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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.

Table 1. Main pros and cons of an index.

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.

Table 2. Issues to be addressed for calculating the dimensions of the overall energy sustainability index (OESI).

Dimensions	Issues to Be Addressed
Economic and Security	The level of energy consumption The level of efficiency of energy production and transmission from an economic point of view The status of the economic condition to provide continuous and adequate energy services 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 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
	Supply efficiency	Supply efficiency of electricity generation	IEC4
		Electric power transmission and distribution losses	IEC5
	Macroeconomic context	Economic growth rate	IEC6
		Government budget balance	IEC7
		Inflation rate	IEC8
		Government debt	IEC9
Environmental	N_2O and CH_4 emissions	N_2O emissions from energy processes	IEN1
		CH_4 emissions from energy processes	IEN2
	CO_2 emissions	CO_2 emissions from solid fuel combustion	IEN3
		CO_2 emissions from liquid fuel combustion	IEN4
		CO_2 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 IEC5	Taking steps to improve the efficiency of energy supplies and to reduce losses during transmission contributes to effective utilization of energy resources [42].
IEC6 IEC7 IEC8 IEC9	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 IEN2	The amount of N_2O and CH_4 emissions per capita is considered as an indicator for environmental sustainability [8].
IEN3 IEN4 IEN5	CO_2 emissions from combustion of fuels for energy contribute heavily to global warming [6].
IEN6 IEN7	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].
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 ISO4 ISO5	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	IEC8 [1]
IEC2	IEC9	
IEC3	IEN1	
IEC4	IEN2	
IEC6	IEN3	
IEC7	IEN4	
IEN6	IEN5	
IEN7	ISO3	
ISO1	ISO4	
ISO2	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 [1]	ISE1
Electricity generation from oil sources [1]	ISE2
Electricity generation from natural gas sources [1]	ISE3
Electricity generation from nuclear sources [1]	ISE4
Electricity generation from hydroelectric sources [1]	ISE5
Electricity generation from renewable sources (except hydroelectric) [1]	ISE6

[1] 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 $\widetilde{M}$=(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]:

$$\widetilde{M} = (l, m, u) \tag{1}$$

$$\left(\widetilde{M}\right)^{-1} = (l, m, u)^{-1} = \left(\frac{1}{u}, \frac{1}{m}, \frac{1}{l}\right) \tag{2}$$

$$\widetilde{M}_1 \oplus \widetilde{M}_2 = (l_1 m_1 u_1) \oplus (l_2 m_2 u_2) = (l_1 + l_2, m_1 + m_2, u_1 + u_2) \tag{3}$$

$$\widetilde{M}_1 - \widetilde{M}_2 = (l_1 m_1 u_1) - (l_2 m_2 u_2) = (l_1 - l_2, m_1 - m_2, u_1 - u_2) \tag{4}$$

$$\widetilde{M}_1 \otimes \widetilde{M}_2 = (l_1 m_1 u_1) \otimes (l_2 m_2 u_2) = (l_1 l_2, m_1 m_2, u_1 u_2) \quad (5)$$

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

$$\prod_{i=1}^{n} \widetilde{M}_i = \left(\prod_{i=1}^{n} l, \prod_{i=1}^{n} m, \prod_{i=1}^{n} u \right) \quad (6)$$

$$\sum_{i=1}^{n} \widetilde{M}_i = \left(\sum_{i=1}^{n} l, \sum_{i=1}^{n} m, \sum_{i=1}^{n} u \right) \quad (7)$$

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

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

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).

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

where

$\widetilde{G}_i$ represents the geometric mean value of triangular fuzzy numbers for criterion C_i,
$\widetilde{R}$ represents the reciprocal of the sum of the geometric mean of fuzzy comparison values, and
$\widetilde{F}_i$ 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 $(C_1, C_2, \ldots, C_m)$ is formed as shown in Equation (10):

$$X_{ij} = \begin{bmatrix} X_{11} & X_{12} & \ldots & X_{1n} \\ X_{21} & X_{22} & \cdots & X_{2n} \\ \vdots & \vdots & \ldots & \vdots \\ X_{n1} & X_{n2} & \cdots & X_{nn} \end{bmatrix} \text{ for } \begin{array}{l} i = 1,2,\ldots,m \\ j = 1,2,\ldots,n \end{array} \tag{10}$$

