



**MARMARA UNIVERSITY  
INSTITUTE FOR GRADUATE STUDIES  
IN PURE AND APPLIED SCIENCES**



**AN EXTENDED GREY RELATIONAL  
ANALYSIS METHOD: A CASE STUDY ON  
RANKING OVERALL ENERGY  
SUSTAINABILITY PERFORMANCES OF  
OECD COUNTRIES**

---

---

**KORAY ALTINTAŞ**

**Ph.D. THESIS**  
Department of Engineering Management

**Thesis Supervisor**  
Prof. Dr. Özalp VAYVAY

**ISTANBUL, 2021**

---

---



**MARMARA UNIVERSITY**  
**INSTITUTE FOR GRADUATE STUDIES**  
**IN PURE AND APPLIED SCIENCES**



**AN EXTENDED GREY RELATIONAL  
ANALYSIS METHOD: A CASE STUDY ON  
RANKING OVERALL ENERGY  
SUSTAINABILITY PERFORMANCES OF  
OECD COUNTRIES**

---

**KORAY ALTINTAŞ**

**(724814009)**

**Ph.D. THESIS**  
Department of Engineering Management

**Thesis Supervisor**  
Prof. Dr. Özalp VAYVAY

**ISTANBUL, 2021**

---

## **ACKNOWLEDGMENT**

I am incredibly grateful to all who have supported me in completing my Ph.D. thesis. I would like to express my sincere gratitude to my advisor Prof. Dr. Özalp Vayvay who inspired me and supported me during my Ph.D. studies. His motivation, inspiration, and guidance have been precious for me.

Associate Professor Sinan Apak deserves my deep appreciation for his continuous support in all stages during my Ph.D. thesis. Sincere thanks to him for spending countless hours when editing my studies and contributing to my thesis work with his extensive knowledge.

I would like to thank my thesis committee member Prof. Dr. Emine Cobanoglu for her helpful, collaborative, and positive approaches in each step of my thesis, journal article, and conference papers as well as her insightful comments.

Last but not the least, I would like to thank my family for supporting me faithfully throughout the thesis study and my life in general.

**March, 2021**

**Koray ALTINTAŞ**

# TABLE OF CONTENTS

ÖZET .....	iii
ABSTRACT.....	iiv
CLAIM FOR ORIGINALITY .....	v
SYMBOLS.....	vi
ABBREVIATIONS .....	vii
LIST OF FIGURES .....	viii
LIST OF TABLES.....	ix
1. INTRODUCTION .....	1
1.1. Background.....	1
1.2. Thesis Objective.....	1
1.3. Thesis Organization .....	2
2. LITERATURE REVIEW .....	3
2.1. Sustainability Indicators & Assessment.....	3
2.1.1. Types of sustainability indicators .....	4
2.1.2. Characteristics of sustainability indicators .....	6
2.1.3. Methodologies for developing sustainability indicators .....	7
2.1.4. Development of composite indicators .....	10
2.2. Energy Sustainability Indicators .....	11
2.3. Energy Sustainability Dimensions .....	12
2.4. Energy Sustainability Indices .....	18
2.4.1. Energy sustainability index (ESI) .....	20
2.4.2. Energy architecture performance index (EAPI) .....	20
2.4.3. Energy architecture performance index (EAPI) .....	21
2.4.4. Renewable energy responsible investment index (RERII) .....	21
2.4.5. Synthetic index of sustainable energy development (SISED) .....	22
2.4.6. World energy trilemma index .....	23
2.4.7. Energy development index (EDI) .....	23
2.4.8. Multidimensional energy poverty index (MEPI).....	23

2.4.9. Sustainable energy index (ENDX).....	24
2.4.10. The International Index of Energy Security Risk .....	24
2.4.11. Sustainable energy security (SES) index .....	25
2.4.12. Energy security index .....	26
2.4.13. Energy technology sustainability index (ETSI) .....	27
2.4.14. Energy index .....	27
2.4.15. Sustainability index.....	29
2.4.16. Combined Sustainability Index.....	30
2.5. Multi-criteria Decision Making Process .....	32
2.5.1. MCDM Classification.....	33
2.5.2. MCDM Methods.....	34
3. CASE STUDY .....	39
3.1. Research Methodology .....	39
3.1.1. OESI.....	39
3.1.2. Fuzzy AHP.....	44
3.1.3. GRA .....	46
3.1.3.1. Overview of GRA.....	46
3.1.3.2. The Discussion for GRA.....	51
3.1.3.3. Revised and Extended GRA Normalization Procedure .....	52
3.2. Representation and Analysis of Results.....	56
4. CONCLUSION.....	66
4.1. Managerial Implications of the Research .....	67
4.2. Limitations of the Research .....	68
4.3. Further Research .....	68
REFERENCES .....	69
APPENDICES .....	83
APPENDIX A.....	83
APPENDIX B .....	86
APPENDIX C .....	98
APPENDIX D.....	103
APPENDIX E .....	110
CV.....	145

## ÖZET

# GENİŞLETİLMİŞ GRI İLİŞKİSEL ANALİZ METODU: OECD ÜLKELERİNİN ENERJİ SÜRDÜRÜLEBİLİRLİĞİ PERFORMANSLARININ KARŞILAŞTIRILMASI ALANINDA VAKA ÇALIŞMASI

İnsanoğlu kaynakların tükenmesi, sosyal eşitsizlikler, enerji kaynaklarına ulaşımında sıkıntılar, ve çevresel kaygılar gibi global problemlerin olduğu bir çağda yaşamaktadır. Bu durum araştırmacıların sürdürülebilirlik ve birbiriyle çelişen ihtiyaçlarda dengenin nasıl sağlanabileceğine dair çalışmalar yapmasını da beraberinde getirmiştir. Ancak sürdürülebilirlik konseptinin kompleks ve çok boyutlu olması nedeni ile bu araştırmacılar için zor bir görev olmuştur. Dolayısıyla, sürdürülebilirliğin değişik alanlarında yapılan ilerlemelerin ölçülmesi büyük önem arz etmektedir. Uygulamaya bağlı olarak, çok kriterli karar verme yöntemleri alternatifler arasında karşılaştırma yapmak ve en ideal alternatifi bulmak gibi alanlarda oldukça yaygın bir şekilde kullanılmaktadır. Bu konu özellikle enerji sürdürülebilirliği açısından ülkelerin birbiri ile karşılaştırılması noktasında önemlidir. Ülkeleri, önceden belirlenmiş değişik kriterleri göz önünde bulundurarak birbiri ile karşılaştırabilen indeksler hem araştırmacılara hem de politika yapıcılara yararlı araçlar olarak karşımıza çıkmaktadır. Bu noktada, bulanık mantık ortamında analitik hiyerarşi prosesi modeli ile entegre edilmiş gri ilişkisel analiz yönteminin revize edilmiş ve genişletilmiş versiyonunu kullanarak 35 OECD ülkesinin enerji sürdürülebilirliğini inceleyen bir indeks çalışması ortaya koyduk. Bu çalışmanın amacı hali hazırda mevcut olan gri ilişkisel analiz normalizasyon prosedürüne eklemeler ve revizyonlar yaparak değişik ülkelerin enerji sürdürülebilirlik performanslarını ölçebilecek bir yöntem sunmaktır. Önerilen yöntem yapısı gereği sürdürülebilirliğin değişik alanlarında da uygulanabilir.

**Anahtar Kelimeler:** Enerji sürdürülebilirliği; çok kriterli karar verme teknikleri; bulanık mantık ortamında analitik hiyerarşi prosesi; indeks; OECD ülkeleri; izleme aracı

## **ABSTRACT**

### **AN EXTENDED GREY RELATIONAL ANALYSIS METHOD: A CASE STUDY ON RANKING OVERALL ENERGY SUSTAINABILITY PERFORMANCES OF OECD COUNTRIES**

We are living in an age where major global issues like depletion of sources, social inequity, lack of energy accessibility and environmental concerns began to draw more and more attention. This have triggered numerous researches on sustainability and how to achieve it by focusing on solutions to balance the fine line between competing needs. However, it has been a tough task due to the complex and multidimensional nature of sustainability. Therefore, it is vital to determine methods to measure the progress of human action towards sustainable development in different areas of sustainability. Depending on the application, multi-criteria decision-making methods have been widely used for making comparisons between alternatives and finding the optimum one among them. This has been an interesting research topic for comparing the performances of different countries from energy sustainability point of view. Developing an index that allows to compare countries depending on their performances for various criteria can be a useful tool for researchers and policy makers. We have proposed an extended and revised version of the grey relational analysis method, which is integrated with the fuzzy analytic hierarchy process to develop a new composite index for comparing the overall energy sustainability performances of 35 OECD member countries. The aim of this dissertation is to introduce new extensions to the current grey relational analysis normalization procedure to capture overall energy sustainability performances of different countries. Proposed method can be used in different applications of sustainability due to its flexible nature since it provides benefits from goal-oriented extensions to capture different aspects of sustainability.

**Keywords:** Overall energy sustainability; multi-criteria decision-making; fuzzy analytic hierarchy process; extended grey relational analysis; composite index; OECD member countries; monitoring tool

## **CLAIM FOR ORIGINALITY**

I hereby declare that this submission is my own work and to the best of my knowledge it contains no materials previously published or written by another person. Any contribution made to the research by others, with whom I have worked at Marmara University or elsewhere, is explicitly acknowledged in the thesis. I also declare that the intellectual content of this thesis is the product of my own work, except to the extent that assistance from others in the project's design and conception or in style, presentation and linguistic expression is acknowledged.



