An Extended GRA Method Integrated with Fuzzy AHP to Construct a Multidimensional Index for Ranking Overall Energy Sustainability Performances

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Abstract: In an age of rapid technological advancement, the increasing need for energy and its related services to satisfy economic and social development has become a critical concern of national governments worldwide. This has triggered researchers to work on metrics for tracking and tracing energy sustainability in order to provide monitoring mechanisms for policy makers. In this regard, multicriteria decision-making (MCDM) methods are becoming more popular to deal with the multidimensional and complex nature of sustainability. We have proposed an extended and revised version of the grey relational analysis (GRA) method, which is integrated with the fuzzy analytic hierarchy process (AHP), to develop a new composite index for comparing the overall energy sustainability performances of 35 OECD member countries. Our case study revealed the performances of selected countries by providing their strengths and weaknesses based on determined criteria as well as the level of change in performances with different criteria weights. The proposed GRA model can be used in different applications of sustainability due to its flexible nature, which provides benefits from goal-oriented extensions in order to adequately capture different aspects of sustainability.

Keywords: overall energy sustainability; multicriteria decision-making; fuzzy analytic hierarchy process; extended grey relational analysis; composite index; OECD member countries; monitoring tool

1. Introduction

Energy plays a key role in improving social and economic wellbeing and is essential to fulfill the needs of modern life [1]. Thus, it is crucial to provide energy services based on the principles of sustainability, which is a dynamic, complex, and multidimensional concept depending on context-specific and long-term goals [2,3]. Overall energy sustainability can be achieved by providing affordable, accessible, and reliable energy services in an environmentally friendly manner by considering the needs of economic and social development for present and future generations [1,4]. The dimensions of energy sustainability should be determined from that point of view, since these dimensions are not fixed due to the dynamic nature of sustainable development and new ideas continue to emerge [5–9].

In order to measure a country’s overall energy sustainability, its performance should be represented as quantitative data so that comparisons can be performed in a systematic way. Using indicators is a reliable way to transform condense, voluminous, and complex data into a simpler and usable form. A set of properly designed indicators is useful to determine the long-term implications of current
decisions as well as interconnections and trade-offs among different dimensions [1,6]. Therefore, energy sustainability indicators can be considered as a tool to reveal the performance of a system to meet predetermined goals so that progress toward sustainability can be easily monitored by reviewing any change in indicator values over time.

Compiling indicators into a single metric in accordance with an underlying model simplifies the measurement of multidimensional problems such as energy sustainability [10]. Indices are useful tools to find common trends across different indicators [11] and to assess the performance of countries or entities on complex concepts that are not directly measurable [12]. Various indices have been proposed by researchers to overcome complex problems regarding different aspects of energy [3,5–9,13–17]. Table 1 provides information about the main pros and cons of using indices.

| Pros                      | Cons                                      |
|---------------------------|-------------------------------------------|
| supports decision-making by summarizing complex issues | may lead to misleading results if poorly constructed |
| allows assessing progress over time | may lead to simplistic policy conclusions |
| makes benchmarking easier by facilitating the interpretation of the results | may require substantial data (depending on the number of sub-indicators) |
| allows to include more information within the existing size limit | involves judgement (identification of underlying model, selection of sub-indicators and related weights) |

Source: [11,18,19].

To construct an index, the underlying model should be clearly defined so that the formulation strategy for normalization, weighting, and aggregation techniques can be determined [10]. In this regard, multicriteria decision-making (MCDM) methods provide promising opportunities to deal with the multidimensional and complex nature of sustainability [20]. MCDM refers to a set of methods to be used for supporting decision-making in a multicriteria environment by analyzing a series of possible alternatives [21,22]. These methods allow users to make their decisions based on their predetermined preferences. The main strategy is breaking the problem into smaller components to obtain the relative preferences of alternatives for each property, and to synthesize the results for ranking alternatives [23].

MCDM methods are distinguished based on their underlying models, and the results obtained may be different from each other [23]. Although the aim of MCDM methods are in common, a method can be developed to fulfill the needs of a specific problem instead of providing a solution for different subject areas. For instance, Stević et al. [24] introduced the measurement of alternatives and ranking according to compromise solution (MARCOS) method for sustainable supplier selection in healthcare industries. Introducing new extensions to existing multicriteria decision-making models such as the extended TOPSIS method by Yu et al. [25] are also gaining popularity for solving specific sustainability problems [26–28]. Furthermore, there are integrated approaches that include multiple MCDM techniques to deal with such problems; for example, the integrated grey based multicriteria decision-making approach for the evaluation of renewable energy sources developed by Çelikbilek and Tüysüz [29].

The general structure of the MCDM process is composed of three major stages: determination of the criteria and evaluation metrics, determination of weights, and execution of MCDM methods. The weight of each criterion plays an important role in the MCDM process, since it reflects the importance over others and, therefore, influences the final decision-making. Consequently, it is common to use a separate MCDM method to deal with the weighting of criteria [30–32].

There are two types of weighting methods: subjective and objective weighting. The relative importance of an individual indicator is determined by considering judgements of decision makers, if a subjective weighting method is used. On the other hand, objective weighting methods benefit from data statistical methods without personal interference to calculate the weights. Both methods
have advantages and disadvantages. While subjective methods are preferred to deal with potential uncertainties in human intuitive judgment, objective methods are considered as being easier to be executed and they are less time-consuming [33].

In this paper, we propose an extended grey relational analysis (GRA) method to be used in the overall energy sustainability index (OESI) that is developed for comparing the performances of 35 OECD member countries. The OESI is based on the GRA method integrated with the fuzzy analytic hierarchy process (AHP). While fuzzy AHP is used to determine the weights of criteria defined for decision-making, GRA is used for ranking alternatives. The proposed GRA method includes revisions and extensions to precisely meet the goals of overall energy sustainability. This new method can also be used for other applications of sustainability. The OESI focuses on three dimensions namely, economic and security, environmental, and social for ranking countries in terms of overall energy sustainability performances. Although other dimensions could still be defined, these three dimensions provide a strong and adequate representation of the multidimensionality of energy sustainability. Proposing energy sustainability indicators and combining them with a new goal-oriented MCDM method will help policy makers and researchers to precisely obtain a snapshot of a country’s performance on energy sustainability and will allow them to determine, develop, and implement policies.

2. Materials and Methods

2.1. OESI Index

To construct an index, the first step is to formulate the vision of sustainability, so that the objective can be defined and issues that are relevant in this context can be determined [34]. The purpose of the OESI has been elaborated in the previous section. Table 2 provides information about the issues to be addressed in order to calculate the dimensions of the OESI.

| Dimensions          | Issues to Be Addressed                                                                                                                                 |
|---------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------|
| Economic and Security | The level of energy consumption<br>The level of efficiency of energy production and transmission from an economic point of view<br>The status of the economic condition to provide continuous and adequate energy services<br>The level of ability to provide continuous energy services without any interruptions (assessed from a source diversification point of view) |
| Environmental       | The impact on the environment of energy-related activities<br>Environmental law and regulation effectiveness ¹                                                                                                                                 |
| Social              | The level of quality, affordability, and accessibility of energy services                                                                                                                                 |

¹ Stringency and enforcement of environmental legislations.

