility design, building, operation, and decommissioning, as well as procurement and material management, must be monitored and reduced. Environmental quality is enhanced by reducing waste, effluents, and emissions [44].

Energy use inevitably generates emissions into the environment. However, an economy should minimize the emissions into the environment per unit of energy use. An economy is more energy-resilient if it generates fewer emissions per unit of energy use.

With the same logic as above, for fair comparing consideration, we use total final energy using number divided by DMU population to obtain the average total number as follows:

per capita residential final emissions ($MtCO_2$) = total residential final emissions ($MtCO_2$)/population

per capita services final emissions ($MtCO_2$) = total Services final emissions/population

From above, this paper will focus on three sub-dimensions:

- Per capita residential final emissions ($MtCO_2$)
- Per capita services final emissions ($MtCO_2$)
- Per capita residential carbon intensity (index 2000)

4. Data Sources and Empirical Findings

4.1. Data Sources

There are 26 economies in this article, including 25 OECD members nations, such as Japan, South Korea, New Zealand, Australia, Belgium, the Czech Republic, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Luxembourg, Norway, Poland, Portugal, the Slovak Republic, Spain, Sweden, Switzerland, Turkey, the United Kingdom, Mexico, the United States, and Brazil, which is the OECD's most important partner.

After reviewing the selection of specific indicators within the aforementioned broad indicators of the government, businesses, and the general public, this study employs twelve specific indicators to determine the energy resilience indicators of the subject economies. The data sources included in Table 1 for compiling the data and eliminating any missing information are the IEA's database of energy efficiency indicators, the IMD's 2020 World Competitiveness Report, the RSF's 2020 press freedom index, and the World Bank's 2020 world development indicators.

Table 1. Definition and data sources of dimension and sub-dimension.

Dimension	Sub-Dimension	Sub-Dimension Definition	Data Source
Society	Transparency	Transparency	IMD
	Control of bribery and corruption	Bribery and corruption	IMD
	Democracy	Democracy index	IMD
	Lack of press Freedom	Press freedom index	RSF
Economy	Residential energy use	Total residential final energy use (PJ)	IEA
	Per capita residential consumption	Total residential final energy use/Population	IEA/World Bank
	Service energy use	Total services final energy use (PJ)	IEA
	Per capita service energy use	Total service final energy us/DMU Population	IEA/World Bank
	Manufacturing energy use	Total manufacturing (ISIC 10–18; 20–32) final energy use (PJ)	IEA
	Per capita manufacturing energy use	Total manufacturing energy use/Population	IEA/World Bank
	Residential energy intensity	Per capita residential intensity (index 2000)	IEA
	Service energy intensity	Per capita services energy intensity (index 2000)	IEA
Environment	Total residential CO_2 emissions	Total residential final CO_2 emissions ($MtCO_2$)	IEA
	Per capita residential CO_2 emissions	Total residential final CO_2 emissions/Population	IEA/World Bank
	Total service energy use	Total services final emissions ($MtCO_2$)	IEA
	Per capita service energy use	Total services final emissions/Population	IEA/World Bank
	Residential carbon intensity	Per capita residential carbon intensity (index 2000)	IEA

Table 2 contains descriptive data for the filtered twenty-six economies' sub-dimensions.

Table 2. Descriptive statistics of sub-dimension indicators.

Dimension/Indicator	Type of Index	Mean	Median	Maximum	Minimum	Std. Dev.
Society						
Transparency	Desirable	4.944	4.919	7.898	1.522	1.841
Control of bribery and corruption	Desirable	5.460	6.153	8.576	0.836	2.369
Democracy	Desirable	7.972	8.015	9.870	4.090	1.254
Lack of press freedom	Undesirable	21.666	22.795	50.020	7.840	10.861
Economy						
Residential energy use	Undesirable	21.512	22.774	34.688	5.420	8.224
Service energy use	Undesirable	12.688	11.986	32.819	1.259	6.985
Manufacturing energy use	Undesirable	27.750	24.323	77.920	9.153	15.399
Residential energy intensity	Undesirable	21.505	22.640	34.830	5.440	8.219
Service energy intensity	Undesirable	12.689	11.990	32.790	1.260	6.992
Environment						
Per capita residential CO_2 emissions	Undesirable	27.750	24.323	77.920	9.153	15.399
Per capita service energy use	Undesirable	3.662	0.940	52.330	0.026	10.093
Per capita residential carbon intensity	Undesirable	1.157	1.060	2.730	0.090	0.672