## SYMBOLS

<b>C</b>	: Cost
<b>D</b>	: Consumption
$\tilde{F}_i$	: Fuzzy weight
$\tilde{G}_i$	: Geometric mean value of triangular fuzzy numbers
[k]	: Optional scalar adjustment
<b>O</b>	: Economic output
$\tilde{R}$	: Reciprocal of the sum of the geometric mean of fuzzy comparison values
<b>S</b>	: Sufficiency
<b>S<sub>a</sub></b>	: Cumulative score of an existing alternative evaluated over the considered wide range of criteria
<b>S<sub>i</sub></b>	: Cumulative score of the ideal alternative evaluated over the considered wide range of criteria.
<b>W<sub>i</sub></b>	: Weight
<b>X<sub>ij</sub>*</b>	: Normalized data
<b>X<sub>oj</sub>*</b>	: Reference sequence
<b>Y<sub>ij</sub></b>	: Pre-normalization value
$\gamma(\mathbf{X}_{oj}, \mathbf{X}_{ij}^*)$	: Grey relational coefficient
$\varsigma$	: Identification coefficient
$\Gamma(\mathbf{X}_i)$	: Grey relational grade

## **ABBREVIATIONS**

**AHP:** Analytical Hierarchy Process

**DEMATEL:** Decision Making Trial and Evaluation Laboratory

**DPSIR:** Driving Force Pressure State Impact Response

**EAPI:** Energy Architecture Performance Index

**EEA:** European Environmental Agency

**EDI:** Energy Development Index

**ELECTRE:** Elimination Et Choice Translating Reality

**ENDX:** Sustainable Energy Index

**ESI:** Energy Sustainability Index

**ESSD:** Environmentally Sound and Sustainable Development

**ETSI:** Energy Technology Sustainability Index

**GDP:** Gross Domestic Product

**GRA:** Grey Relational Analysis

**MCDM:** Multi-criteria decision making

**MEPI:** Multidimensional Energy Poverty Index

**OECD:** Organization for Economic Co-operation and Development

**OESI:** Overall Energy Sustainability Index

**PROMETHEE:** Preference Ranking Organization Methods for Enrichment Evaluation

**PSR:** Pressure-State-Response

**RERII:** Renewable Energy Responsible Investment Index

**SEDI:** Sustainable Energy Development Index

**SES:** Sustainable Energy Security

**SISED:** Synthetic Index of Sustainable Energy Development

## **LIST OF FIGURES**

**Figure 2.1.** Characteristics of ESSD Indicators

**Figure 2.2.** Interconnections within DPSIR

**Figure 2.3.** Steps to develop a composite indicator

**Figure 2.4.** Aspects and indicators of RERII

**Figure 2.5.** Energy Sub-systems

**Figure 2.6.** Schematic representation of Energy Index

**Figure 2.7.** Computation of Energy Index

**Figure 2.8.** Criteria used for choosing energy efficiency measures

**Figure 2.9.** Stages of MCDM

**Figure 2.10.** Classification of MCDM Methods

**Figure 2.11.** Advantages & disadvantages of MCDM methods

**Figure 2.12.** MCDM methods in the sub-area of energy sustainability

**Figure 3.1.** Graphical representation of normalization procedure for all the optimal values lies between the maximum and minimum alternative values.

**Figure 3.2.** Graphical representation of normalization procedure for the set of optimal values includes the minimum or maximum alternative value and not the other.

**Figure A.1.** SDFS Flow chart of the overall procedure

**Figure A.2.** Flow chart of the revised and extended GRA procedure

## **LIST OF TABLES**

**Table 2.1.** Types of sustainability indicators

**Table 2.2.** Frameworks and their limitations

**Table 2.3.** Categorizing research based on energy sustainability indicators/sub-indicators (economic, environmental, and social dimensions)

**Table 2.4.** Categorizing research based on energy sustainability indicators/sub-indicators (other dimensions)

**Table 2.5.** Energy sustainability indices based on their application areas

**Table 2.6.** Energy technology sustainability dimensions and related indicators

**Table 2.7.** Sustainability index based on weighted sums

**Table 3.1.** Issues to be addressed in OESI

**Table 3.2.** Criteria for indicator selection

**Table 3.3.** Hierarchical structure of the OESI

**Table 3.4.** Units and brief descriptions of indicators

**Table 3.5.** Relevance of indicators

**Table 3.6.** Academic sources used for determining indicators for OESI

**Table 3.7.** Impact of each indicator value on OESI

**Table 3.8.** Sub-indicators for calculating IEC3 (closer to the desired value the better)

**Table 3.9.** Linguistic terms and corresponding triangular fuzzy numbers

**Table 3.10.** GRA studies between 2010 – 2020

**Table 3.11.** Different scenarios and equations to be applied

**Table 3.12.** Representation of different functions (max is better)

**Table 3.13.** Indicator weights

**Table 3.14.** Criteria weights

**Table 3.15.** OESI results

**Table 3.16.** Weighted indicator values (economic and security dimension)

**Table 3.17.** Weighted indicator values (environmental)

**Table 3.18.** Weighted indicator values (social)

**Table 3.19.** Results of OESI (with two functions)

**Table 3.20.** Sub-indicator values (single function case)

**Table 3.21.** Sub-indicator values (two functions case)

**Table C.1.** Sub-indicator values (two functions case)

**Table C.2.** Pre-normalization step

**Table C.3.** Normalization step

**Table C.4.** Absolute value of the difference

**Table C.5.** Grey Relational Grade

**Table D.1.** Data source for indicators

**Table D.2.** Steps to calculate IEN1

**Table D.3.** Steps to calculate IEN2

**Table D.4.** Steps to calculate IEN3

**Table D.5.** Steps to calculate IEN4

**Table D.6.** Steps to calculate IEN5

**Table D.7.** Steps to calculate IEC3

# **1. INTRODUCTION**

## **1.1. Background**

Energy is a vital element to improve economic and social wellbeing in a country and therefore plays a major role in today's modern life (Lu et al., 2020). It is a global commodity and serves as a cornerstone for socio-economic development. The ability of providing energy services based on the principles of sustainability has a significant importance (Vera and Langlois, 2007). Sustainability is a dynamic, and a multidimensional concept depending on context-specific and long-term goals. Overall energy sustainability is achieved by providing affordable, accessible, and reliable energy services in an environmentally-sound manner by taking necessary requirements of economic and social development for present as well as future generations into account (Rosen, 2009; Cîrstea et al., 2018; Mog, 2004).

It is important to find a way to represent the performance of a country from the overall energy sustainability perspective to make comparisons in a systematic way. This would allow to monitor any progress easily to make policies. Therefore, compiling data into a single metric based on a pre-determined underlying model is the way for measuring overall energy sustainability, and in this regard, multi-criteria decision-making (MCDM) methods provide promising opportunities (Bertoni, 2019; Sahin, 2020).

It is possible to define MCDM as a branch of operational research dealing with finding optimal results in complex scenarios including various indicators, conflicting objectives, and criteria. This tool has gained popularity in recent years in the field of energy planning due to the flexibility it provides to decision makers which allows them to take decisions while taking all the criteria and objectives into account simultaneously (Kumar et al., 2017).

## **1.2. Thesis Objective**

In this thesis, a new overall energy sustainability index (OESI) is proposed for comparing the performances of 35 OECD member countries. OESI is based on the grey relational analysis (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 objective of this thesis is to introduce revisions and extensions on normalization of GRA method to meet the goals of overall energy sustainability. It provides promising opportunities to be used in other applications of sustainability, due to its flexible nature. It will be useful for policy makers and researchers to obtain a snapshot of a country's performance on energy sustainability and will allow them to determine, develop, and implement policies.

### **1.3. Thesis Organization**

The structure of the thesis is arranged in a way where the literature review is presented to provide background information about energy sustainability, then methodology is provided to show how the method has been developed and the case study has been revealed to indicate the results.

In the part of literature review, the concept of sustainability and its necessity to use indicators for measuring it have been discussed. The types as well as characteristics of sustainability indicators and existing methodologies for developing have been given in this chapter. Indicators, dimensions, and indices have been also evaluated in detail from energy sustainability point of view. Additionally, while the information on MCDM methods and process have been given, the method to be focused (GRA) has been described individually.

The methodology part consists of 3 different sections. The first part is all about the index to be created (indicators, criteria, dimensions, weights etc.). In the second part the procedure of the fuzzy AHP method used in this thesis have been provided. The last step is where GRA is evaluated in detail. The existing, revised, and extended versions of the normalization procedure of GRA has been given.

Lastly, in the part of case study, all the results have been provided with tables. This makes it possible to reveal the weaknesses and strength of different countries in different areas. All calculated criteria weights, and scores for each indicator can be found in this section. The means of doing it such as the codes are provided in appendices.

## **2. LITERATURE REVIEW**

### **2.1. Sustainability Indicators & Assessment**

Quantitative data have been used by scientists and experts for measuring any type of condition which makes it possible to compare data in a systematic way. For instance, stock indices and gross domestic product (GDP) can be given as important examples which are used by economists. Another example would be the Human Development Index that is created by United Nations for ranking countries based on their economic, health and education attainment measures by considering various indicators such as life expectancy and literacy. Using numerical measures is the reliable way to reduce complex problems or situations into simpler ones and indicators play an important role for transforming complex data into a form that is much simpler and usable. This enables scientists to see the whole picture of the situation and to develop research strategies based on the data (Brown and Sovacool, 2007).

In terms of energy sustainability indices, it is significant to reflect the resources that are consumed for meeting current energy demands while also including the ability of future generations to meet their needs. This can be quantified by using total energy consumption per capita or energy use per GDP, which are considered as measures of energy intensity or energy productivity that can recognize the correlation between energy use and level of economic activity. Furthermore, there are various discrete indicators defined in the literature that can be useful. It is important to find a way to reduce these indicators into one metric, so that it becomes possible to reflect all dimensions in a single index value (Brown and Sovacool, 2007).

Sustainability indicators can be considered as a tool that reveals how well a system is working to meet the previously determined goals and therefore progress towards sustainability can also be monitored by reviewing any change in indicator values in a certain time period.

The question of how to identify sustainability indicators triggered researchers to guide. For example, Hardi and Zdan (1997) suggested to use guidelines, which is also known as the Bellagio principles, for the whole of the assessment process including the system design and identification of indicators as well interpretation and communication of the result. Since these indicators are interconnected, it is required to apply them as a complete set. Another example would be the

indicator set proposed by Kemmler and Spreng (2007) that is based on a pragmatic notion of sustainability, in which it is vital to give equal consideration and weight to economic, social, and environmental aspects for assuring sustainability. In other words, course of action taken for economic development that omits social and environmental aspects is unsustainable.