The selection of indicators plays a significant role in addressing the OESI. Although there are guidelines such as the Bellagio principles [35] or frameworks such as the systems approach [36] formulated for indicator selection, there is no commonly accepted methodology [34]. However, there have been studies on the requirements that should be met by selected indicators [3,17,37–41]. They can be summarized as sensitivity, interpretability, relevance, accessibility, sensitivity, and timeliness (presented in Table 3).
Table 3. Criteria for indicator selection.

| Criteria                    | Brief Description                                                                                                                                 |
|-----------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------|
| Sensitivity                 | Indicators should be sensitive to any change in the system in order to reflect the changes [39–41].                                               |
| Interpretability            | Indicators should be clearly defined. They must be understandable and measurable [17,37,39–41].                                                    |
| Relevance                   | Indicators should have relevancy to the sustainability [37].                                                                                       |
| Accessibility               | Relevant data must be available 1 [17,39–41].                                                                                                    |
| Timeliness                  | Indicators should be based on timely information [17].                                                                                           |

1 Information provided should be relevant to the time.

The hierarchical structure of the OESI is presented in Table 4.

Table 4. Hierarchical structure of the OESI.

| Dimensions                  | Criteria                           | Indicators                                                                 | Code  |
|-----------------------------|-------------------------------------|---------------------------------------------------------------------------|-------|
| Economic and Security       | Energy use patterns and diversification | Energy use per capita                                                      | IEC1  |
|                             |                                     | Energy use per GDP                                                        | IEC2  |
|                             |                                     | Diversification of sources for electricity generation                     | IEC3  |
| Macroeconomic context       | Supply efficiency                   | Supply efficiency of electricity generation                               | IEC4  |
|                             |                                     | Electric power transmission and distribution losses                       | IEC5  |
|                             | Economic growth rate                |                                                                           | IEC6  |
|                             | Government budget balance           |                                                                           | IEC7  |
|                             | Inflation rate                      |                                                                           | IEC8  |
|                             | Government debt                     |                                                                           | IEC9  |
| Environmental               | N₂O and CH₄ emissions               | N₂O emissions from energy processes                                       | IEN1  |
|                             |                                     | CH₄ emissions from energy processes                                       | IEN2  |
|                             | CO₂ emissions                       | CO₂ emissions from solid fuel combustion                                  | IEN3  |
|                             |                                     | CO₂ emissions from liquid fuel combustion                                 | IEN4  |
|                             |                                     | CO₂ emissions from gaseous fuel combustion                                 | IEN5  |
|                             | Environmental regulations           | Stringency of environmental regulations                                  | IEN6  |
|                             |                                     | Enforcement of environmental regulations                                 | IEN7  |
| Social                      | Quality of supply and equity        | Access to electricity                                                     | ISO1  |
|                             |                                     | Quality of electricity supply                                              | ISO2  |
|                             | Affordability                       | Affordability of electricity price for household consumers                | ISO3  |
|                             |                                     | Affordability of pump price for diesel fuel                               | ISO4  |
|                             |                                     | Affordability of pump price for gasoline fuel                             | ISO5  |

Note: Criteria at the first level are referred to as “dimensions”, subcriteria at the second level are referred to as “criteria”, and subcriteria at the third level are referred to as “indicators” for simplifying the representation.

The relevance of energy sustainability indicators is presented in Table 5. Each indicator identified has an impact on the index. An indicator can be

- Larger the better
- Smaller the better
- Closer to the desired value the better
- Closer to the desired set of values the better.

Table 6 shows the impact of each indicator value on the index.
Table 5. Indicators and relevance.

| Code  | Relevance                                                                 |
|-------|---------------------------------------------------------------------------|
| IEC1  | Plays a role in aggregating energy intensity [42].                         |
| IEC2  | Reflects the relationship between economic development and energy use [42].|
| IEC3  | The mixture of energy supply is considered as a key determinant of energy security [42]. |
| IEC4  | Taking steps to improve the efficiency of energy supplies and to reduce losses during transmission contributes to effective utilization of energy resources [42]. |
| IEC5  |                                                                                       |
| IEC6  | Macroeconomic stability plays an important role in economic growth, as instability creates uncertainty about future values of economic variables. Since economic development enables the provision of better energy services, macroeconomic conditions of an economy have an effect on the economic dimension [43]. |
| IEN1  | The amount of N₂O and CH₄ emissions per capita is considered as an indicator for environmental sustainability [8]. |
| IEN2  |                                                                                       |
| IEN3  | CO₂ emissions from combustion of fuels for energy contribute heavily to global warming [6]. |
| IEN4  | Developing environmental legislation is an important step for the international community to organize itself to take environmental action [44]. Not only the design but also the enforcement of legislation plays an important role for it to “work” [45]. |
| IEN5  |                                                                                       |
| ISO1  | Access to modern energy services is required to avoid poverty as well as deprivation [42]. |
| ISO2  | The level of access to electricity supply is considered as an indicator of environmental energy equity [9]. |
| ISO3  | For social development, affordability of modern energy services across the population should be examined [42]. |

Note: Subindicators used for calculating the level of diversification of sources for electricity generation are excluded.

Table 6. Impacts of indicators.

| Larger the Better | Smaller the Better | Closer to the Desired Value or Set of Values the Better |
|-------------------|--------------------|-----------------------------------------------------|
| IEC1, IEC5        | IEC2, IEC9         | IEC8 ¹                                               |
| IEC3, IEN1        | IEC4, IEN2         |                                                     |
| IEC6, IEN3        | IEN4               |                                                     |
| IEN6, IEN7        | ISO3               |                                                     |
| ISO1, ISO4        | ISO5               |                                                     |

¹ The desired set of values is determined as the values lying between 0.5% and 2.9% [46].

The value of IEC3 was determined by applying the GRA method to indicators represented in Table 7 with equal weights.
Table 7. Subindicators for calculating IEC3 (closer to the desired value the better).

| Indicators                                                                 | Code |
|---------------------------------------------------------------------------|------|
| Electricity generation from coal sources                                 | ISE1 |
| Electricity generation from oil sources                                  | ISE2 |
| Electricity generation from natural gas sources                          | ISE3 |
| Electricity generation from nuclear sources                             | ISE4 |
| Electricity generation from hydroelectric sources                        | ISE5 |
| Electricity generation from renewable sources (except hydroelectric)     | ISE6 |

*The desired value was determined to be 16.667% (authors’ projection based on World Bank data). Units, and brief descriptions of indicators are presented in Appendix A.*

2.2. Fuzzy AHP

AHP is a useful MCDM method to cope with different problematic situations that may include selection of alternatives in a multi-objective environment, allocation of scarce resources, and forecasting [47]. This methodology is based on pairwise comparisons along with judgments from decision makers in a hierarchical manner for calculating weights of criteria within a complex decision-making process [48,49]. AHP has a flexible nature that allows it to be integrated with other methods, so that benefiting from the combined methods becomes possible [50–53].

AHP is a method in which judgements from experts are based on crisp logic. Criteria belonging to the same level in a hierarchical structure are compared with each other by using a nine-point numerical scale to determine how much more a criterion is important than another [54,55]. Since there is vagueness in personal judgments in real-life applications, something greater than a nine-point numerical scale is required to describe the opinion of a decision maker [56]. In order to deal with such uncertainties of a decision problem, fuzzy integrated AHP is commonly used in the literature [57–60].

In this study a fuzzy AHP methodology was used to determine the criteria weights required for ranking alternatives with the GRA method. This was achieved by transforming linguistic variables from decision maker(s) to triangular fuzzy numbers to find fuzzy weights with the geometric mean approach. The linguistic variables used in this work are indicated in Table 8.