In Table 2, quantitative metrics of energy resilience are offered. Therefore, the DEA approach must be utilized to further show the contrasts between the facts about each economy in the complete indicator data while simultaneously constructing the fundamental indicator framework for evaluating a country's energy resilience. Additionally, Equation (2) is used to generate the indicators used in this article to evaluate energy resilience. Even if the units of measurement are altered, it is not a problem to employ the original data in their entirety. In this instance, we shall use the main data source directly. This is the only method to explain the information more thoroughly and transparently.

Note that lack of press freedom, residential energy use, service energy use, manufacturing energy use, residential energy intensity, service energy intensity, per capita residential CO_2 emissions, per capita residential energy use, and per capita residential carbon intensity are inverse indices, which means that their scores improve as they decrease. Consequently, these indicators may be configured to signify negative consequences within the DEA analytical paradigm. All other measures of energy resilience fall under the category of indicators, for which higher values are sought since they indicate more desirable outcomes.

Table 3 depicts the correlation of output item indicator variables. Generally, there is no significant linear interdependence with a correlation coefficient higher than 0.9 between any two desirable or undesirable output variables, and, hence, these sub-dimensions are distinctive from each other.

Table 3. Sub-dimensional correlation coefficients.

Sub-Dimension	1	2	3	4	5	6	7	8	9	10	11	12
1. Transparency	1.000											
2. Control of bribery and corruption	0.851	1.000										
3. Democracy	0.772	0.699	1.000									
4. Lack of press freedom	−0.701	−0.669	−0.896	1.000								
5. Residential energy use	0.498	0.501	0.479	−0.577	1.000							
6. Service energy use	0.601	0.622	0.559	−0.561	0.797	1.000						
7. Manufacturing energy use	0.458	0.460	0.462	−0.526	0.515	0.620	1.000					
8. Residential energy intensity	0.500	0.503	0.479	−0.577	1.000	0.799	0.517	1.000				
9. Service energy intensity	0.601	0.623	0.559	−0.560	0.796	1.000	0.620	0.798	1.000			
10. Per capita residential CO_2 emissions	0.458	0.460	0.462	−0.526	0.515	0.620	1.000	0.517	0.620	1.000		
11. Per capita service energy use	0.253	0.231	0.221	−0.221	0.372	0.643	0.216	0.371	0.642	0.216	1.000	
12. Per capita residential carbon intensity	0.024	0.210	0.051	−0.025	0.470	0.418	0.060	0.470	0.418	0.060	0.121	1.000

4.2. Empirical Findings

The twelve sub-dimension indicators are organized into three main dimensions: society, economy, and environment. That is, each category is further subdivided into specific sub-dimensions as indicators. The broad index for energy resilience is then calculated by using Equations (1)–(3).

We use Equation (1) to predict the ideal efficiency point for the aforementioned society, economy, and environment, and Equation (2) to determine the indicator for comparing the energy resilience of the economies of various areas. Table 4 and Figure 1 show the rating of energy resilience and related scores.

Table 4. Rankings in energy resiliency scores.

Rank	Economy	Rank	Economy	Rank	Economy
1	USA	1	Sweden	19	South Korea
1	Australia	1	Ireland	20	Turkey
1	United Kingdom	1	Spain	21	Luxembourg
1	Brazil	1	Japan	22	Poland
1	Switzerland	1	Portugal	23	Italy
1	Finland	1	Norway	24	Belgium
1	France	1	Mexico	25	Hungary
1	Germany	1	New Zealand	26	Czech Republic
1	Greece	18	South Korea		