Although it is not possible to indicate a standardized or a commonly accepted methodology for choosing sustainability indicators, some steps are usually mentioned in the literature. For instance, Bossel (1999) stated that the indicator set must encompass the visions as well as the values of the community for which it is developed. Indicators should be clear, practical, and reproducible, which allow deduction of the viability and sustainability of the developments. A framework, process and criteria are also required to find the adequate set of indicators.

It is significant to develop a framework that addresses issues identified which are relevant in the context of sustainable development. Developing such a framework makes it possible to organize as well as to link an entire sustainable development information system. The utility as well as the quality of the proposed indicators are also highly dependent on the context and the use to which they are put (Goldblatt et al., 2000; Kemmler and Spreng, 2007; Bossel, 1999). The framework that is developed must reflect the vision that will be put. It must be designed in a way that the balance between different dimensions must be considered.

### **2.1.1. Types of sustainability indicators**

Different type of indicators has been introduced in the literature. Table 2.1 below is given for providing as an example for such indicators. As observed in this table, different studies provide different kind of categories for indicators. Iddrisu and Bhattacharyya (2015) have reviewed indicator from structure point of view. Thus, they categorized indicators as single, dashboard and composite. On the other hand, in the work of Patlitzianas (2008) indicators are categorized based on descriptions. So, various methodological categorizations have been developed. Based on these facts, it is possible to claim that the type of indicators is also based on point of view of researchers, and they are dependent on the type of the research that is conducted. Furthermore, the application that has been evaluated may also play a role in determining such categorizations in each research.

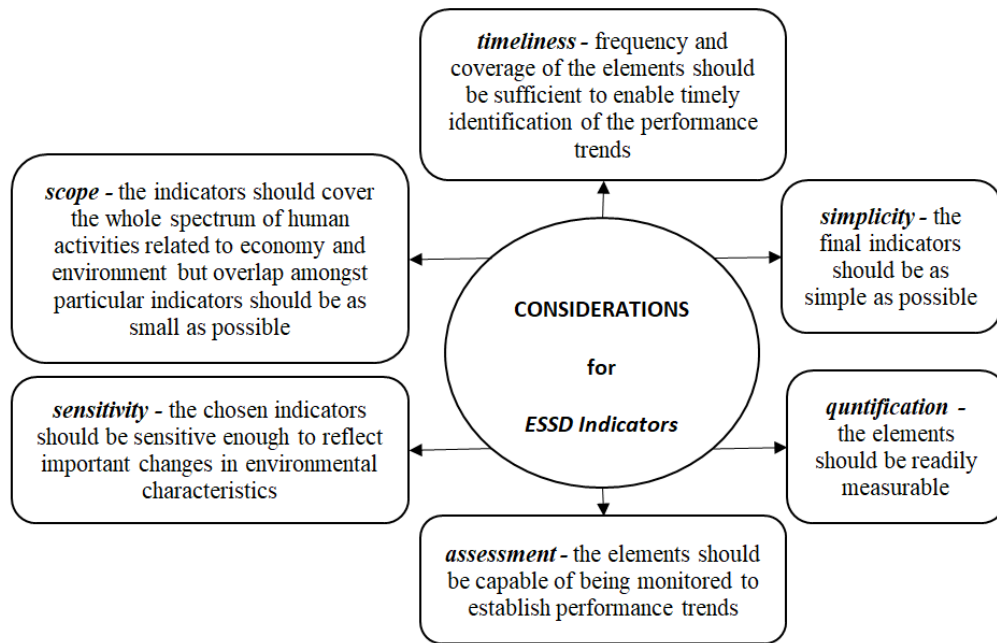
**Table 2.1.** Types of sustainability indicators.

<u>SOURCE</u>	<u>CRITERIA</u>	<u>BRIEF EXPLANATION</u>
<i>Iddrisu and Bhattacharyya (2015)</i>	Single Indicators	Single indicators are unidimensional point values that are simple to interpret. However, using them can result with leaving vital information. This makes these indicators unsuitable for measuring multidimensional issues, even though they are less susceptible to errors like weighting subjectivity biases that are encountered in some composite indices.
	Dashboard Indicators	Since the developmental issues are complex and the use of several variables to capture different components of interactively distinct dimensions is required, dashboard indicators have been suggested to deal with such issues.
	Composite Indices	Composite indices are simple values that can be easily interpreted like unidimensional indicators, but they are also able to capture the multidimensionality of the issue. By using composite indices, it is possible to minimize the pool of information which would have been provided by many dashboard indicators to a level that makes analysis convenient.
<i>Patlitzianas et al. (2008)</i>	Descriptive Indicators	The example of the ratio of energy per fuel was given for descriptive indicators. It would show the mixture of supplies used to provide energy in a community.
	Basic Normalized Indicators	They illustrate the total energy use of per population or GDP.
	Comparative Indicators	Comparative indicators illustrate the similarities of characteristics between various countries by using required normalizations.
	Intensity Indicators	The use of energy for a specific activity
	Decomposition Indicators	Decomposition indicators illustrate how different sections of total use of energy influence the total releases.
	Casual Indicators	Casual indicators illustrate which kind of fundamental economic, demographic, or geographical parameters influence most the use of energy.
	Consequential indicators	The connection between the human activities and the use of energy in terms of any negative effect on environment was provided as an example for consequential indicators. They can be useful to emphasize the consequences of any activity on social and economic as well as environmental dimensions.
Physical indicators	Physical indicators illustrate the change in energy performance and productivity.	

### 2.1.2. Characteristics of sustainability indicators

Assessing as well as evaluating current performance, anticipating trends for improvement, ensuring the prevention of economic, environmental, and social damage by providing early information and supporting decision-making by providing necessary information to develop strategies are the application areas of sustainability indicators (Singh et al., 2009). It is a must for sustainable indicators to point to areas where connections between society, environment and economy are in the weakest level and to areas that reflect that there is a strong connection between economy, society, and environment (Olsson et al., 2004).

When generating a suitable list of indicators, which can then be used to measure total sustainability, it is important to take specific considerations into account. These considerations then form the main characteristics of sustainability indicators. Harger and Meyer (1996) provided selection criteria for environmentally sound and sustainable development (ESSD) indicators. Basic features for ESSD indicators based on the work of Harger and Meyer (1996) are provided in Figure 2.1.



**Figure 2.1.** Characteristics of ESSD Indicators.

### **2.1.3. Methodologies for developing sustainability indicators**

A sustainable development indicator framework is needed for bringing the social, economic, and environmental aspects of society together and for emphasizing any interconnection between these aspects (Olsson et al., 2004) in ways which are useful for decision makers. Moreover, making decision makers to understand the interlinkages between various issues enable them to determine, develop policies which solve problems at suitable levels (Linster and Fletcher, 2001).

Even tough frameworks and models are fundamental tools to develop and select indicators, they can be too strict in their analysis of issues and interactions. Thus, they must be used in a way, that ensures flexibility by allowing additional information to support them. Moreover, it is possible to benefit from multiple models in different cases. For instance, OECD benefits from PSR framework for its work on the core set of environmental and sectoral indicators, on the other hand it also benefits from accounting frameworks for developing indicators on the use of natural resources (Linster and Fletcher, 2001).

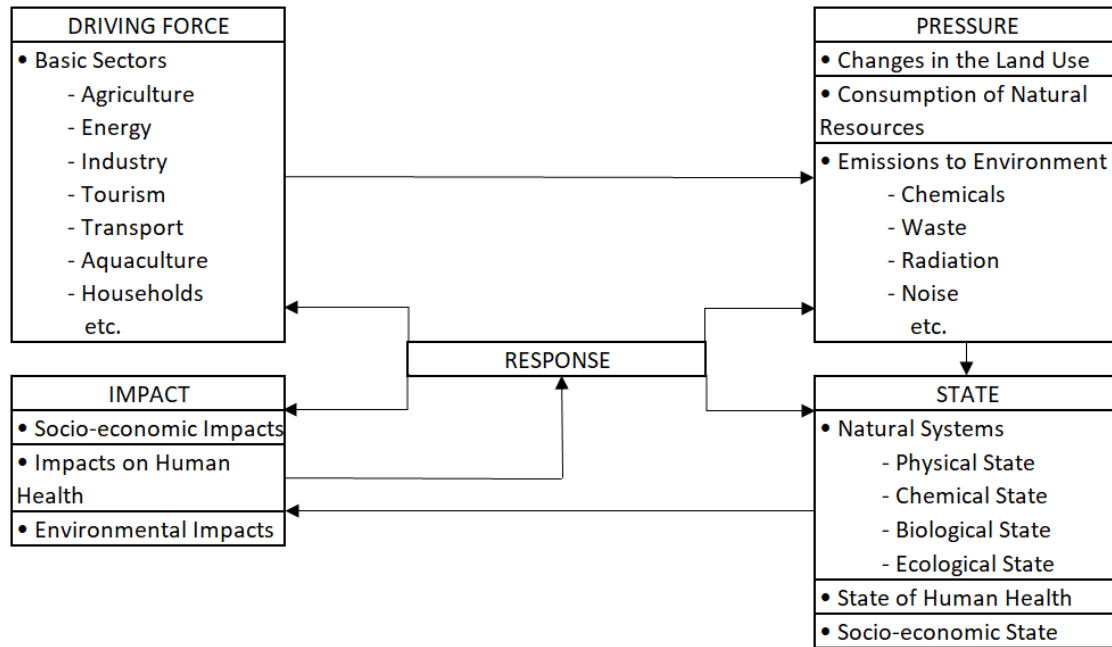
Reasons such as diversity of core values and indicator processes have led to the development as well as application of various frameworks. The major differences between these frameworks are the ways in which they form a concept of the important dimensions/aspects of sustainable development, the interconnections among these dimensions/aspects, the way they form a group the issues to be measured and the concepts by justifying for selection and aggregation of indicators (The Department of Economic and Social Affairs of the United Nations, 2007).