Table 8. Linguistic terms and corresponding triangular fuzzy numbers.

| Definition                  | Fuzzy Triangular Scale $\tilde{M} = (l,m,u)$ |
|-----------------------------|---------------------------------------------|
| equally important           | (1,1,1)                                     |
| weakly important            | (1,3,5)                                     |
| fairly important            | (3,5,7)                                     |
| strongly important          | (5,7,9)                                     |
| absolutely important        | (7,9,9)                                     |

Note: All criteria at the same level are compared with each other in the sets of two by using the abovementioned definitions. Therefore, there would be $(n^2-n)/2$ comparisons if there were $n$ criteria at the same level. Fuzzy triangular scale was determined based on the work of Yıldırım and Yeşilyurt [61].

A triangular fuzzy number is defined as $(l, m, u)$, where $(l \leq m \leq u)$. While $m$ indicates the most promising value, $l$ and $u$ denote smallest and largest possible value, respectively. The mathematical notation of a fuzzy number and algebraic operations between two fuzzy numbers are indicated by the following equations [62]:

$$\tilde{M} = (l, m, u)$$

$$\left(\tilde{M}\right)^{-1} = (l, m, u)^{-1} = \left(\frac{1}{u}, \frac{1}{m}, \frac{1}{l}\right)$$

$$\tilde{M}_1 \oplus \tilde{M}_2 = (l_1 m_1 u_1) \oplus (l_2 m_2 u_2) = (l_1 + l_2, m_1 + m_2, u_1 + u_2)$$

$$\tilde{M}_1 - \tilde{M}_2 = (l_1 m_1 u_1) - (l_2 m_2 u_2) = (l_1 - l_2, m_1 - m_2, u_1 - u_2)$$
\[ \widetilde{M}_1 \otimes \widetilde{M}_2 = (l_1m_1u_1) \otimes (l_2m_2u_2) = (l_1l_2, m_1m_2, u_1u_2) \] (5)

Based on Equations (3) and (5), multiplication and addition of fuzzy numbers can be indicated as following equations:

\[ \prod_{i=1}^{n} \widetilde{M}_i = \left( \prod_{i=1}^{n} l_i \prod_{i=1}^{n} m_i \prod_{i=1}^{n} u_i \right) \] (6)

\[ \sum_{i=1}^{n} \widetilde{M}_i = \left( \sum_{i=1}^{n} l_i \sum_{i=1}^{n} m_i \sum_{i=1}^{n} u_i \right) \] (7)

Based on the responses from the decision maker, a judgement matrix is formed to demonstrate triangular fuzzy numbers, as indicated by Equation (8):

\[ \widetilde{M}_{ij} = \begin{bmatrix} \widetilde{M}_{11} & \widetilde{M}_{12} & \cdots & \widetilde{M}_{1n} \\ \widetilde{M}_{21} & \widetilde{M}_{22} & \cdots & \widetilde{M}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \widetilde{M}_{n1} & \widetilde{M}_{n2} & \cdots & \widetilde{M}_{nn} \end{bmatrix} = \begin{bmatrix} l_{11}m_{11}u_{11} & l_{12}m_{12}u_{12} & \cdots & l_{1n}m_{1n}u_{1n} \\ l_{21}m_{21}u_{21} & l_{22}m_{22}u_{22} & \cdots & l_{2n}m_{2n}u_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ l_{n1}m_{n1}u_{n1} & l_{n2}m_{n2}u_{n2} & \cdots & l_{nn}m_{nn}u_{nn} \end{bmatrix} \text{ for } i = 1, 2, \ldots, n, j = 1, 2, \ldots, n \] (8)

For each criterion, the geometric mean of fuzzy comparison values should be calculated before converting them back into crisp values and performing normalization. This is achieved by Equation (9).

\[ \overline{F}_i = \overline{R} \otimes \overline{G}_i = \left( \sum_{i=1}^{n} \prod_{j=1}^{n} \widetilde{M}_{ij} \right)^{-1} \otimes \left( \prod_{j=1}^{n} \overline{M}_{ij} \right) \] (9)

where

\[ \overline{G}_i \] represents the geometric mean value of triangular fuzzy numbers for criterion \( C_i \),

\[ \overline{R} \] represents the reciprocal of the sum of the geometric mean of fuzzy comparison values, and

\[ \overline{F}_i \] represents the fuzzy weight for criterion \( C_i \).

The final steps to determine the final criteria weights with fuzzy AHP include taking the arithmetic mean of fuzzy weights and normalizing it so that the sum of the weights is equal to 1. If there is more than one decision maker, the arithmetic means of the final criteria weights calculated for each decision maker should be taken.

2.3. GRA

GRA depends on the concept of grey theory, which was introduced by Deng in 1982 in order to make decisions where there was incomplete information and data sample. A system is called “grey” if it has incomplete and uncertain information, while a “white” system contains all the information and a “black” system contains no data. In addition to the ability of computing with uncertainty and incomplete information, another key advantage of the grey system is its ability to provide methods which do not require an excessive sample size and any sample distribution for ranking alternatives [63,64].

GRA aims to determine the correlation between sequences by using the data available. This is achieved by creating comparative sequences based on the performances of alternatives as well as by defining the ideal sequence, so that the trend correlation between the reference sequence (ideal sequence) and comparative sequences can be calculated. The comparative sequence that leans more toward concordance with the reference sequence has the highest grey relational degree and, therefore, the related alternative will be the best choice [65–67].
2.3.1. Existing GRA Procedure

The decision matrix for a MCDM problem that consists of a set of alternatives \((A_1, A_2, \ldots, A_m)\) and criteria \((C_1, C_2, \ldots, C_n)\) is formed as shown in Equation (10):

\[
X_{ij} = \begin{bmatrix}
X_{i1} & X_{i2} & \cdots & X_{in} \\
X_{i1} & X_{i2} & \cdots & X_{in} \\
\vdots & \vdots & \ddots & \vdots \\
X_{i1} & X_{i2} & \cdots & X_{in}
\end{bmatrix}
\]

for \(i = 1, 2, \ldots, m \) and \(j = 1, 2, \ldots, n\)

where

\(X_{ij}\) represents the performance of alternative \(A_i\) for criterion \(C_j\).

After the decision matrix is formed, the ideal sequence should be determined and added to the decision matrix as a reference. The reference sequence may consist of “larger the better” criteria, “smaller the better” criteria, and “closer to the desired value the better” criteria.

It is important to perform normalization for transforming input data into a comparable form. Normalization for GRA, which is also called grey relational generating, is performed by one of the three equations described below. Equation (11) is used for larger the better criteria, Equation (12) is used for smaller the better criteria, and Equation (13) is used for closer to the desired value the better criteria [68,69]:

\[
X_{ij}^* = \frac{X_{ij} - \min(X_{ij}, i = 1, 2, \ldots, m)}{\max(X_{ij}, i = 1, 2, \ldots, m) - \min(X_{ij}, i = 1, 2, \ldots, m)} \quad \text{for } i = 1, 2, \ldots, m \quad j = 1, 2, \ldots, n
\]

(11)

\[
X_{ij}^* = \frac{\max(X_{ij}, i = 1, 2, \ldots, m) - X_{ij}}{\max(X_{ij}, i = 1, 2, \ldots, m) - \min(X_{ij}, i = 1, 2, \ldots, m)} \quad \text{for } i = 1, 2, \ldots, m \quad j = 1, 2, \ldots, n
\]

(12)

\[
X_{ij}^* = 1 - \frac{|X_{ij} - X_{dvj}|}{\max|\max(X_{ij}, i = 1, 2, \ldots, m) - X_{dvj}, X_{dvj} - \min(X_{ij}, i = 1, 2, \ldots, m)|} \quad \text{for } i = 1, 2, \ldots, m \quad j = 1, 2, \ldots, n
\]

(13)

where

\(X_{ij}^*\) represents the normalized data of alternative \(A_i\) for criterion \(C_j\), and

\(X_{dvj}\) is the desired value for criterion \(C_j\).