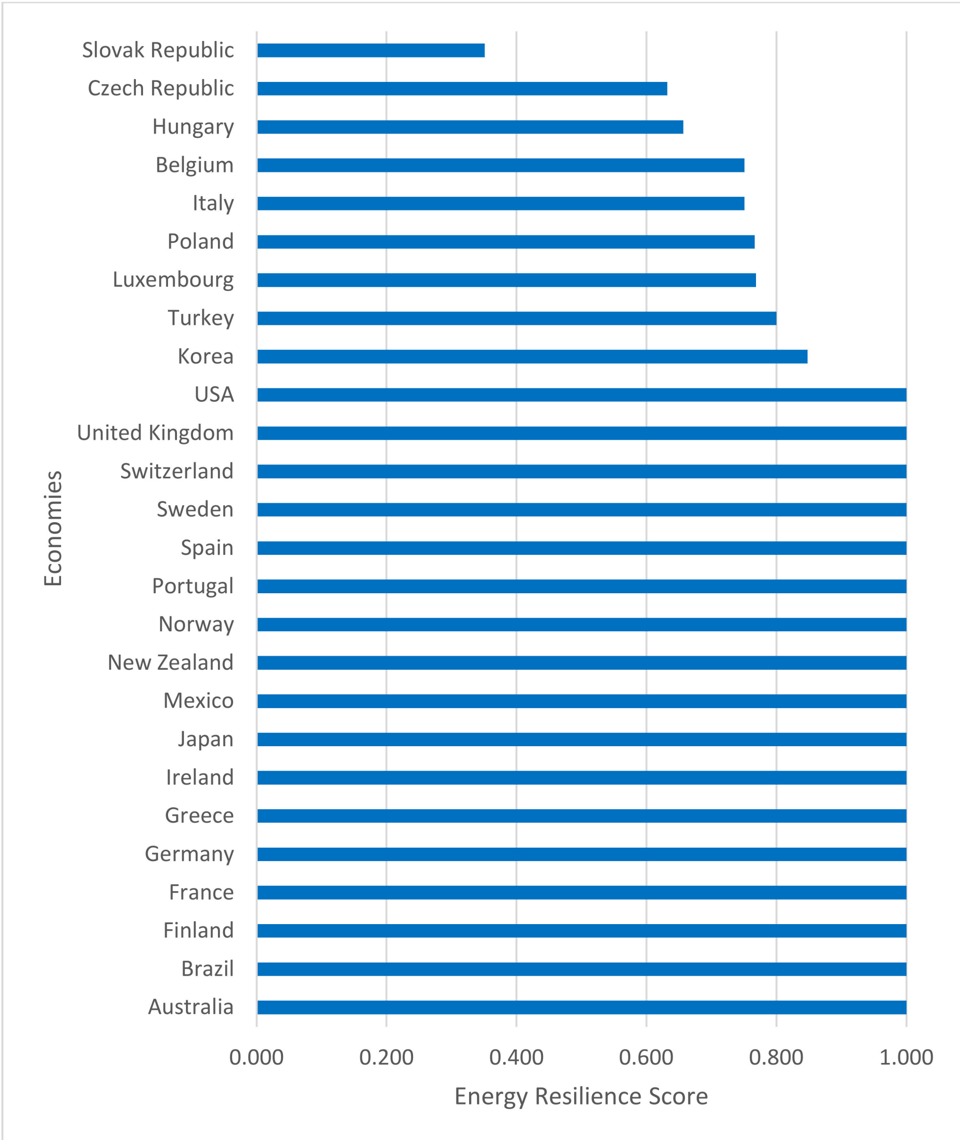

Figure 1. Economies' energy resiliency scores.

Applying Equation (1) to the society, economy, and environment described in the introduction produces the optimal efficiency point, while Equation (2) offers the metric for gauging energy resilience. When negative energy problems show up, as shown by the sub-dimension indicators, Equation (2) is used to determine the energy resilience indicator. Table 4 shows the rankings of energy resilience. There are seventeen subject economies at the efficiency point. Under the peer comparison condition, it indicates that they have no room for enhancement in energy resilience when compared to other economies. The USA, Japan, New Zealand, Australia, the United Kingdom, Brazil, Switzerland, Finland, Germany, France, Greece, Sweden, Ireland, Spain, Portugal, Norway, and Mexico are among the countries involved.

This study further separates twenty-six economies into three different areas—Europe (twenty economies), America (three economies), and Asia-Pacific (three economies)—and reports the analyzed results separately as follows.