Causal-based frameworks present the notion of cause-and-effect relationships among indicators. One of the widely accepted casual framework is the pressure-state-response (PSR) (Nathan and Reddy, 2008), which is a simple tool to formalize problems regarding environment (Levrel et al., 2009). It is based on the concept of causality that implies any activity causing pressure on the environment (Singh et al., 2009) and changes its environmental conditions or the state of the environment. This pressure caused by the human activities is occurred due to the harmful activity itself such as discharging of pollutants and waste materials, modifying natural habitats, and changing landforms. The response from the society is to make changes through environmental, and economic policies and regulations or initiate any other corrective actions like awareness and

behavior for alleviating these negative effects (Neri et al., 2016; Organisation for Economic Co-operation and Development, 2001). These steps (pressure, state, and response) form part of an environmental (policy) cycle that consists of problem perception, policy formulation, monitoring, and policy evaluation (Organisation for Economic Co-operation and Development, 1993).

Driving Force Pressure State Impact Response (DPSIR) model is an extension to PSR framework (Singh et al., 2009). Driving force indicators are used to determine socio-economic requirements and to identify any motivation which triggers the existence of human activity. They lead to activities that are necessary to meet human needs. These processes cause pressures on environment by affecting the quality of different environmental compartments. These changes in the “state” may result with any “impact” on the human health as well as the economic and social performance of the society, which leads to “responses” coming from society and policy makers to improve the system concerning not just the environment but also socio-economic aspects (Kristensen, 2004; Martins et al., 2012).

DPSIR is also a handy tool to demonstrate any links between its elements (driving force, pressure, state, impact, and response). For example, Kristensen (2004) stated that the relationship between the driving force and pressure based on economic activities can be illustrated as a function of eco-efficiency of the systems that are used. If there is an improvement in eco-efficiency, it is expected to have less pressure coming from driving forces. These interconnections are illustrated in Figure 2.2 that is developed based on (Kristensen, 2004; Shah, 2000; Martins et al., 2012). Another research undertaken by Dzoga et al. (2020) benefits from DPSIR framework to identify issues related with coastal and marine fisheries, which were determined as harmful human activities due to excessive mining and agriculture operations in the region. Based on this research it is concluded that additional policies must be introduced to improve the existing regulations for natural resource management. It shows that DPSIR is a strong tool for identifying main triggers of environmental issues and helps decision makers to understand the relationship between cause and effects in detail. This would lead to more accurate policy development and change in the regulations if it is required to do.



**Figure 2.2.** Interconnections within DPSIR.

In issue or theme-based frameworks, indicators are distinguished based on various themes and issues relating to sustainable development. These issues and themes within the frameworks are identified in accordance with the policy relevance and the indicators developed are goal driven. Connecting indicators to policy processes and targets makes it available to send a clear message to decision-makers and facilitates both communicating with and raising the public awareness. The frameworks are well suited to monitor any progress in achieving the objectives and goals and provide adequate flexibility to adapt to new priorities and policy objectives over time. Theme-based frameworks are widely used by different countries which have developed sustainable development indicators based at national level. In addition to that there are regional strategies and indicator programs such as the Baltic 21 Action Program, which benefit from such frameworks (Nathan and Reddy, 2008; The Department of Economic and Social Affairs of the United Nations, 2007).

In the case of capital approach frameworks, the national wealth is calculated as a function of the sum of different kinds of capital including financial, human, social, natural, and institutional. Since different forms of capital are taken into consideration, common terms such as monetary terms are required to express these various capitals (The Department of Economic and Social Affairs of the United Nations, 2007). The capitals used in the framework can differ based on the

application that is used. For example, in the study by Wu and Tsai (2014), an inclusive concept of human-made capital was introduced to present human, physical, and social dimensions as a complete capital for investigating their interactions of these sub-capitals with natural capital. Frameworks and their constraints are illustrated in Table 2.2.

**Table 2.2.** Frameworks and their limitations.

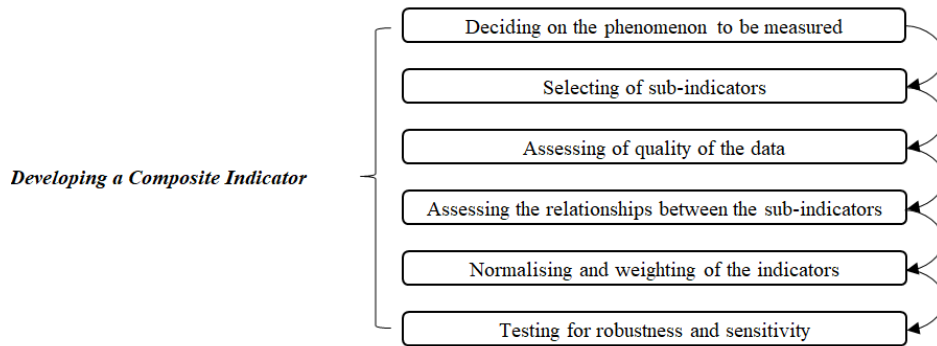
Frameworks	Limitations
Causal-Based	There are uncertainties over causal linkages and inconsistencies in determining whether an indicator is a driving force, pressure, or state, because the focus of the viewer may change depending on the underlying objective (Nathan and Reddy, 2008).
Issue or Theme-Based	Being goal-oriented may result with ignoring the multi-dimensional holistic nature of sustainable development (Nathan and Reddy, 2008).
Capital-Based	Expressing all forms of capital in monetary terms can lead to disagreements, which can make these frameworks inherently debatable (The Department of Economic and Social Affairs of the United Nations, 2007; Nathan and Reddy, 2008).

#### 2.1.4. Development of composite indicators

A sustainable development indicator framework is needed for bringing all aspects of society together and for emphasizing the interconnections between these aspects (Olsson et al., 2004) in ways which are useful for both decision makers. Moreover, making decision makers understand the interlinkages between various issues enable them to determine, develop and implement policies which address problems at the suitable levels (Linster and Fletcher, 2001).

Individual indicators form a composite indicator when they are compiled into a single index based on an underlying model. Multidimensional concepts should ideally be measured with composite indicators which is not possible to be captured by a single indicator (Organization for Economic Co-operation and Development, 2008). Since the development of (composite) indicators is a complex process, different aggregation methods are introduced. Moreover, sub-

indicators do not have any common measurement unit of measurement which makes it difficult to assign weights (Singh et al., 2009). The steps for developing composite indicators are indicated by Figure 2.3.



**Figure 2.3.** Steps to develop a composite indicator

## 2.2. Energy Sustainability Indicators

Energy is one of the essential components of modern human lifestyle. It is an entity that is used by every living person on the planet either directly or indirectly. It is used to power vehicles, light workplaces, produce food, manufacture as well as distribute products (Brown, and Sovacool, 2007). Energy plays a key role for improving social and economic wellbeing and it is imperative to most wealth creation. It is critical for reducing poverty, improving living standards and prosperity (Škobalj et al., 2017). To sum up, energy is something that mankind needs in all aspects of the modern life, since the roots of modern society highly depends on the capability to harness energy that is needed for development as well as prosperity.

It is vital to provide policies which ensure basic energy demands while protecting the environment and avoiding autonomous growth of some sectors compared to others that may cause social inequality locally. To achieve sustainable economic development, it is necessary to be reasonable on the use of resources, technology, suitable economic incentives, and strategic policy planning both at local as well as national levels. Within this scope, it is needed to have a vision for energy development in a sustainable manner considering all dimensions. Consequently, it is required to determine criteria for guiding decision makers to identify better ways to provide sustainable energy for different scales of communities. Sustainability indicators are flexible tools for decision makers and analysts to monitor the impacts of recently developed

policies as well as the potential impacts of changes in those policies (Candido and Cavalcanti, 2016; Škopalj et al., 2017).

Policy makers require ways for measuring and assessing any effect of energy consumption on society, air, water, soil, and health. It is essential for them to be aware of the status of their country regarding energy sustainability, to determine how to make improvements to the current situation. For that matter, indicators are useful for tracking any progress achieved to meet goals determined by the policy makers. For instance, analyzing indicators which are related to energy use, efficiency, population, and economic growth, and identifying all the factors that are most responsive to a potential policy change would be a key factor to understand the level of success in limiting emissions caused by the energy sector (Vera and Langlois, 2007). With respect to the study of Afgan et al. (2000), the set of indicators was defined to demonstrate the decision-making procedure for energy system assessment.

### **2.3. Energy Sustainability Dimensions**

According to Rennings and Wiggering (1997), there are three different management rules of resource use in terms of sustainability. These can be listed as follows:

- i. ensuring harvest rates of renewable resources do not exceed regeneration rates,
- ii. ensuring waste emissions do not exceed relative assimilative capacities of ecosystems,
- iii. exploiting non-renewable resources in a quasi-sustainable manner by limiting their rate of depletion to the rate of creation of renewable substitutes.

It is important for any country to sustain its welfare to future generations through respecting sustainable development goals. There must not be negative effects on environment and society while increasing welfare. This makes issue-based sustainability problems important. The sustainability concept should be assessed from energy point of view. Energy sustainability is defined as providing affordable, accessible, and reliable energy services that meet the economic, social, and environmental needs within the overall developmental context of the society for which the services are intended, while recognizing equitable distribution in meeting those needs. (Vidadili et al., 2017; Davidson and Sparks, 2002; Oyedepo, 2012).

Producing, transporting, and consuming energy create pressures on the environment. The impacts due to energy consumption can occur at all levels (household, workplace, community, national, regional, and global) (Vera and Langlois, 2007). Moreover, it is required to consider how production and consumption process affects health and well-being of people and to determine the level of generating jobs and income. These are all related with the three dimensions (economic, social, and environmental) of energy sustainability. Economic dimension identifies the profit rate of productive activity. Social dimension is checked by determining basic levels of requirements and lastly the environmental dimension is identified by deterioration level of environment due to energy use (Candido and Cavalcanti, 2016). Table 2.3 is created by reviewing 20 different studies conducted on energy sustainability, shows research based on energy sustainability indicators/sub-indicators including dimensions of economic, environmental, and social. Furthermore, other dimensions mentioned in these studies are indicated by Table 2.4.