With the grey relational generating process, data are adjusted in a way so that each value falls within the range of \([0,1]\). If the normalized value of an alternative is equal to 1 or closer to 1 than any other normalized alternative value for a specific criterion, the performance of that alternative is the best one for that criterion. In contrast, if the normalized value of an alternative is equal to 0 or closer to 0 than any other normalized alternative value for a specific criterion, the performance of that alternative is the worst one for that criterion.

The grey relational coefficient should be calculated after the normalization process. It is used to determine how close the normalized sequence is to the corresponding reference sequence. It is calculated by using Equations (14) and (15):

\[
\Delta ij = |X_{ij}^* - X_{oj}| \quad \text{for } i = 1, 2, \ldots, m \quad j = 1, 2, \ldots, n
\]

(14)

\[
\gamma(X_{oj}, X_{ij}^*) = \frac{\min(\Delta ij, i = 1, 2, \ldots, m; j = 1, 2, \ldots, n) + \max(\Delta ij, i = 1, 2, \ldots, m; j = 1, 2, \ldots, n)}{\Delta ij + \max(\Delta ij, i = 1, 2, \ldots, m; j = 1, 2, \ldots, n)} \quad \text{for } i = 1, 2, \ldots, m \quad j = 1, 2, \ldots, n
\]

(15)

where

\(\gamma(X_{oj}, X_{ij}^*)\) is the grey relational coefficient of alternative \(A_i\) for criterion \(C_j\).
$X_{ij^*}$ is the reference sequence for criterion $C_j$ and takes the value of 1, and $\varsigma$ is defined as the identification coefficient.

The identification coefficient is used for either compressing or expanding the range of the grey relational coefficient to be calculated. The identification coefficient is determined as 0.5 in the literature [64–66,68,69].

The grey relational grade represents the final correlation between the comparative and reference sequences. It is calculated by Equation (16):

$$\Gamma(X_i) = \sum_{j=1}^{n} W_j \gamma(X_{ij}, X_{ij^*}) \text{ for } i = 1, 2, \ldots, m$$

where

$\Gamma(X_i)$ represents the grey relational grade for alternative $A_i$, and $W_j$ is the weight of $C_j$ obtained with fuzzy AHP.

The higher the value of the grey relational grade, the better the performance of the corresponding alternative.

2.3.2. Revised GRA Normalization Procedure

The normalization procedure for the closer to the desired value the better criteria mentioned in the previous section, represented by Equation (13), does not align with the concept of the procedures applied for the larger the better and the smaller the better criteria indicated by Equations (11) and (12), respectively. The idea should be to assign 1 to the best alternative available and 0 to the worst alternative available based on their performance. However, this cannot be achieved by using Equation (13) if there is no alternative available with the desired value. In that case, the performance of the best alternative cannot reach 1.

Our proposed solution is to add another normalization step to overcome this problem. The proposed method is demonstrated by Equations (17) and (18). Equation (17) is a prenormalization step and Equation (18) is used for normalizing values obtained by using Equation (17):

$$Y_{ij} = \frac{|X_{ij} - X_{dvj}|}{\max(Y_{ij}, i = 1, 2, \ldots, m) - \min(Y_{ij}, i = 1, 2, \ldots, m)} \text{ for } i = 1, 2, \ldots, m$$

$$X_{ij^*} = \frac{\max(Y_{ij}, i = 1, 2, \ldots, m) - Y_{ij}}{\max(Y_{ij}, i = 1, 2, \ldots, m) - \min(Y_{ij}, i = 1, 2, \ldots, m)} \text{ for } i = 1, 2, \ldots, m$$

where

$Y_{ij}$ is the prenormalization value.

By using the abovementioned equations, the range of data is adjusted so that each value falls within the range of [0,1]. The alternative that is closest to desired value takes 1 and the value of the outmost alternative takes 0.

2.3.3. Extended GRA Normalization Procedure

There may be cases where a set of values is considered optimum instead of a single value. We propose two-step normalization procedures, such as the one applied in the previous section, to solve
such issues. If the set of optimal values lies between the maximum and minimum alternative values, Equation (19) can be used to determine the prenormalization value before using Equation (18):

\[
Y_{ij} = \begin{cases} 
\frac{|X_{ij} - X_{\text{maxopt}}|}{\max(X_{ij}, i=1,2,\ldots,m) - \min(X_{ij}, i=1,2,\ldots,m)}, & \text{where } X_{\text{maxopt}} < X_{ij} \leq \max(X_{ij}, i=1,2,\ldots,m) \\
0, & \text{where } X_{\text{minopt}} \leq X_{ij} \leq X_{\text{maxopt}} \\
\frac{|X_{ij} - X_{\text{minopt}}|}{\max(X_{ij}, i=1,2,\ldots,m) - \min(X_{ij}, i=1,2,\ldots,m)}, & \text{where } \min(X_{ij}, i=1,2,\ldots,m) \leq X_{ij} < X_{\text{minopt}}
\end{cases}
\]  

(19)

where

\(X_{\text{maxopt}}\) represents the maximum value of the optimal data set, and

\(X_{\text{minopt}}\) represents the minimum value of the optimal data set.

Equation (19) ensures that best alternative(s) takes the value of 1 after the grey relational generating process, whether there is any optimum or not. However, the proposed equation is not useful in cases where the set optimal values do not lie between maximum and minimum alternative values. It is easy to compute if the minimum value of the optimal data set is greater than the maximum alternative value or if the maximum value of the optimal data set is smaller than the minimum alternative value, since Equations (11) or (12) can be used, respectively. On the other hand, Equation (20) should be used to determine the prenormalization value in cases where the set of optimal values includes the minimum or maximum alternative value and not the other:

\[
Y_{ij} = \begin{cases} 
\frac{|X_{ij} - X_{\text{maxopt}}|}{X_{\text{maxopt}} - \min(X_{ij}, i=1,2,\ldots,m)}, & \text{where } \min(X_{ij}, i=1,2,\ldots,m) < X_{\text{minopt}} < \max(X_{ij}, i=1,2,\ldots,m) < X_{\text{maxopt}} \\
\frac{|X_{ij} - X_{\text{minopt}}|}{\max(X_{ij}, i=1,2,\ldots,m) - X_{\text{maxopt}}}, & \text{where } X_{\text{minopt}} < \min(X_{ij}, i=1,2,\ldots,m) < X_{\text{maxopt}} < \max(X_{ij}, i=1,2,\ldots,m)
\end{cases}
\]  

(20)

Flow chart of the procedures used for calculating the OESI is presented in Appendix B (Figures A1 and A2).

3. Results and Discussion

The weights of the criteria had a considerable effect on the results of the OESI. Tables 9 and 10 show the weights of criteria and indicators determined by applying fuzzy AHP procedures. It was observed that the economic and security dimension had the greatest impact, while the environmental and social dimensions had similar impacts on the index.