European economies have the most economies in this research, with twenty economies in our research subjects. According to the sub-dimension energy resilience value of European economies, as shown in Table 5 and Figure 2, there are twelve of the subject economies on the efficiency frontier. Under the peer comparison condition, it indicates that they have relatively full energy resilience when compared to other economies. Greece, Sweden, Finland, Germany, France, Ireland, Norway, Spain, the United Kingdom, Australia, Portugal, and Switzerland are among the countries involved. Turkey, Poland, Hungary, the Czech Republic, Belgium, the Slovak Republic, and Luxembourg can enhance their related sub-dimension energy resilience value. For example, Italy should reduce its per capita manufacturing energy consumption. Poland should reduce its per capita service energy consumption amount. The Czech Republic should decrease its per capita residential carbon intensity.

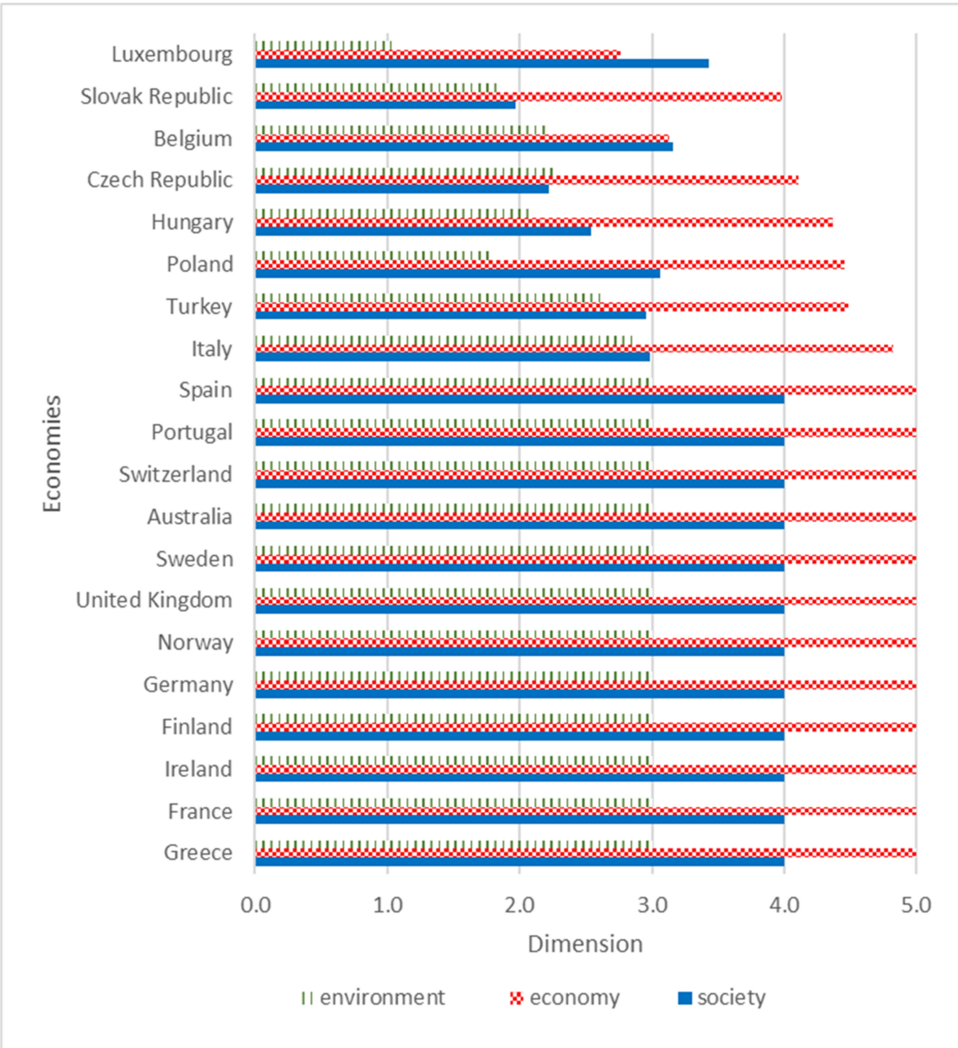

Figure 2. Sub-dimensional energy resilience of European economies.