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]:

$$X_{ij^*} = \frac{X_{ij} - \min\left(X_{ij}, i = 1,2,\ldots,m\right)}{\max\left(X_{ij}, i = 1,2,\ldots,m\right) - \min\left(X_{ij}, i = 1,2,\ldots,m\right)} \text{ for } \begin{array}{l} i = 1,2,\ldots,m \\ j = 1,2,\ldots,n \end{array} \tag{11}$$

$$X_{ij^*} = \frac{\max\left(X_{ij}, i = 1,2,\ldots,m\right) - X_{ij}}{\max\left(X_{ij}, i = 1,2,\ldots,m\right) - \min\left(X_{ij}, i = 1,2,\ldots,m\right)} \text{ for } \begin{array}{l} i = 1,2,\ldots,m \\ j = 1,2,\ldots,n \end{array} \tag{12}$$

$$X_{ij^*} = 1 - \frac{\left|X_{ij} - X_{dvj}\right|}{\max\left\{\max\left(X_{ij}, i=1,2,\ldots,m\right) - X_{dvj},\ X_{dvj} - \min\left(X_{ij}, i=1,2,\ldots,m\right)\right\}} \text{ for } \begin{array}{l} i = 1,2,\ldots,m \\ j = 1,2,\ldots,n \end{array} \tag{13}$$

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):

$$\Delta ij = \left|Xij* - X_{oj}\right| \text{ for } i = 1,2,\ldots m \quad j = 1,2,\ldots n \tag{14}$$

$$\gamma(X_{oj}, X_{ij^*}) = \frac{\min(\Delta ij, i=1,2,\ldots m; j=1,2,\ldots n) + \varsigma\max(\Delta ij, i=1,2,\ldots,m; j=1,2,\ldots,n)}{\Delta ij + \varsigma\max(\Delta ij, i=1,2,\ldots,m; j=1,2,\ldots,n)} \text{ for } \begin{array}{l} i = 1,2,\ldots,m \\ j = 1,2,\ldots,n \end{array} \tag{15}$$

where

$\gamma(X_{oj}, X_{ij^*})$ is the grey relational coefficient of alternative A_i for criterion C_j,

X_{oj^*} is the reference sequence for criterion C_j and takes the value of 1, and
ς 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):

$$\Gamma(X_i) = \sum_{j=1}^{n} W_j \gamma(X_{oj}, X_{ij^*}) \text{ for } i = 1, 2, \ldots, m \tag{16}$$

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):

$$Y_{ij} = \frac{\left|X_{ij} - X_{dvj}\right|}{\max\left(X_{ij}, i = 1, 2, \ldots, m\right) - \min\left(X_{ij}, i = 1, 2, \ldots, m\right)} \text{ for } \begin{array}{l} i = 1, 2, \ldots, m \\ j = 1, 2, \ldots, n \end{array} \tag{17}$$

$$X_{ij^*} = \frac{\max\left(Y_{ij}, i = 1, 2, \ldots, m\right) - Y_{ij}}{\max\left(Y_{ij}, i = 1, 2, \ldots, m\right) - \min\left(Y_{ij}, i = 1, 2, \ldots, m\right)} \text{ for } \begin{array}{l} i = 1, 2, \ldots, m \\ j = 1, 2, \ldots, n \end{array} \tag{18}$$

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):

$$Y_{ij} = \begin{cases} \frac{|X_{ij} - X_{maxopt}|}{\max(X_{ij}, i=1,2,\ldots,m) - \min(Xij, i=1,2,\ldots,m)} & , \text{where } X_{maxopt} < X_{ij} \leq max(X_{ij}, i = 1, 2, \ldots, m) \\ 0 & , \text{where } X_{minopt} \leq X_{ij} \leq X_{maxopt} \\ \frac{|X_{ij} - X_{minopt}|}{\max(X_{ij}, i=1,2,\ldots,m) - \min(X_{ij}, i=1,2,\ldots,m)} & , \text{where } min(X_{ij}, i = 1, 2, \ldots, m) \leq X_{ij} < X_{minopt} \end{cases} \tag{19}$$

where

X_{maxopt} represents the maximum value of the optimal data set, and
X_{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:

$$Y_{ij} = \begin{cases} \frac{|X_{ij} - X_{minopt}|}{X_{minopt} - \min(Xij, i=1,2,\ldots,m)}, \text{where} & \begin{matrix} min(X_{ij}, i = 1, 2, \ldots, m) < X_{minopt} < max(X_{ij}, i = 1, 2, \ldots, m) < X_{maxopt} \\ X_{ij} < X_{minopt} \end{matrix} \\ \frac{|X_{ij} - X_{maxopt}|}{\max(X_{ij}, i=1,2,\ldots,m) - X_{maxopt}}, \text{where} & \begin{matrix} X_{minopt} < min(X_{ij}, i = 1, 2, \ldots, m) < X_{maxopt} < max(X_{ij}, i = 1, 2, \ldots, m) \\ X_{ij} > X_{maxopt} \end{matrix} \end{cases} \tag{20}$$

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	N_2O and CH_4 emissions	9.70
		CO_2 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.) [1]	Rank (Ec. and Se.) [1]	Score (Env.) [2]	Rank (Env.) [2]	Score (Soc.) [3]	Rank (Soc.) [3]
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	0.2032	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 needs 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	0.008	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	0.055	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_2O, 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 Kingdom	0.063	0.061	0.031	0.010	0.014
United States	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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Conflicts of Interest: The authors declare no conflict of interest.