Table 9. Indicator weights.

| Indicators | Weights | Criteria | Weights | Indicators | Weights |
|------------|---------|----------|---------|------------|---------|
| IEC1       | 0.065   | IEC8     | 0.012   | IEN6       | 0.019   |
| IEC2       | 0.065   | IEC9     | 0.009   | IEN7       | 0.012   |
| IEC3       | 0.111   | IEN1     | 0.033   | ISO1       | 0.063   |
| IEC4       | 0.104   | IEN2     | 0.064   | ISO2       | 0.071   |
| IEC5       | 0.104   | IEN3     | 0.039   | ISO3       | 0.052   |
| IEC6       | 0.02    | IEN4     | 0.039   | ISO4       | 0.015   |
| IEC7       | 0.013   | IEN5     | 0.071   | ISO5       | 0.021   |

Note: Weights indicated in the table are out of 1. Sum of the weights indicated in the table may not be equal to 1 due to fractional rounding.

Among 35 OECD member countries, Iceland took first place in terms of overall energy sustainability performance. Iceland ranked first among other OECD member countries in the economic and security, and the environmental dimensions, and ranked eighth in the social dimension.

By comparing other energy sustainability indices with the OESI, similarities were observed in the results. Although each energy sustainability index has its own objective and considers different
indicators, European countries take the highest scores. For instance, Norway, Sweden, Switzerland, New Zealand, and Austria scored in the top 10 in the OESI, the Global Energy Architecture Performance Index [8], and World Energy Trilemma Index [9]. Results are presented in Table 11.

| Table 10. Criteria weights. |
|-----------------------------|
| Dimensions          | Weights (%) | Criteria                              | Weights (%) |
| Economic and Security  | 50.33        | Energy use patterns and diversification | 24.06        |
|                        |             | Supply efficiency                      | 20.81        |
|                        |             | Macroeconomic context                  | 5.46         |
| Environmental         | 27.61        | N₂O and CH₄ emissions                  | 9.70         |
|                        |             | CO₂ emissions                           | 14.84        |
|                        |             | Environmental regulations               | 3.06         |
| Social                | 22.07        | Quality of supply and equity            | 18.54        |
|                        |             | Affordability                           | 3.53         |

Note: Sum of the weights indicated in the table may not be equal to 100 due to fractional rounding.

| Table 11. Results of OESI. |
|----------------------------|
| Countries       | Score (Total) | Rank (Total) | Score (Ec. and Se.) | Rank (Ec. and Se.) | Score (Env.) | Rank (Env.) | Score (Soc.) | Rank (Soc.) |
| Australia       | 0.5482        | 31           | 0.2477              | 16                 | 0.1387       | 35          | 0.1617       | 22          |
| Austria         | 0.6559        | 6            | 0.2686              | 6                  | 0.2085       | 11          | 0.1787       | 15          |
| Belgium         | 0.6076        | 21           | 0.2357              | 23                 | 0.1956       | 24          | 0.1763       | 17          |
| Canada          | 0.6174        | 16           | 0.255               | 9                  | 0.1685       | 33          | 0.1938       | 6           |
| Chile           | 0.6013        | 23           | 0.2517              | 13                 | 0.2214       | 4           | 0.1281       | 32          |
| Czechia         | 0.5893        | 26           | 0.2373              | 21                 | 0.199       | 21          | 0.153        | 25          |
| Denmark         | 0.6331        | 9            | 0.2217              | 31                 | 0.2163       | 6           | 0.195        | 5           |
| Estonia         | 0.5655        | 29           | 0.2329              | 24                 | 0.1902       | 27          | 0.1424       | 28          |
| Finland         | 0.6611        | 5            | 0.275               | 4                  | 0.198        | 22          | 0.188        | 9           |
| France          | 0.6124        | 18           | 0.2197              | 32                 | 0.2026       | 17          | 0.1902       | 7           |
| Germany         | 0.6187        | 14           | 0.2511              | 14                 | 0.2005       | 19          | 0.1671       | 20          |
| Greece          | 0.6244        | 12           | 0.2798              | 3                  | 0.2101       | 9           | 0.1346       | 30          |
| Hungary         | 0.5528        | 30           | 0.2149              | 34                 | 0.2083       | 12          | 0.1296       | 31          |
| Iceland         | 0.8067        | 1            | 0.3772              | 1                  | 0.2393       | 1           | 0.1901       | 8           |
| Ireland         | 0.5764        | 27           | 0.2176              | 33                 | 0.1892       | 28          | 0.1696       | 19          |
| Israel          | 0.6183        | 15           | 0.2479              | 15                 | 0.1997       | 20          | 0.1707       | 18          |
| Italy           | 0.6011        | 24           | 0.2416              | 19                 | 0.2036       | 14          | 0.1559       | 24          |
| Japan           | 0.6356        | 8            | 0.2523              | 11                 | 0.2020       | 15          | 0.1801       | 13          |
| Korea           | 0.6281        | 11           | 0.2649              | 7                  | 0.1843       | 29          | 0.1789       | 14          |
| Latvia          | 0.5444        | 33           | 0.2256              | 29                 | 0.197        | 23          | 0.1217       | 33          |
| Luxembourg      | 0.6089        | 20           | 0.2425              | 18                 | 0.1713       | 31          | 0.1951       | 4           |
| Mexico          | 0.5177        | 35           | 0.2233              | 30                 | 0.2096       | 10          | 0.0848       | 35          |
| Netherlands     | 0.6163        | 17           | 0.2358              | 22                 | 0.1945       | 26          | 0.186        | 11          |
| New Zealand     | 0.6449        | 7            | 0.2525              | 10                 | 0.1952       | 25          | 0.1972       | 3           |
| Norway          | 0.6749        | 3            | 0.2856              | 2                  | 0.1686       | 32          | 0.2207       | 1           |
| Poland          | 0.5465        | 32           | 0.2302              | 25                 | 0.1804       | 30          | 0.1359       | 29          |
| Portugal        | 0.5933        | 25           | 0.2276              | 28                 | 0.2214       | 5           | 0.1443       | 26          |
| Slovakia        | 0.6206        | 13           | 0.2742              | 5                  | 0.2037       | 13          | 0.1426       | 27          |
| Slovenia        | 0.606         | 22           | 0.241               | 20                 | 0.2018       | 18          | 0.1633       | 21          |
| Spain           | 0.6331        | 10           | 0.26                | 8                  | 0.2137       | 7           | 0.1594       | 23          |
| Sweden          | 0.6764        | 2            | 0.2519              | 12                 | 0.2374       | 3           | 0.1871       | 10          |
| Switzerland     | 0.6719        | 4            | 0.2286              | 27                 | 0.2379       | 2           | 0.2055       | 2           |
| Turkey          | 0.5331        | 34           | 0.2028              | 35                 | 0.2101       | 8           | 0.1203       | 34          |
| United Kingdom  | 0.6096        | 19           | 0.2288              | 26                 | 0.2029       | 16          | 0.1779       | 16          |
| United States   | 0.5673        | 28           | 0.2432              | 17                 | 0.1415       | 34          | 0.1827       | 12          |

1 Ec. and Se. refers to Economic and Security. 2 Env. refers to Environmental. 3 Soc. refers to Social.
OESI is a tool that provides a snapshot of overall energy sustainability performances of countries on a comparative scale and its significance must be interpreted with circumspection. Although a country with a high value of OESI may be perceived as more developed than other countries with lower values, a disaggregated evaluation at the subcriteria level is further required in order to gain a comprehensive insight into energy sustainability. This allows policy makers to focus on areas that need to be improved. Tables 12–14 present weighted indicator values.