Table 5. Sub-dimensional energy resilience scores of European economies.

Country\Sub-Dimension	Transparency	Control of Bribery and Corruption	Democracy	Lack of Press Freedom	Residential Energy Use	Service Energy Use	Manufacturing Energy Use	Residential Energy Intensity	Service Energy Intensity	Per Capita Residential CO_2 Emissions	Per Capita Service Energy Use	Per Capita Residential Carbon Intensity
Greece	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Finland	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
France	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Germany	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Ireland	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Sweden	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Norway	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Spain	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
United Kingdom	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Australia	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Portugal	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Switzerland	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Italy	0.618	0.461	0.909	1.000	0.991	0.971	0.880	1.000	0.980	0.880	1.000	1.000
Turkey	0.799	1.000	0.549	0.606	1.000	0.795	0.912	0.992	0.789	0.912	0.920	0.809
Poland	0.594	0.778	0.808	0.877	0.863	0.990	0.729	0.872	1.000	0.729	0.474	0.602
Hungary	0.676	0.360	0.791	0.716	0.682	1.000	1.000	0.682	1.000	1.000	0.309	0.762
Czech Republic	0.537	0.368	0.838	0.476	0.554	0.996	1.000	0.556	1.000	1.000	0.939	0.315
Belgium	0.584	0.878	0.827	0.875	0.458	0.662	0.883	0.460	0.665	0.883	1.000	0.317
Slovak Republic	0.248	0.124	0.835	0.759	0.515	0.995	0.957	0.518	1.000	0.957	0.479	0.433
Luxembourg	0.821	0.946	0.976	0.687	0.715	0.456	0.416	0.716	0.456	0.416	0.052	0.560

Table 6. Sub-dimensional energy resilience scores of economies in the Americas.

Country\Sub-Dimension	Transparency	Control of Bribery and Corruption	Democracy	Lack of Press Freedom	Residential Energy Use	Service Energy Use	Manufacturing Energy Use	Residential Energy Intensity	Service Energy Intensity	Per Capita Residential CO_2 Emissions	Per Capita Service Energy Use	Per Capita Residential Carbon Intensity
Brazil	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Mexico	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
USA	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000

Table 7. Sub-dimensional energy resilience scores of economies in the Asia-Pacific.

Country\Sub-Dimension	Transparency	Control of Bribery and Corruption	Democracy	Lack of Press Freedom	Residential Energy Use	Service Energy Use	Manufacturing Energy Use	Residential Energy Intensity	Service Energy Intensity	Per Capita Residential CO_2 Emissions	Per Capita Service Energy Use	Per Capita Residential Carbon Intensity
Japan	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
New Zealand	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
South Korea	0.946	0.824	1.000	1.000	1.000	0.503	0.439	0.998	0.502	0.439	1.000	0.705

Only three countries in the Americas—Brazil, Mexico, and the United States—serve as case studies for our research; all three have attained maximum energy resilience efficiency. Even though it is not a member of the OECD, Brazil is a significant ally. Despite not being a member, Brazil actively participates in OECD operations, offering crucial insights and raising the importance of policy discussions by taking part in OECD political dialogues, polls, and databases [11]. The sub-dimensional scores of economies in America are shown in Table 6 and Figure 3.

Moreover, there are only three countries as our research subjects in Asia-Pacific. Both Japan and New Zealand meet full energy resilience efficiency, followed by South Korea. South Korea needs to improve its transparency, control of bribery and corruption, service energy use, manufacturing energy use, residential energy intensity, service energy intensity, per capita residential CO_2 emissions, and per capita residential carbon intensity. These Asia-Pacific economies' sub-dimensional scores are shown in Table 7 and Figure 4.