Energy sustainability also deals with two-way problems such as the one with the well-being of people. Although providing energy for communities is an environmentally degrading process which affect human well-being from health point of view, there can be consequences of not providing energy services to people. Lack of access to energy services may cause physical problems in human health. Such a dilemma also exists in different occasions such as creating additional jobs. Increasing energy production facilities may also harm the number of existing jobs in a community.

By analyzing the scores of energy sustainability dimensions, it is possible to understand the weight of the balance that must be achieved to meet the goals of energy sustainability. This allows decision makers to see the bigger picture that can be provided by energy sustainability indicators. It is also important to consider the underlying model of each dimension since different techniques for aggregation of indicators can be used for each dimension. In such cases, it is important to find out which indicators/criteria play the major role and if they are independent from any other criteria especially belonging to any other dimension. If so, any alteration on that indicator may cause huge differences in the balance between the dimensions, which can make the assessment of dimension scores more complex.

**Table 2.3.** Categorizing research based on energy sustainability indicators/sub-indicators (economic, environmental, and social dimensions).

<b><i>Indicators</i></b>	<b><i>Researches</i></b>	
<b>Economic</b>	Afgan et al. (2000)	Begic and Afgan (2007)
	Vera and Langlois (2007)	Afgan and Carvalho (2008)
	Neves and Leal (2010)	Tsai (2010) [economic pressure]
	Abouelnaga et al. (2010) [economical]	Streimikiene and Sarvutyte (2010)
	Martchamadol and Kumar (2013)	Liu (2014)
	Maxim (2014)	Luthra et al. (2015)
	Mainali and Silveria (2015)	Lee and Zhong (2015)
	Iddrisu and Bhattacharyya (2015) Škobalj et al. (2017)	Candido and Cavalcandi (2016)
<b>Environmental</b>	Afgan et al. (2000) [environment]	Afgan and Carvalho (2004) [environment]
	Begic and Afgan (2007) [environment]	Vera and Langlois (2007)
	Afgan and Carvalho (2008) [environment]	Patlitzianas et al. (2008) [environmental protection]
	Abouelnaga et al. (2010)	Neves and Leal (2010)
	Tsai (2010) [environmental quality]	Onat and Bayar (2010) [environmental influence]
	Streimikiene and Sarvutyte (2010)	Martchamadol and Kumar (2013)
	Maxim (2014)	Liu (2014)
	Luthra et al. (2015)	Mainali and Silveria (2015)
	Lee and Zhong (2015) Candido and Cavalcandi (2016)	Iddrisu and Bhattacharyya (2015) Škobalj et al. (2017)
<b>Social</b>	Afgan et al. (2000)	Afgan and Carvalho (2004)
	Begic and Afgan (2007)	Vera and Langlois (2007)
	Afgan and Carvalho (2008)	Onat and Bayar (2010) [social influence]
	Tsai (2010) [social pressure]	Neves and Leal (2010)
	Streimikiene and Sarvutyte (2010)	Martchamadol and Kumar (2013)
	Liu (2014)	Luthra et al. (2015)
	Mainali and Silveria (2015)	Lee and Zhong (2015)
	Iddrisu and Bhattacharyya (2015) Škobalj et al. (2017)	Candido and Cavalcandi (2016)

**Table 2.4.** Categorizing research based on energy sustainability indicators/sub-indicators (other dimensions).

<i>Indicators</i>	<i>Researches</i>	
<b>Technological</b>	Maxim (2014)	Luthra et al. (2015)
	Candido and Cavalcandi (2016)	
<b>Market</b>	Afgan and Carvalho (2004)	Patlitzianas et al. (2008) [competitive energy market]
	Onat and Bayar (2010) [market environment]	
<b>Resource</b>	Afgan et al. (2000)	Begic and Afgan (2007)
	Onat and Bayar (2010) [resource environment]	Škobalj et al. (2017)
<b>Technical</b>	Mainali and Silveria (2015)	Iddrisu and Bhattacharyya (2015)
<b>Institutional</b>	Tsai (2010) [institutional response]	Martchamadol and Kumar (2013)
	Mainali and Silveria (2015)	Iddrisu and Bhattacharyya (2015)
<b>Socio-political</b>	Abouelnaga et al. (2010)	Maxim (2014)
<b>Country Governance</b>	Lee and Zhong (2015)	
<b>Political</b>	Candido and Cavalcandi (2016) [dimension policy]	
<b>Cultural</b>	Candido and Cavalcandi (2016)	
<b>Territorial</b>	Candido and Cavalcandi (2016)	
<b>Ecological</b>	Tsai (2010) [ecological resources]	
<b>Sustainable Urban Development</b>	Tsai (2010)	
<b>Operational</b>	Luthra et al. (2015)	
<b>Comprehensive Competition</b>	Onat and Bayar (2010)	
<b>Political &amp; Economy Environment</b>	Onat and Bayar (2010)	
<b>Performance</b>	Afgan and Carvalho (2004)	
<b>Security of Energy Supply</b>	Patlitzianas et al. (2008)	

**Technological Indicators:** Luthra et al. (2015) classified technological indicators as adoption and continuous up graduation of smart technologies and the flexibility to incorporate latest advanced technologies. Therefore, indicators related with technology adoption and technology innovation can be identified as such indicators.

**Market Indicators:** While Afgan and Carvalho (2004) defined market indicators as a measure of the market penetration of the respective products, Patlitzianas et al. (2008) benefited from competitive of energy market indicators to reflect the capacity for providing energy products and services that can compete with the international standards.

**Resource indicators:** Resource indicators are defined as the ratio of total amount of the respective material resource (the amount of fuel, carbon steel, copper, or aluminum) used in the design of the system to the total annual energy production (Afgan et al., 2000). It is important to highlight that the process of identification of resource indicators must be done with a life-cycle point of view. This means that resources are not the only ones that are used in operational phase but also required in the construction of the power supply facility and other necessary infrastructure.

**Technical Indicators:** Iddrisu and Bhattacharyya (2015) determined the indicators of the technical dimension as the share of depletable energies in total consumption of non-renewable energies, depletion coefficient of local energy resources and overall system conversion efficiency.

**Institutional Indicators:** This is the dimension that defines the system structure and framework of processes and where policy decisions on the future structure are introduced (Iddrisu and Bhattacharyya, 2015).

**Socio-political Indicators:** Maxim (2014) define the indicators of socio-political dimension as job creation, social acceptability, external supply risk and external costs (human health).

**Country Governance Indicators:** Country governance is the country's political systems and relations as well as their functioning considering the legislative system, public administration, and democratic participation. It concerns about the co-operation between government and non-governmental organizations assesses if these entities are working together to achieve the predetermined common goals (Lee and Zhong, 2015).

**Political Indicators:** Political dimension measures any effect of the agencies of regulation in the

development of energy sector and makes it possible to determine how much state aid is necessary for the sector to be improved. This would be helpful for policy makers to evaluate current political decisions precisely (Candido, Cavalcandi, 2016).

***Cultural Indicators:*** This dimension assesses the relationship of communities. Discussing such a relationship is beneficial especially in cases where the balance between tradition and innovation must be measured. In this case, such an indicator will be useful to check if the energy enterprises that are implemented in any region is aligned with concept of respecting for the customs of community (Candido, Cavalcandi, 2016).

***Territorial Indicators:*** The purpose to utilize territorial indicators is to emphasize issues relevant today such as the pattern of migration of citizens from rural areas into urban areas (Candido and Cavalcandi, 2016).

***Ecological Indicators:*** Ecological indicators are environmental indicators considering natural sources like the ratio of areas depleted of natural resources (Tsai, 2010).

***Sustainable Urban Development Indicators:*** They are identified as indicators that can measure the change in the urban development area (Tsai, 2010).

***Operational Indicators:*** Operational indicators measure the effect of any operational activity which has been applied to improve in the energy efficiency from technical point of view. For instance, improving any system that has adequate flexibility to match supply and demand will not only increase the ability of this system to adapt any fluctuations but also will make it more resilient (Luthra et al., 2015).

***Comprehensive Competition Indicators:*** Indicators related to operation and performance, technical level, human resource, technical innovation, and management are grouped as the comprehensive competition indicators (Onat and Bayar, 2010; Niu et al., 2008).

***Political & Economy Environment Indicators:*** Indicators related to social political condition and macroeconomic situation are grouped as the political and economic environment indicators that can be used for evaluating the international businesses (Onat and Bayar, 2010; Niu et al., 2008).

***Performance Indicators:*** Afgan and Carvalho (2004) introduced the performance indicator

which is composed of several sub-indicators that are efficiency, total energy cost, capital cost and lifetime.

***Security of Energy Supply Indicators:*** According to Patlitzianas et al. (2008), the reason of using such indicators is about minimizing potential dangers that can occur due to high dependency on an external supply. Therefore, indicators relevant to risks due to a potential disruption of energy supply can be grouped under such indicators.