Table 12. Weighted indicator values (economic and security dimension).

| Countries | IEC1 | IEC2 | IEC3 | IEC4 | IEC5 | IEC6 | IEC7 | IEC8 | IEC9 |
|-----------|------|------|------|------|------|------|------|------|------|
| Australia | 0.026 | 0.024 | 0.048 | 0.045 | 0.071 | 0.009 | 0.005 | 0.012 | 0.007 |
| Austria   | 0.024 | 0.023 | 0.058 | 0.062 | 0.071 | 0.008 | 0.005 | 0.012 | 0.006 |
| Belgium   | 0.025 | 0.024 | 0.050 | 0.036 | 0.071 | 0.008 | 0.005 | 0.012 | 0.005 |
| Canada    | 0.029 | 0.028 | 0.055 | 0.063 | 0.050 | 0.008 | 0.005 | 0.012 | 0.005 |
| Chile     | 0.022 | 0.023 | 0.066 | 0.052 | 0.059 | 0.008 | 0.005 | 0.009 | 0.008 |
| Czechia   | 0.024 | 0.025 | 0.043 | 0.040 | 0.071 | 0.009 | 0.006 | 0.012 | 0.007 |
| Denmark   | 0.022 | 0.022 | 0.046 | 0.035 | 0.064 | 0.009 | 0.005 | 0.011 | 0.007 |
| Estonia   | 0.025 | 0.027 | 0.043 | 0.043 | 0.059 | 0.010 | 0.006 | 0.012 | 0.009 |
| Finland   | 0.027 | 0.027 | 0.068 | 0.043 | 0.080 | 0.009 | 0.005 | 0.011 | 0.006 |
| France    | 0.024 | 0.024 | 0.043 | 0.037 | 0.064 | 0.008 | 0.005 | 0.011 | 0.005 |
| Germany   | 0.024 | 0.023 | 0.054 | 0.039 | 0.080 | 0.009 | 0.006 | 0.011 | 0.006 |
| Greece    | 0.022 | 0.023 | 0.111 | 0.044 | 0.054 | 0.007 | 0.006 | 0.010 | 0.004 |
| Hungary   | 0.022 | 0.023 | 0.060 | 0.037 | 0.041 | 0.009 | 0.005 | 0.011 | 0.006 |
| Iceland   | 0.065 | 0.065 | 0.039 | 0.066 | 0.090 | 0.020 | 0.013 | 0.012 | 0.007 |
| Ireland   | 0.023 | 0.022 | 0.046 | 0.040 | 0.054 | 0.012 | 0.005 | 0.009 | 0.006 |
| Israel    | 0.023 | 0.023 | 0.038 | 0.044 | 0.090 | 0.011 | 0.005 | 0.008 | 0.006 |
| Italy     | 0.022 | 0.022 | 0.069 | 0.043 | 0.059 | 0.008 | 0.005 | 0.009 | 0.004 |
| Japan     | 0.023 | 0.023 | 0.058 | 0.044 | 0.080 | 0.007 | 0.005 | 0.009 | 0.003 |
| Korea     | 0.025 | 0.027 | 0.048 | 0.041 | 0.090 | 0.009 | 0.006 | 0.012 | 0.007 |
| Latvia    | 0.022 | 0.024 | 0.046 | 0.052 | 0.050 | 0.008 | 0.005 | 0.010 | 0.008 |
| Luxembourg | 0.028 | 0.022 | 0.048 | 0.047 | 0.064 | 0.009 | 0.006 | 0.010 | 0.008 |
| Mexico    | 0.022 | 0.023 | 0.066 | 0.044 | 0.037 | 0.009 | 0.005 | 0.012 | 0.006 |
| Netherlands | 0.024 | 0.023 | 0.046 | 0.041 | 0.071 | 0.009 | 0.005 | 0.010 | 0.006 |
| New Zealand | 0.025 | 0.025 | 0.051 | 0.057 | 0.059 | 0.010 | 0.006 | 0.012 | 0.008 |
| Norway    | 0.026 | 0.023 | 0.037 | 0.104 | 0.064 | 0.006 | 0.007 | 0.009 | 0.008 |
| Poland    | 0.022 | 0.024 | 0.043 | 0.044 | 0.064 | 0.010 | 0.005 | 0.012 | 0.007 |
| Portugal  | 0.022 | 0.023 | 0.064 | 0.043 | 0.047 | 0.008 | 0.005 | 0.012 | 0.004 |
| Slovakia  | 0.022 | 0.024 | 0.054 | 0.040 | 0.104 | 0.010 | 0.005 | 0.008 | 0.007 |
| Slovenia  | 0.023 | 0.024 | 0.046 | 0.046 | 0.071 | 0.010 | 0.005 | 0.009 | 0.006 |
| Spain     | 0.022 | 0.023 | 0.100 | 0.039 | 0.047 | 0.010 | 0.004 | 0.009 | 0.005 |
| Sweden    | 0.025 | 0.024 | 0.049 | 0.049 | 0.071 | 0.009 | 0.005 | 0.012 | 0.007 |
| Switzerland | 0.023 | 0.022 | 0.039 | 0.057 | 0.059 | 0.008 | 0.006 | 0.009 | 0.007 |
| Turkey    | 0.022 | 0.022 | 0.047 | 0.051 | 0.035 | 0.010 | 0.005 | 0.004 | 0.008 |
| United Kingdom | 0.023 | 0.022 | 0.061 | 0.038 | 0.054 | 0.008 | 0.005 | 0.012 | 0.005 |
| United States | 0.028 | 0.025 | 0.054 | 0.042 | 0.064 | 0.008 | 0.005 | 0.012 | 0.005 |

Note: Fractional rounding is performed.
Table 13. Weighted indicator values (environmental dimension).