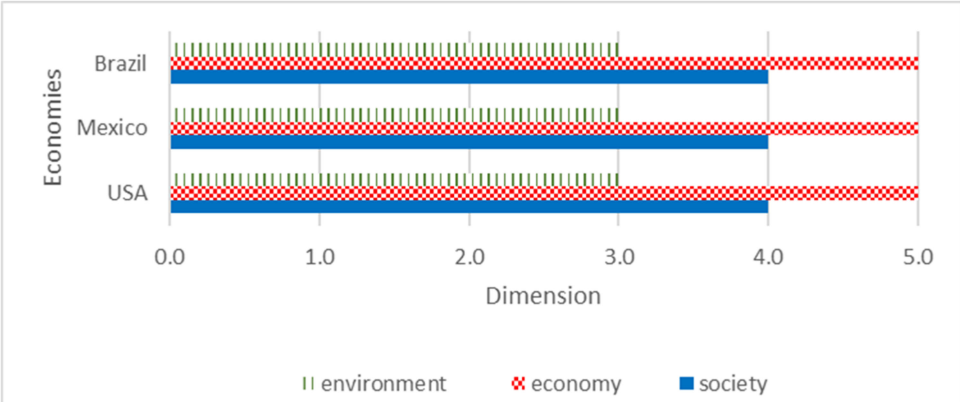

Figure 3. Sub-dimensional energy resilience of American economies.

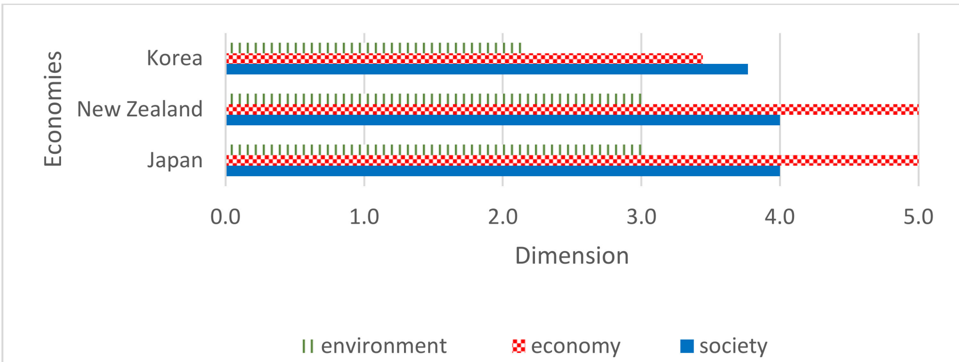

Figure 4. Sub-dimensional energy resilience of the Asia-Pacific economies.

To sum up, twelve of twenty European economies, all three American economies, and two of the three Asia-Pacific economies achieved a fully efficient situation.

According to the energy resilience value of the society component indicated in Appendix A Table A2, sixteen of the analyzed economies are located on the efficiency frontier (Mexico, USA, France, Greece, Japan, Ireland, Brazil, Sweden, Finland, Germany, Norway, United Kingdom, Australia, Switzerland, New Zealand, Spain, and Portugal). The peer comparison criterion shows that their energy resilience is reasonably complete in contrast to other economies. South Korea, Luxembourg, Belgium, Poland, Italy, Turkey, Hungary, the Czech Republic, and the Slovak Republic may increase the energy resilience rating associated with their respective social dimensions. For instance, the Slovak Republic should increase its degree of openness, bribery, and corruption. The Czech Republic should increase press freedom. Turkey should increase its degree of democracy.

According to the economic energy resilience value of the economic dimension as shown in Appendix A Table A3, seventeen of the analyzed economies are on the efficiency frontier (Japan, Spain, Greece, France, Ireland, the USA, Brazil, Sweden, Mexico, Portugal, Finland, Germany, Norway, the United Kingdom, Australia, Switzerland, and New Zealand). The peer comparison criterion shows that their energy resilience is reasonably complete in contrast to other economies. Italy, Turkey, Poland, Hungary, the Czech Republic, the Slovak Republic, Belgium, and Luxembourg can increase their respective energy resilience values. For instance, Belgium should decrease its domestic energy consumption and residential energy intensity. Luxembourg needs to minimize its service energy consumption, manufacturing energy consumption, and service energy intensity.

According to environmental energy resilience, seventeen of the subject economies are on the efficiency frontier, as shown in Appendix A Table A4. The peer comparison criterion shows that their energy resilience is reasonably complete in contrast to other economies. Italy, Turkey, the Czech Republic, Belgium, South Korea, Hungary, the Slovak Republic, Poland, and Luxembourg can increase their respective energy resilience values. For example, Luxembourg could cut its CO_2 emissions and service energy use per capita. Slovakia should try to minimize its domestic carbon intensity per capita.