#### **2.4. Energy Sustainability Indices**

It is difficult to determine the extent to which energy resources, technologies and infrastructure are truly keeping up with emerging challenges related to climate change, environment, population growth and economic wellbeing without a standardized set of metrics to evaluate national energy systems (Brown, and Sovacool, 2007). Although indicators are effective tools to be used in measuring progress and identify lack of progress from energy sustainability point of view, it is required to have complete metric, which is easy to be implemented and easy to be interpreted (Razmjoo et al., 2019). Using such a metric will also allow to make interpretations about the indicators used, which will make it easy for decision makers to analyze the importance of individual indicators and to change or remove them if needed. This will also increase the overall effectiveness of the measuring method to be proposed. Energy sustainability indices can be the solution for informing the status about the national energy conditions as well as for guiding decision makers to make appropriate decisions. The main objective is to assess energy sustainability in a detailed and comprehensive way instead of promoting some abstract idea of sustainability. Table 2.5 is created in accordance with the literature available regarding the applications of *assessing the level of energy sustainability for the selected country; assessing the level of energy access sustainability for the selected country; assessing the level of energy security sustainability for the selected country; assessing a firm's energy productivity in terms of sustainability; assessing energy generation technologies in terms of sustainability; assessing energy storage alternatives in terms of sustainability and assessing energy efficiency measures in terms of sustainability.*

**Table 2.5.** Energy sustainability indices based on their application areas.

INDEX	APPLICATION AREA
<i>1.</i> Energy Sustainability Index (ESI) (Brown and Sovacool, 2007)	Assessing the level of energy sustainability for the selected country
<i>2.</i> Energy Architecture Performance Index (EAPI) (Bocca and Mehlum, 2012)	
<i>3.</i> Sustainable Energy Development Index (SEDI) (Iddrisu and Bhattacharyya, 2015)	
<i>4.</i> Renewable Energy Responsible Investment Index (Lee and Zhong, 2015)	
<i>5.</i> Synthetic Index of Sustainable Energy Development (SISED) (García-Álvarez et al., 2016)	
<i>6.</i> World Energy Trilemma Index (World Energy Council, 2016)	
<i>7.</i> Energy Development Index (EDI) (International Energy Agency, 2012)	Assessing the level of energy access sustainability for the selected country
<i>8.</i> Multidimensional Energy Poverty Index (MEPI) (Nussbaumer et al., 2012)	
<i>9.</i> Sustainable Energy Index (ENDX) (Overturf and McKnight, 2012)	Assessing a firm's energy productivity in terms of sustainability
<i>10.</i> The International Index of Energy Security Risk (U.S. Chamber of Commerce's Institute for 21st Century Energy, 2012)	Assessing the level of energy security sustainability for the selected country
<i>11.</i> Sustainable Energy Security (SES) (Narula and Reddy, 2016)	
<i>12.</i> Energy Security Index (Radovanović et al., 2017)	
<i>13.</i> Energy Technology Sustainability Index (ETSI) (Mainali and Silveria, 2015)	Assessing energy generation technologies in terms of sustainability
<i>14.</i> Energy Index (Jha and Puppala, 2017)	
<i>15.</i> Sustainability Index (Raza et al., 2014)	Assessing energy storage alternatives in terms of sustainability
<i>16.</i> Combined Sustainability Index (Goldrath et al., 2015)	Assessing energy efficiency measures in terms of sustainability

### **2.4.1. Energy sustainability index (ESI)**

Energy Sustainability Index (ESI) was created for informing analysts, investors, and policy makers about the status of energy conditions. It is based on 12 different indicators (natural gas prices, retail electricity prices, availability of non-petroleum fuels, oil imports, sulfur dioxide emissions, petroleum prices, energy use per capita, fuel economy of vehicles, energy intensity, natural gas imports, annual investment in transmission and distribution, and carbon dioxide emissions) covering 4 dimensions of the US (provided as the selected country) energy system. These dimensions were determined as environmental quality, oil security, energy efficiency, and electricity reliability. It was also indicated that decision makers in US were not successful to provide solutions of current problems regarding energy sector and it is concluded that the conditions have deteriorated (Brown and Sovacool, 2007). ESI is one of the first sustainability indices proposed in the literature. It only benefits from one level of criteria instead of multiple which refer as dimensions. However, it provides essential information on measuring progress related with energy systems, especially in the environmental area.

### **2.4.2. Energy architecture performance index (EAPI)**

EAPI is one of the indices that is introduced as a tool for policy makers to monitor the current situation in the country and benchmark the progress of their transition against a series of indicators. In order to score and rank each country's energy architecture performance, it focuses on tracking 16 indicators corresponding to 3 different sub-indices which were determined as economic growth & development, environmental sustainability, and energy access & security (Bocca and Mehlum, 2012). It is one of the earliest indices that integrates energy security into energy sustainability indices and provide indicators of social progress of energy sustainability under energy access indicators.

Each of the sub-indices received equal priority and weighting, while different weights were assigned for indicators (this only applies for the economic growth and development basket, other indicators were equally weighted). The sub-indices were then aggregated to measure the overall score of EAPI. The scores of sub-indices and EAPI were illustrated on a scale between 0 to 1. For instance, Norway was presented as the country that achieved the highest overall score with 0.75 in EAPI 2013 (Bocca and Mehlum, 2012).

### **2.4.3. Sustainable Energy Development Index (SEDI)**

SEDI was proposed for capturing sustainability dimension adequately. Indicators were defined such that each computed dimension (technical, environmental, social, economic, and institutional) could be expressed as a ratio between 0 and 1, where 0 represents no sustainability and 1 represents full sustainability. The overall index was calculated by taking the arithmetic mean of all dimensions (Iddrisu and Bhattacharyya, 2015).

Unlike many indices, Iddrisu and Bhattacharyya (2015) interpret self-sufficiency related indicator as institutional dimension in SEDI. They support their claim by stating that overall self-sufficiency is highly related with political stability which is an institutional matter.

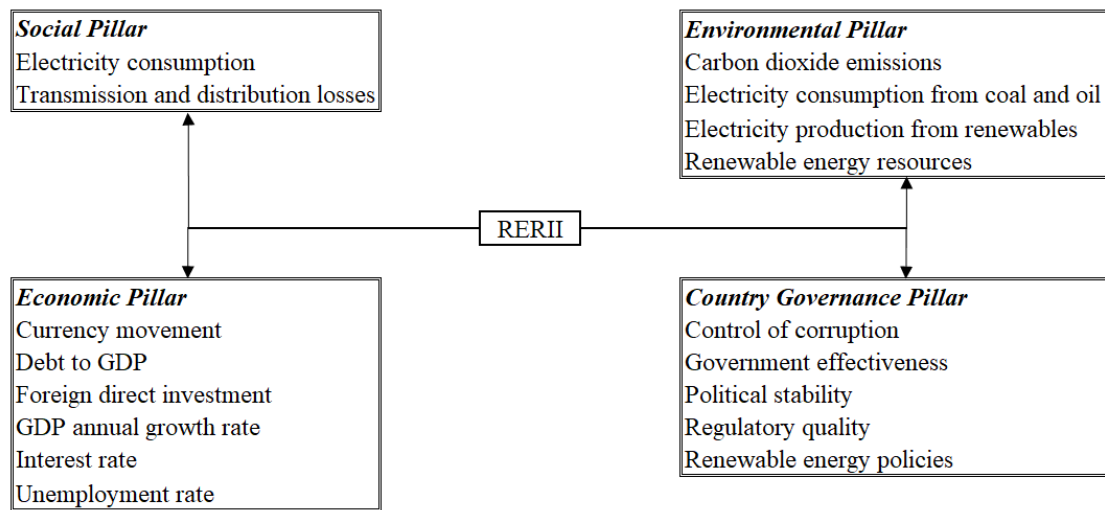
In the work of Iddrisu and Bhattacharyya (2015) the normalization process used by United Nations Development Programme for the calculation of the Human Development Index has been adopted. However, two different scenarios were defined to suit two directional objectives. This means that the performance is better for some indicators if they have better values. On the other hand, converse holds for other indicators. The definition of a directional indicator is such that if a higher value is better, the equation for normalization is calculated as the ratio of the difference between actual indicator value and the minimum indicator value to the difference between maximum indicator value to the minimum indicator value. However, if the opposite is valid, then the equation is modified as the ratio of the difference between maximum indicator value and the actual indicator value to the difference between maximum indicator value to the minimum indicator value.

### **2.4.4. Renewable energy responsible investment index (RERII)**

RERII was proposed to provide a useful tool for investors who would like to invest in renewable energy projects. It was intended to establish an investment tool that can be used by stakeholders to develop new renewable energy investment approaches as well as to revise the existing ones. RERII is a tool for investment screening and decision making and it gives information about both previous and current situation of all dimensions of countries (Lee and Zhong 2015).

According to Lee and Zhong (2015) the first step to construct the composite index would be developing the conceptual framework to present the structure of the index, and the selection

criteria. After developing a conceptual framework and selecting the appropriate indicators, data processing procedure is performed. After achieving a complete database of indicators, multivariate analysis is performed. This analysis is done to assess the structure of the database and the methodological choices for both aggregation and weighting. The last step is normalization. It is required to transform simple samples of indicators into dimensionless numbers before the processes of weighting and aggregating since they often have different measurement units. After data processing procedure, weighting as well as aggregating procedure and robustness assessment are performed. RERII is composed of 4 different aspects. Figure 2.4 is constructed to demonstrate relevant aspects and indicators based on the work of Lee and Zhong (2015).



**Figure 2.4.** Aspects and indicators of RERII.

### 2.4.5. Synthetic index of sustainable energy development (SISED)

García-Álvarez et al. (2016) proposed a set of sustainable energy policy indicators to develop the index referred as SISED, since there was a lack of research on standardized methods to aggregate sustainable energy development indicators into one index according to the work of Schlör et al. (2013). The purpose of this index is to rank countries of EU-15 (Denmark, Austria, United Kingdom, Greece, Netherlands, France, Germany, Ireland, Sweden, Finland, Italy, Belgium, Portugal, Luxembourg, and Spain) based on their sustainable energy development performances between the years 2002 and 2012.

#### **2.4.6. World energy trilemma index**

This index was proposed as a country ranking system with the aim of demonstrating any effect of energy policies developed by different countries over time (Shortall and Davidsdottir, 2017). The index reviews indicators in four areas that were determined as, energy equity, energy security, country context, and environmental sustainability (World Energy Council, 2016).

The ranking of the index was displayed as a number which summarizes the overall energy trilemma performance of a country and shows its comparative positioning among other countries. The balance score, displayed as three letters (e.g., CDA), was used for demonstrating how successful a country is in balancing the three dimensions (environmental sustainability, energy equity, and energy security).

The indicator selection was guided in accordance with a set of pragmatic principles including robustness, contextual sensitivity, relevance, distinctiveness, coverage, comparability, and balance. Indicator scores were calculated after collecting and verifying data for each indicator. The indicator-level results were standardized using the z-score and rescaled to a range between 0 –100. This made it possible to combine indicators into dimension scores based on the weights assigned to each indicator. By taking mean and standard deviation into account, the balance score grade was assigned for each dimension of the index (World Energy Council, 2016).