| Countries     | IEN1 | IEN2 | IEN3 | IEN4 | IEN5 | IEN6 | IEN7 |
|---------------|------|------|------|------|------|------|------|
| Australia     | 0.018 | 0.028 | 0.019 | 0.022 | 0.030 | 0.013 | 0.009 |
| Austria       | 0.025 | 0.035 | 0.033 | 0.026 | 0.040 | 0.019 | 0.011 |
| Belgium       | 0.028 | 0.059 | 0.034 | 0.024 | 0.033 | 0.012 | 0.007 |
| Canada        | 0.017 | 0.033 | 0.030 | 0.019 | 0.055 | 0.009 | 0.006 |
| Chile         | 0.033 | 0.054 | 0.032 | 0.029 | 0.059 | 0.008 | 0.006 |
| Czechia       | 0.021 | 0.048 | 0.039 | 0.032 | 0.044 | 0.010 | 0.005 |
| Denmark       | 0.024 | 0.055 | 0.038 | 0.028 | 0.047 | 0.014 | 0.010 |
| Estonia       | 0.024 | 0.043 | 0.013 | 0.039 | 0.053 | 0.011 | 0.007 |
| Finland       | 0.011 | 0.058 | 0.026 | 0.024 | 0.048 | 0.019 | 0.012 |
| France        | 0.029 | 0.046 | 0.036 | 0.028 | 0.047 | 0.010 | 0.006 |
| Germany       | 0.027 | 0.057 | 0.025 | 0.027 | 0.039 | 0.016 | 0.009 |
| Greece        | 0.027 | 0.057 | 0.029 | 0.028 | 0.057 | 0.008 | 0.004 |
| Hungary       | 0.033 | 0.056 | 0.034 | 0.033 | 0.041 | 0.007 | 0.004 |
| Iceland       | 0.031 | 0.064 | 0.034 | 0.022 | 0.071 | 0.011 | 0.007 |
| Ireland       | 0.027 | 0.049 | 0.031 | 0.026 | 0.039 | 0.010 | 0.007 |
| Israel        | 0.032 | 0.058 | 0.027 | 0.029 | 0.040 | 0.008 | 0.005 |
| Italy         | 0.029 | 0.060 | 0.035 | 0.030 | 0.038 | 0.007 | 0.004 |
| Japan         | 0.029 | 0.063 | 0.025 | 0.025 | 0.038 | 0.014 | 0.008 |
| Korea         | 0.028 | 0.058 | 0.020 | 0.027 | 0.038 | 0.008 | 0.005 |
| Latvia        | 0.027 | 0.041 | 0.038 | 0.032 | 0.046 | 0.008 | 0.005 |
| Luxembourg    | 0.019 | 0.054 | 0.037 | 0.013 | 0.028 | 0.013 | 0.008 |
| Mexico        | 0.033 | 0.051 | 0.037 | 0.031 | 0.047 | 0.007 | 0.004 |
| Netherlands   | 0.031 | 0.052 | 0.038 | 0.025 | 0.026 | 0.014 | 0.009 |
| New Zealand   | 0.027 | 0.054 | 0.033 | 0.025 | 0.036 | 0.013 | 0.008 |
| Norway        | 0.028 | 0.021 | 0.036 | 0.020 | 0.036 | 0.017 | 0.010 |
| Poland        | 0.024 | 0.036 | 0.022 | 0.034 | 0.052 | 0.008 | 0.004 |
| Portugal      | 0.030 | 0.058 | 0.034 | 0.030 | 0.053 | 0.011 | 0.006 |
| Slovakia      | 0.027 | 0.057 | 0.029 | 0.035 | 0.041 | 0.009 | 0.006 |
| Slovenia      | 0.027 | 0.046 | 0.030 | 0.027 | 0.054 | 0.011 | 0.006 |
| Spain         | 0.029 | 0.061 | 0.034 | 0.029 | 0.047 | 0.009 | 0.006 |
| Sweden        | 0.022 | 0.059 | 0.035 | 0.027 | 0.065 | 0.019 | 0.011 |
| Switzerland   | 0.030 | 0.058 | 0.039 | 0.027 | 0.053 | 0.019 | 0.012 |
| Turkey        | 0.031 | 0.056 | 0.031 | 0.036 | 0.046 | 0.006 | 0.004 |
| United Kingdom| 0.032 | 0.055 | 0.031 | 0.029 | 0.036 | 0.011 | 0.007 |
| United States | 0.016 | 0.042 | 0.022 | 0.019 | 0.024 | 0.011 | 0.007 |

Note: Fractional rounding is performed.

The results indicate that countries with high performance in OESI managed to link various aspects of energy sustainability. Overall scores were distributed between 0.807 and 0.518 out of 1. Since OECD member countries were considered as alternatives in the study, the absence of scores under 0.5 is not surprising.

From the dimension point of view, economic and security dimension had much more effect on the OESI among other dimensions. Countries which were efficient in energy use, benefitted from various energy resources, and had high productive uses of energy, achieved high points in this dimension. Thus, policy makers should put their best efforts to improve these areas in order to maximize energy sustainability.

Environmental dimension occupied the second place in reference to other dimensions. With respect to this dimension, climate related issues (CO$_2$, N$_2$O, and CH$_4$ emissions) were the main drivers of environmental problems. Furthermore, creating environmental awareness and promoting environmental education are the means to ensure pressure on governments from society to develop...
laws and regulations aimed at protecting the environment. Enforcement of regulations is also required for proper environmental care.

Table 14. Weighted indicator values (social dimension).

| Countries   | ISO1  | ISO2  | ISO3  | ISO4  | ISO5  |
|-------------|-------|-------|-------|-------|-------|
| Australia   | 0.063 | 0.036 | 0.035 | 0.012 | 0.017 |
| Austria     | 0.063 | 0.057 | 0.034 | 0.010 | 0.014 |
| Belgium     | 0.063 | 0.054 | 0.034 | 0.011 | 0.015 |
| Canada      | 0.063 | 0.057 | 0.045 | 0.012 | 0.017 |
| Chile       | 0.039 | 0.043 | 0.026 | 0.009 | 0.011 |
| Czechia     | 0.063 | 0.054 | 0.021 | 0.006 | 0.009 |
| Denmark     | 0.063 | 0.066 | 0.039 | 0.012 | 0.016 |
| Estonia     | 0.063 | 0.038 | 0.026 | 0.007 | 0.009 |
| Finland     | 0.063 | 0.061 | 0.039 | 0.011 | 0.015 |
| France      | 0.063 | 0.066 | 0.038 | 0.010 | 0.014 |
| Germany     | 0.063 | 0.045 | 0.033 | 0.011 | 0.015 |
| Greece      | 0.063 | 0.032 | 0.025 | 0.006 | 0.009 |
| Hungary     | 0.063 | 0.029 | 0.024 | 0.005 | 0.008 |
| Iceland     | 0.063 | 0.061 | 0.042 | 0.010 | 0.014 |
| Ireland     | 0.063 | 0.048 | 0.034 | 0.011 | 0.015 |
| Israel      | 0.063 | 0.051 | 0.037 | 0.009 | 0.012 |
| Italy       | 0.063 | 0.039 | 0.032 | 0.009 | 0.013 |
| Japan       | 0.063 | 0.061 | 0.031 | 0.011 | 0.014 |
| Korea       | 0.063 | 0.051 | 0.042 | 0.010 | 0.014 |
| Latvia      | 0.063 | 0.030 | 0.017 | 0.005 | 0.007 |
| Luxembourg  | 0.063 | 0.061 | 0.042 | 0.012 | 0.017 |
| Mexico      | 0.021 | 0.027 | 0.023 | 0.006 | 0.008 |
| Netherlands | 0.063 | 0.066 | 0.034 | 0.010 | 0.014 |
| New Zealand | 0.063 | 0.054 | 0.048 | 0.014 | 0.019 |
| Norway      | 0.063 | 0.071 | 0.052 | 0.015 | 0.021 |
| Poland      | 0.063 | 0.033 | 0.024 | 0.007 | 0.010 |
| Portugal    | 0.063 | 0.045 | 0.020 | 0.007 | 0.009 |
| Slovakia    | 0.063 | 0.041 | 0.024 | 0.006 | 0.009 |
| Slovenia    | 0.063 | 0.051 | 0.030 | 0.008 | 0.012 |
| Spain       | 0.063 | 0.045 | 0.029 | 0.009 | 0.013 |
| Sweden      | 0.063 | 0.057 | 0.040 | 0.011 | 0.016 |
| Switzerland | 0.063 | 0.071 | 0.043 | 0.012 | 0.017 |
| Turkey      | 0.063 | 0.024 | 0.020 | 0.006 | 0.008 |
| United      | 0.063 | 0.061 | 0.031 | 0.010 | 0.014 |
| Kingdom     | 0.063 | 0.045 | 0.044 | 0.013 | 0.018 |

Note: Fractional rounding was performed.