5. Conclusions, Research Limitations, and Future Suggestions

5.1. Conclusions

This article collects data from a few remarkable international data sources and uses 26 economies from three areas as an energy resilience analytical subject. It then summarizes the twelve sub-dimension categories by three dimensions and uses the VRS-SBM-DEA method to determine the energy resilience ratings and rank of each economy. The research results provide policymakers with a baseline for future policy planning. This research differs from earlier studies in that it proposes a methodology for assessing different areas' energy resilience scores rather than comparing various areas within an economy or attempting to determine what factors impact regional energy resilience.

The empirical results show that there are seventeen economies where energy resilience measures have reached efficiency status, indicating that they have relatively full energy resilience, including the USA, Australia, United Kingdom, Brazil, Switzerland, Finland, France, Germany, Greece, Sweden, Ireland, Spain, Japan, Portugal, Norway, Mexico, and New Zealand. Twelve of twenty European economies, all three American economies, and two Asia-Pacific economies are relatively energy-resilient. Further, there are sixteen economies in society dimensions, seventeen economies in economy dimensions, and seventeen economies in environment dimensions that are relatively energy-resilient. Notably, this research uses the VRS-SBM-DEA approach to quantify energy resilience. This indicates that the economies on the efficiency frontier represent the most efficient economies in the sample.

According to the energy resilience value of the society component, sixteen of the economies evaluated are situated on the efficiency frontier. According to the energy resilience scores of the sustainable development components, seventeen of the assessed economies are at the frontier of efficiency. According to environmental energy resilience, seventeen of the examined economies are on the efficiency frontier.

5.2. Research Limitations and Future Suggestions

The research limitations of this study are based on data constraints: we cannot compare all the OECD economies to obtain more benchmarks for this study. Further, most of the selected sub-dimensions (the output indexes) of this study did not consider resource inputs, such that the energy resilience ratings evaluated in this study should be interpreted as performance outcomes rather than input-output efficiency. These are limitations to notice in interpreting the findings of this research.

On the other hand, for future research ideas, the post-COVID-19 period is a good time to compare each economy's recovery to that of its peers. This way, each economy's energy resilience performance can be studied more thoroughly, which could consider the real recovery context and should be a top priority for future research.

This research is one of the first efforts to measure and compute energy resilience scores in addition to the conceptual descriptions in previous studies. Of course, the output index framework constructed in this study is only a start and there is still much room for future researchers to extend and improve the evaluation framework of energy resilience.

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Data Availability Statement: All the data used in this article are obtained from publicized sources.

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

Appendix A

Table A1. Rankings and scores of energy resilience.

Economy	Score	Rank	Economy	Score	Rank
USA	1.000	1	Portugal	1.000	1
Australia	1.000	1	Norway	1.000	1
United Kingdom	1.000	1	Mexico	1.000	1
Brazil	1.000	1	New Zealand	1.000	1
Switzerland	1.000	1	South Korea	0.848	18
Finland	1.000	1	Turkey	0.800	19
France	1.000	1	Luxembourg	0.768	20
Germany	1.000	1	Poland	0.767	21
Greece	1.000	1	Italy	0.751	22
Sweden	1.000	1	Belgium	0.751	23
Ireland	1.000	1	Hungary	0.657	24
Spain	1.000	1	Czech Republic	0.632	25
Japan	1.000	1	Slovak Republic	0.351	26

Table A2. Output efficiency in the society dimension.