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 CO_2 equivalent per capita	N_2O emissions from energy-related processes on a per capita basis
IEN2	ton of CO_2 equivalent per capita	CH_4 emissions from energy-related processes on a per capita basis
IEN3	ton of CO_2 per capita	CO_2 emissions from solid fuel combustion on a per capita basis
IEN4	ton of CO_2 per capita	CO_2 emissions from liquid fuel combustion on a per capita basis
IEN5	ton of CO_2 per capita	CO_2 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.

Table A2. Academic sources used for determining indicators.

Code	Sources	Code	Sources	Code	Sources
IEC1	[42]	IEC8	[3,9,43,46]	IEN6	[44,45,72,73]
IEC2	[42]	IEC9	[9,43,46]	IEN7	[44,45,72,73]
IEC3	[42]	IEN1	[8]	ISO1	[42]
IEC4	[42,73]	IEN2	[8]	ISO2	[9]
IEC5	[42]	IEN3	[6]	ISO3	[9,42]
IEC6	[3,9,43]	IEN4	[6]	ISO4	[9,42]
IEC7	[9,43,46]	IEN5	[6]	ISO5	[9,42]

Appendix B

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

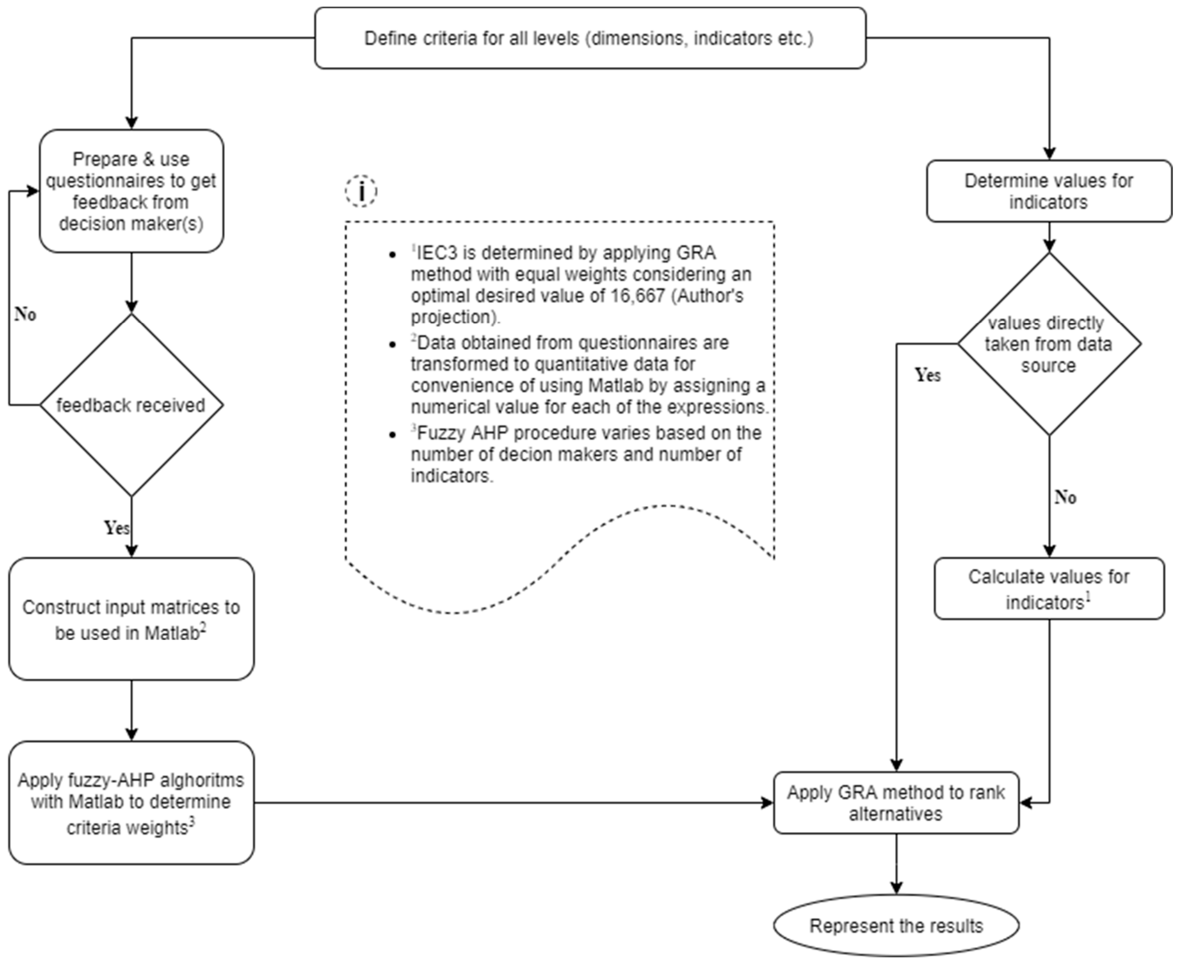

Figure A1. Flow chart of the overall procedure (Supplementary Materials).

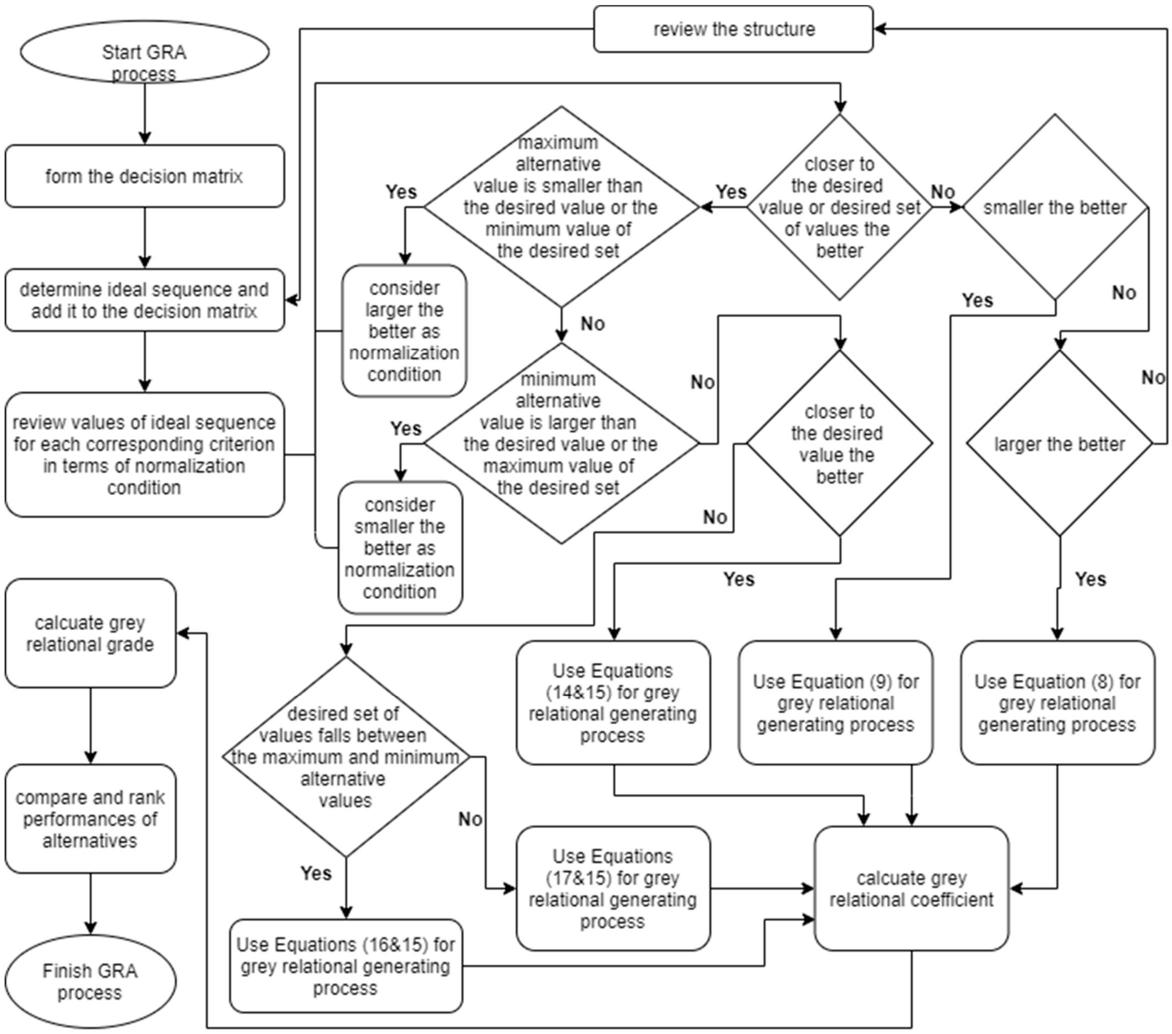

Figure A2. Flow chart of the revised and extended GRA procedure (Supplementary Materials).

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