Social dimension held the last place in the list. Any policy aiming to implement a transition towards energy sustainability needs to be evaluated regarding their influences on accessibility, quality and affordability of energy services.

“Diversification of sources for electricity generation” is one of the most significant indicators in terms of criteria weights. In recent studies, the importance of diversification of energy supply has been emphasized with other factors, such as political stability, energy resource availability, energy dependence, and reserve-to-production ratio [8,70,71]. Using the GRA method to create an additional energy security dimension by including such factors may provide a more comprehensive approach to rank countries in future works. Those factors should be dependent on each other and their weights must be arranged on a country basis. Furthermore, taking steps to include future projection data for all dimensions can contribute to the efforts of developing the OESI.

As a future direction, using an integrated method consisting of a specific function that determines the overall weights of indicators based on obtained data from both subjective and objective weighting
procedures will be highly beneficial. In addition, taking further steps in developing existing fuzzy AHP methodology or proposing a more suitable subjective weighting model to allow more scalability may provide the ability to benefit from additional dimensions. Especially, creating a separated energy policy dimension will significantly contribute to the efforts to improve the OESI.

The analyses performed in the OESI were mostly based on data with a five-year time frame due to data unavailability. Since the precision of the indicated results increases along with improvements in timely data collection, further efforts should include improved data collection to track performances of countries on an annual basis.

4. Conclusions

In our study, a framework was built to develop an index for measuring the overall energy sustainability of various countries. The aim of proposing such an index was to provide a benchmark for policy makers to assess energy sustainability performances by introducing a new underlying model that can also be used in different applications of sustainability. Such an approach contributes to efforts of researchers working on decision-making methods for dealing with sustainability issues.

Three major contributions of this research can be summarized as follows:

- providing a research strategy that benefits from a specific, integrated MCDM method (fuzzy AHP with GRA) to deal with complex sustainability issues;
- introducing new extensions for the existing GRA method due to its insufficiency in providing accurate results after the grey relational generating process in specific situations; and
- proposing an index with the purpose of assessing the overall energy sustainability performances of various countries serving as a mechanism to monitor their strengths and weaknesses.

Our research has mainly focused on proposing revisions and extensions regarding the normalization procedure of GRA method. We introduced a simple procedure to overcome the inconsistency problem encountered in the normalization step for the closer to the desired value the better criteria. Furthermore, we used this approach to develop additional steps in the normalization process to solve problems that include closer to the desired set of values the better criteria. We believe these additional procedures make GRA a very suitable method for ranking alternatives in sustainability problems, due to their contribution to provide solutions in dealing with criteria that cannot be modelled as larger the better or smaller the better. This can also make an important contribution to MCDM literature.

While the OESI was rigorously developed, there are some limitations providing opportunities for future papers. This study used fuzzy AHP in order to determine the weights of each indicator, due to its specific properties such as simplicity, and flexibility. However, difficulties in deciding whether an expert is qualified in the selected research area, reaching adequate number of experts, and receiving timely feedback from them pose problems. Moreover, we have faced scalability issues due to the increasing number of comparisons, which quickly becomes unmanageable. Therefore, including integrated methods using both subjective and objective weighting, and any procedure that provides solutions for scalability issues in subjective weighting is important in the future work. This will increase the reliability of the study and will allow to increase the number of dimensions, criteria and indicators to be used in the OESI. In addition to constraints caused by fuzzy AHP, data availability has been also an important issue. Even though criteria for indicator selection presented in Table 3 has been carefully considered during indicator selection, further efforts are required in timely data collection. Replicating the methodology in regions with less information (especially non-developed nations) may be difficult due to data unavailability.

For further research, using non-linear functions such as radical functions instead of a linear approach in the normalization step can be a promising area for interested researchers. Although this would be a more comprehensive approach for ranking purposes, it would include more subjectivity
(determining the function, using multiple functions etc.). Nevertheless, we believe it is a promising research area which is applicable especially for creating an additional security dimension.

**Supplementary Materials:** The following are available online at http://www.mdpi.com/2071-1050/12/4/1602/s1, Excel File S1: Data, Excel File S2: Matlab_Output, Excel File S3: Questionnaire & Answers, Excel File S4: Results of Questionnaire, Excel File S5: RESULTS (ALTINTAS), Excel File S6: RESULTS (GURBUZ), Excel File S7: RESULTS (KAVAKLIOGLU), MATLAB File S8: FUZZY_AHP, Figure S9: Flow chart of the overall procedure, Figure S10: Flow chart of the revised & extended GRA procedure, Text File S11:FUZZY_AHP, Word File S12: General.

**Author Contributions:** Conceptualization, K.A., O.V., S.A., and E.C.; methodology, K.A., O.V., S.A., and E.C.; software, K.A.; validation, O.V., S.A., and E.C.; formal analysis, K.A and S.A.; investigation, K.A.; resources, K.A.; data curation, K.A.; writing—original draft preparation, K.A.; writing—review and editing, K.A., O.V., S.A. and E.C.; supervision, O.V., S.A., and E.C.; project administration, K.A., O.V., S.A., and E.C. All authors have read and agreed to the published version of the manuscript.

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## Appendix A

### Table A1. Indicators, units, and brief descriptions.

| Code | Unit | Description |
|------|------|-------------|
| IEC1 | kgoe ¹ per capita | primary energy consumption ² on a per capita basis |
| IEC2 | kgoe per GDP ³ | primary energy consumption on a GDP basis |
| IEC3 | % | level of energy supply diversification |
| IEC4 | % | level of supply efficiency for electricity generation |
| IEC5 | % | level of losses during electric power transmission ⁴ |
| IEC6 | % | annual growth rate of GDP |
| IEC7 | % | budget surplus or deficit as a percentage of GDP |
| IEC8 | % | annual change in goods and services |
| IEC9 | % | gross general government debt as a percentage of GDP |
| IEN1 | ton of CO₂ equivalent per capita | N₂O emissions from energy-related processes on a per capita basis |
| IEN2 | ton of CO₂ equivalent per capita | CH₄ emissions from energy-related processes on a per capita basis |
| IEN3 | ton of CO₂ per capita | CO₂ emissions from solid fuel combustion on a per capita basis |
| IEN4 | ton of CO₂ per capita | CO₂ emissions from liquid fuel combustion on a per capita basis |
| IEN5 | ton of CO₂ per capita | CO₂ emissions from gaseous fuel combustion on a per capita basis |
| IEN6 | score 1–7 | level of stringency of environmental regulations |
| IEN7 | score 1–7 | level of enforcement of environmental regulations |
| ISO1 | % | percentage of population with access to electricity |
| ISO2 | score 1–7 | quality of electricity supply |
| ISO3 | # | affordability of electricity consumption |
| ISO4 | # | affordability of diesel consumption |
| ISO5 | # | affordability of gasoline consumption |

¹ kgoe (kilograms of oil equivalent) refers to the amount of energy generated from burning kg ton of crude oil.

² primary energy refers to any energy form that has not been transformed to other end-use fuels.

³ GDP is converted to USD by using 2011 rates of purchasing power parity.

⁴ pilferage is included.
Appendix B

MATLAB (R2018b) was used for calculating weights with fuzzy AHP and Microsoft Excel (2016) was used to apply GRA methods.

Figure A1. Flow chart of the overall procedure (Supplementary Materials).
Figure A2. Flow chart of the revised and extended GRA procedure (Supplementary Materials).

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