#### **2.4.7. Energy development index (EDI)**

EDI is developed to track progress towards providing modern energy access for 80 different countries. The index measures energy development of a country at different levels. Several variables were identified and monitored as a means of measuring energy development. The household indicator is composed of the geometric mean of share of population with electricity access and per capita residential consumption, as well as share of modern fuels at the residential sector (excluding electricity to avoid double counting) (International Energy Agency, 2012).

#### **2.4.8. Multidimensional energy poverty index (MEPI)**

MEPI is one of the indices proposed for measuring energy poverty (Nussbaumer et al., 2012). MEPI was calculated as the product of the ratio of people categorized as energy poor and their average intensity of deprivation (Nussbaumer et al., 2012; Iddrisu and Bhattacharyya, 2015).

#### 2.4.9. Sustainable energy index (ENDX)

Sustainable Energy Index (ENDX) was proposed to track the energy productivity of a business, to characterize the description of energy risk on business operations, to support the continuous improvement of energy productivity, and to disassociate energy investments from cognitive bias. ENDX can also be considered as an energy management tool that is to be used by managers to identify business areas that is open for improvement and the progress that have been made on that issue. If a business is improving its relative cost position and reducing its energy risk, a positive trend is observed. On the other hand, a negative change of the index implies the opposite. ENDX was calculated by using Equation (2.1), which takes economic output (can be quantified as standard output - sales dollars, units shipped, or earned value), energy cost (the total energy expenditures for a given time period) and energy sufficiency ratio (the ratio of self-generated/controlled energy sources to the total energy consumed) into account (Overturf and McKnight, 2012).

$$ENDX = O \frac{S}{CD} [k] \quad (2.1)$$

Where:

- O - Economic Output,
- S - Sufficiency,
- C - Cost,
- D - Consumption,
- [k] - Optional scalar adjustment.

#### 2.4.10. The International Index of Energy Security Risk

It is vital for a country to provide uninterrupted and continuous energy services to its citizens. Any issue that can trigger disruption in the provision would cause a huge problem. This would cause disruption in all essential services such as healthcare that are vital for communities. The consequences of large energy interruptions would be devastating for people and politicians. Thus, in assessing security as well as risk, it is vital to have an improved understanding of the likelihood of an energy shock of some kind and how that might impact the economy of a country. This would allow them to take necessary precautions to avoid such problems. For that matter, this index was designed to allow comparisons of energy security risks across different countries as

well as country groups and to indicate how these risks change over time (U.S. Chamber of Commerce's Institute for 21st Century Energy, 2016).

The index provides energy security risks across different countries (Turkey, Canada, Norway, Denmark, Russian Federation, Japan, Indonesia, France, South Africa, Brazil, Netherlands, South Korea, Ukraine, Australia, Thailand, Italy, China, Germany, Poland, New Zealand, India, Mexico, United Kingdom, Spain, and United States of America) for the years 1980 through 2014 (U.S. Chamber of Commerce's Institute for 21st Century Energy, 2016).

In order to calculate the index 29 different metrics corresponding to 8 broad categories were developed that cover wide range of energy supplies, emissions, generating capacity, energy end uses, and operations. The risk index for a country in any given year is equal to the sum of the metric values, each multiplied by its assigned weighted share (U.S. Chamber of Commerce's Institute for 21st Century Energy, 2016).

#### **2.4.11. Sustainable energy security (SES) index**

Narula and Reddy (2016) claimed that sustainable energy security (SES) implies a sustainable and a secure energy system which includes:

- i. harvesting / extracting energy resources,
- ii. transforming energy from one form to another (primary to secondary such as electricity),
- iii. ensuring the transportation / distribution of all forms of energy,
- iv. supplying final energy to various sectors of economy.

This approach considers the entire energy system and acknowledges that a disruption anywhere along the energy chain may result in non-provisioning of energy services to the consumer. Therefore, all risks that are caused by, or have an impact on the energy chains should be considered (Narula and Reddy, 2016; Winzer, 2012).

Narula and Reddy (2016) presented an analytical framework for the assessment of SES of an energy system and proposed a methodology in order to construct a multidimensional SES index. With respect to the proposed hierarchical structure, the energy system was divided into 3 subsystems (supply, conversion & distribution, and demand as shown in Figure 2.5) and each subsystem was further divided into its components which were evaluated according to pre-determined dimensions. Figure 2.5 is created based on the work of Narula and Reddy (2016).

Supply Sub-System	Conversion & Distribution Sub-System	Demand Sub-System
<i>Harvesting / extracting resources and transporting resources to Conversion &amp; Distribution Sub-System</i>	<i>Transforming primary energy sources into different forms of secondary energy and transporting them to Demand Sub-System</i>	<i>Final energy is consumed in various sectors of economy</i>
<ul style="list-style-type: none"> <li>* Extracting fossil fuels <ul style="list-style-type: none"> <li>• Coal</li> <li>• Gas</li> <li>• Oil</li> <li>• Coal</li> </ul> </li> <li>* Harvesting energy from renewable sources <ul style="list-style-type: none"> <li>• Hydro</li> <li>• Solar</li> <li>• Wind</li> <li>• Biomass</li> </ul> </li> <li>* Extracting and pre-processing nuclear energy</li> </ul>	<ul style="list-style-type: none"> <li>* Electricity</li> <li>* Oil products</li> <li>* Coal</li> <li>* Natural Gas</li> <li>* Biomass</li> </ul>	<ul style="list-style-type: none"> <li>* Residential</li> <li>* Industrial</li> <li>* Commercial</li> <li>* Agriculture</li> <li>* Transport</li> </ul>

**Figure 2.5.** Energy sub-systems.

#### 2.4.12. Energy security index

Due to limited and unevenly distributed energy resources, there is an increasing demand for energy which pose a challenge for countries undergoing rapid development to provide continuous energy services. Therefore, energy security is considered as one of the priority issues of each country's development (Radovanović et al., 2017; Kruyt et al., 2009; Cohen et al., 2011).

Radovanović et al. (2017) defined a new indicator for energy security (Energy Security Index) and tested it in a sample of 28 different European Union (EU) countries for a period of 23 years (1990-2012). The main objective was defining a sustainable approach to energy security measurement by introducing new indicators and determining their level of impact on energy security. Environmental as well as social issues have also been considered in developing this index. The study is based on the method of weighting coefficients, which corresponds to the fact that energy security is affected by different indicators at varying intensity. Each indicator was assigned certain importance, whereby the sum of all their values is equal to 100. Moreover, the impact of indicators on result can be positive or negative depending on the real impact on energy security. The weighting coefficients were determined by using the approach of experts' opinion on the importance of specific indicators for the observed system. The index was calculated by using Equation (2.2).

$$ESI = EI \times 20 + FEC \times 20 - ED \times 20 + GDP/pc \times 10 - CI \times 10 + SRN \times 20 \quad (2.2)$$

Where:

<i>ESI</i>	-	Energy Security Index,
<i>EI</i>	-	Energy intensity,
<i>FEC</i>	-	Final energy consumption,
<i>ED</i>	-	Energy dependency,
<i>GDP/pc</i>	-	GDP per capita,
<i>CI</i>	-	Carbon intensity and,
<i>SRN</i>	-	Share of renewable and nuclear energy.

#### 2.4.13. Energy technology sustainability index (ETSI)

Energy Technology Sustainability Index (ETSI) was proposed by Mainali and Silveria (2015) for assessing sustainability performances of different energy systems applied in rural electrification in the case of India. It was constructed by aggregating individual indicators, which were selected carefully covering various dimensions of sustainability. Table 2.6 indicates the energy technology sustainability dimensions as well as related indicators based on the work of Mainali and Silveria (2015).

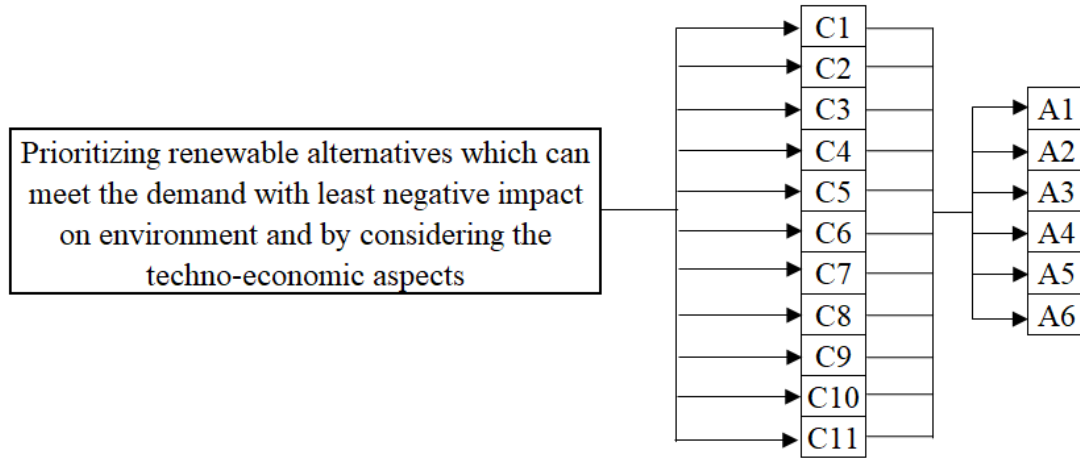
**Table 2.6.** Energy technology sustainability dimensions and related indicators.

<i>DIMENSIONS</i>	<i>INDICATORS</i>
<i>TECHNICAL</i>	Energy Availability
	Efficiency of Energy Conversion
	System Reliability
<i>ECONOMIC</i>	Capital Investment
	Operation & Maintenance Cost
	Fuel Cost
<i>ENVIRONMENTAL</i>	Greenhouse Gas Emissions
	Land Uses
<i>SOCIAL</i>	Local Employment Generation
	Compatibility of the Technology with Different End Uses
<i>INSTITUTIONAL</i>	Operational & Management Capability Required

#### 2.4.14. Energy index

Jha and Puppala (2017) archived the status of renewable energy alternatives in India while focusing on prioritizing these sources based on a proposed parameter defined as Energy Index. This index was evaluated by using cumulative scores which were obtained for alternative sources. The cumulative scores of each alternative were computed by using Fuzzy Analytical Hierarchy

Process (AHP) and the dominance of one alternative to another one for each of the criteria was measured on a fuzzy Saaty Scale. The schematic representation of the present study is indicated by Figure 2.6.