Economy\Sub-Dimension	Transparency	Control of Bribery and Corruption	Democracy	Lack of Press Freedom
Mexico	1.000	1.000	1.000	1.000
USA	1.000	1.000	1.000	1.000
France	1.000	1.000	1.000	1.000
Greece	1.000	1.000	1.000	1.000
Japan	1.000	1.000	1.000	1.000
Ireland	1.000	1.000	1.000	1.000
Brazil	1.000	1.000	1.000	1.000
Sweden	1.000	1.000	1.000	1.000
Finland	1.000	1.000	1.000	1.000
Germany	1.000	1.000	1.000	1.000
Norway	1.000	1.000	1.000	1.000
United Kingdom	1.000	1.000	1.000	1.000
Australia	1.000	1.000	1.000	1.000

Table A2. *Cont.*

Economy\Sub-Dimension	Transparency	Control of Bribery and Corruption	Democracy	Lack of Press Freedom
Switzerland	1.000	1.000	1.000	1.000
New Zealand	1.000	1.000	1.000	1.000
Spain	1.000	1.000	1.000	1.000
Portugal	1.000	1.000	1.000	1.000
South Korea	0.946	0.824	1.000	1.000
Luxembourg	0.821	0.946	0.976	0.687
Belgium	0.584	0.878	0.827	0.875
Poland	0.594	0.778	0.808	0.877
Italy	0.618	0.461	0.909	1.000
Turkey	0.799	1.000	0.549	0.606
Hungary	0.676	0.360	0.791	0.716
Czech Republic	0.537	0.368	0.838	0.476
Slovak Republic	0.248	0.124	0.835	0.759

Table A3. Output efficiency in the economic dimension.

Economy\Sub-Dimension	Residential Energy Use	Service Energy Use	Manufacturing Energy Use	Residential Energy Intensity	Service Energy Intensity
Japan	1.000	1.000	1.000	1.000	1.000
Spain	1.000	1.000	1.000	1.000	1.000
USA	1.000	1.000	1.000	1.000	1.000
France	1.000	1.000	1.000	1.000	1.000
Greece	1.000	1.000	1.000	1.000	1.000
Ireland	1.000	1.000	1.000	1.000	1.000
Brazil	1.000	1.000	1.000	1.000	1.000
Sweden	1.000	1.000	1.000	1.000	1.000
Mexico	1.000	1.000	1.000	1.000	1.000
Portugal	1.000	1.000	1.000	1.000	1.000
Finland	1.000	1.000	1.000	1.000	1.000
Germany	1.000	1.000	1.000	1.000	1.000
Norway	1.000	1.000	1.000	1.000	1.000
United Kingdom	1.000	1.000	1.000	1.000	1.000
Australia	1.000	1.000	1.000	1.000	1.000
Switzerland	1.000	1.000	1.000	1.000	1.000
New Zealand	1.000	1.000	1.000	1.000	1.000
Italy	0.991	0.971	0.880	1.000	0.980
Turkey	1.000	0.795	0.912	0.992	0.789
Poland	0.863	0.990	0.729	0.872	1.000
Hungary	0.682	1.000	1.000	0.682	1.000
Czech Republic	0.554	0.996	1.000	0.556	1.000
Slovak Republic	0.515	0.995	0.957	0.518	1.000
South Korea	1.000	0.503	0.439	0.998	0.502
Belgium	0.458	0.662	0.883	0.460	0.665
Luxembourg	0.715	0.456	0.416	0.716	0.456

Table A4. Output efficiency scores in the environment dimension.

Economy\ Sub-Dimension	Per Capita Residential CO_2 Emissions	Per capita Service Energy Use	Per Capita Residential Carbon Intensity
Greece	1.000	1.000	1.000
France	1.000	1.000	1.000
New Zealand	1.000	1.000	1.000
Ireland	1.000	1.000	1.000
Finland	1.000	1.000	1.000
Germany	1.000	1.000	1.000
Norway	1.000	1.000	1.000
Australia	1.000	1.000	1.000
USA	1.000	1.000	1.000
Mexico	1.000	1.000	1.000
United Kingdom	1.000	1.000	1.000
Switzerland	1.000	1.000	1.000
Brazil	1.000	1.000	1.000
Sweden	1.000	1.000	1.000
Japan	1.000	1.000	1.000
Portugal	1.000	1.000	1.000
Spain	1.000	1.000	1.000
Italy	0.880	1.000	1.000
Turkey	0.912	0.920	0.809
Czech Republic	1.000	0.939	0.315
Belgium	0.883	1.000	0.317
South Korea	0.439	1.000	0.705
Hungary	1.000	0.309	0.762
Slovak Republic	0.957	0.479	0.433
Poland	0.729	0.474	0.602
Luxembourg	0.416	0.052	0.560

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