**Figure 2.6.** Schematic representation of Energy Index.

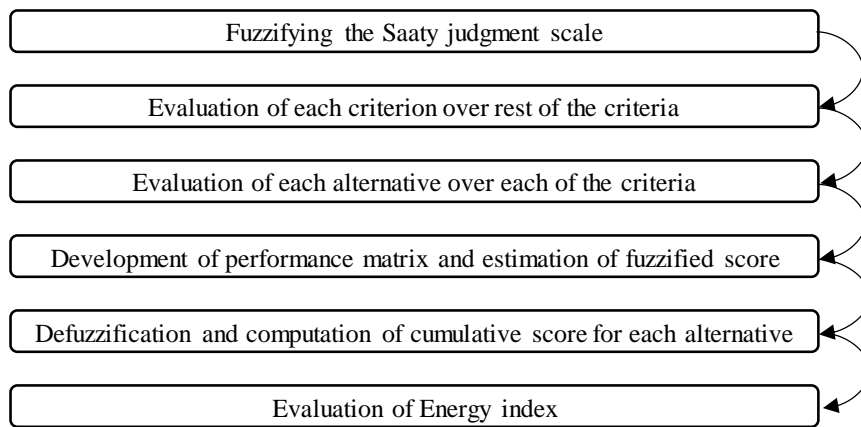
Energy Index identifies the best alternative source among the existing sources compared with the ideal source in order to draw the priority order and to understand the deviation with the ideal source quantitatively. The computation of the index involved 6 steps, which are demonstrated in Figure 2.7 and the mathematical representation of the index is provided by the Equation (2.3) (Jha and Puppala, 2017).

$$\text{Energy Index} = S_a / S_i \quad (2.3)$$

Where:

$S_a$  - cumulative score of an existing alternative evaluated over the considered wide range of criteria and,

$S_i$  - cumulative score of the ideal alternative evaluated over the considered wide range of criteria.



**Figure 2.7.** Computation of Energy Index.

### 2.4.15. Sustainability index

It is a well-known fact that the stability of an electric grid is dependent on the ability of balancing supply and demand. Electricity production systems that are centralized and mainly based on fossil fuels produce electricity continuously depending on the demand. In such a case a storage system for electricity is not required. The reason behind this lies in the ability of activating and disactivating the supply in case of demand increase or decrease. However, since electricity that is generated from renewable sources fluctuate irrespective of the demand, it is necessary to use systems for electricity storage for ensuring uninterrupted electricity supply. Thus, a long-term strategy is required to plan large-scale energy storage facilities (Ibrahim et al., 2008; Raza et al., 2014), which is a challenge since storing huge amount of electricity is not economically feasible and brings a lot of technical problems to the equation.

There are different electricity storage systems that are currently used today. One of them is the pumped hydroelectric systems which benefits from existing hydroelectric facilities from infrastructure point of view. The concept is based on pumping water while there is little demand on supply and converting the potential energy to kinetic energy when there is a peak load. Although such systems seem to provide promising opportunities, it is important to keep in mind that the availability of the necessary geographic sites are required to benefit from such systems. Compressed air storage is another popular type of storage used in different locations. The logic is remarkably similar to the pumped hydroelectric systems. The idea is to use a motor during off-peak demand times to compress air and store it. However, it is revealed that keeping large volume

of compressed air is technically challenging. Furthermore, the process is economically not feasible. Using flywheels is an effective solution for energy storage problems. The concept is to provide energy by accelerating a rotor. These systems suffer from the low efficiency rates. The ratio of electricity discharge is high in such systems which makes storage for long term nearly impossible. Besides operational costs are much higher than any other energy storage method. In case of hydrogen energy storage systems, generating hydrogen through electrolysis process is financially challenging even though the efficiency of generating energy from hydrogen is high. Based on these facts, Raza et al. (2014) state that the best solution for energy storage can be provided with battery technologies.

Raza et al. (2014) proposed the Sustainability Index for suggesting an energy storage system for a coastal town in Pakistan. The significant factors to select the energy storage systems were determined as the ability to work alone and the ability to provide uninterrupted electricity. For that matter, three battery energy storage options were compared for an intermittent renewable energy source (photovoltaic) through the index to find out the most feasible option. A weighted sum approach was used where some factors are more important compared to others. Thus, according to its relative importance, each factor was assigned a certain weight on a scale of 1 to 10 and the weighted sum of all the factors was calculated. The distribution of the weights was performed through six different groups corresponding to 11 defined factors, which are indicated in Table 2.7.

**Table 2.7.** Sustainability index based on weighted sums.

<i>Group</i>	<i>Factor</i>	<i>Weightage</i>	<i>Lead Acid</i>	<i>Lithium</i>	<i>Fuel Cell</i>
1	Cost	10	50	10	37.7
2	Reliability	8	24	24	40
	Fast load response capability	8	40	40	16
3	System life	7	7	21	35
	Efficiency	7	35	35	7
	Capacity or efficient variation	7	14	14	35
	Risk factor	7	-35	-7	-35
4	Environmental impacts	5	-25	-20	-5
5	Modularity in production	3	10	10	6
6	Energy density ratio	1	1	1	5
<i>Total Index</i>			121	128	141.7

#### **2.4.16. Combined Sustainability Index**

Energy efficiency is defined as meeting a desired level of energy services, while using less

energy. Some of the common examples of energy efficiency measures are more efficient air conditioners, refrigerators, lamps, and motors (Berry, 2008). Energy efficiency measures play major role in reducing energy consumption and therefore, in the efforts of minimizing greenhouse gas emissions (Goldrath et al., 2015).

Goldrath et al. (2015) aimed to define and supply indices which support a decision-making process between energy efficiency measures and to demonstrate their methodology of use through the case study of Israeli electricity market. For that matter, five main electricity consumption sectors were determined, and one measure was chosen based on the criteria shown in Figure 2.8 to represent each sector of consumption (refrigerators for residential sector, chillers for industrial sector, air conditioning systems for commercial sector, streetlights for municipal sector and water pumps for water sector). Based on the expert's questionnaire, field data and literature, each of those indices was estimated and scored. The values, which are received from calculations, were normalized in reference to the lowest or highest value. In cases where the index shows a positive trend Equation (2.4) was used, otherwise Equation (2.5) was applied.

$$\frac{IV_{max}-IV_i}{IV_{max}-IV_{min}} = rate_i \quad (2.4)$$

$$\frac{IV_i-IV_{min}}{IV_{max}-IV_{min}} = rate_i \quad (2.5)$$

Where:

- $IV_{min}$  - the minimal value for measure i,
- $IV_{max}$  - the maximum value for measure i,
- $IV_i$  - the value of the specific index,
- $rate_i$  - the rate of the index per measure i.

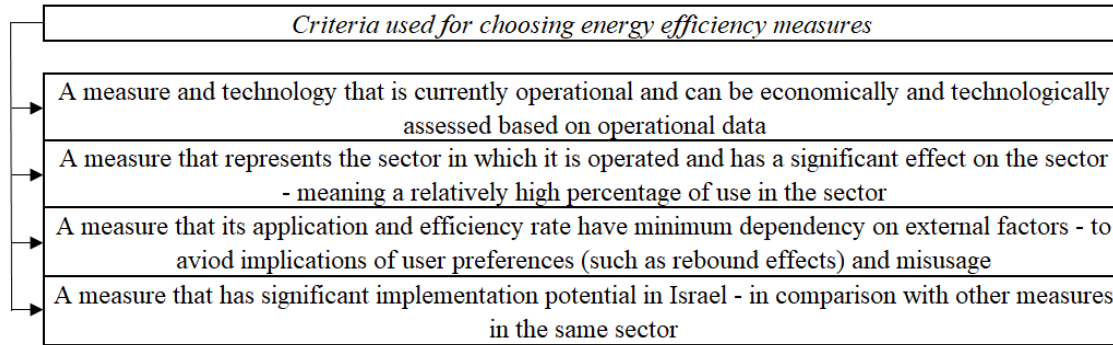
For the calculation of the Combined Sustainability Index that is indicated by Equation (2.6), same weights were given for each of the indices and the rating method is applying 1 to the worst and 0 to the best result, which means that higher rates indicate worse results (Goldrath et al., 2015).

$$rate_{measure} = \sum_i (rate_{(i)}) \quad (2.6)$$

Where:

- $rate_{measure}$  - the combined rate for every measure and,

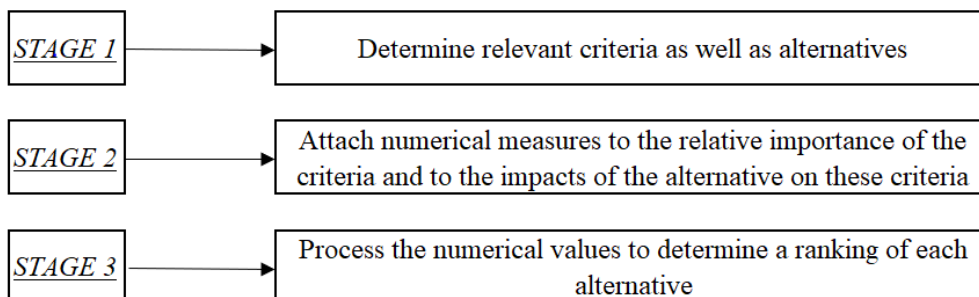
rate<sub>(i)</sub> - the rate score of index i, where i refers to economic, environmental, technological, social, and political index.



**Figure 2.8.** Criteria used for choosing energy efficiency measures.

### 2.5. Multi-criteria Decision-Making Process

Multi-criteria decision-making (MCDM) is a discipline that encompasses different fields of studies including mathematics, economics, psychology, management, social sciences and informatics. MCDM methods were developed to support decision makers for solving any problem where an important decision needs to be made, and a solution is reached by making compromises. Since these methods play an important role in decision making processes for decision makers, they incorporate subjective information (Ishizaka et al., 2013). MCDM methods deal with the evaluation of a set of alternatives by considering decision criteria which are numerous and often conflicting in nature (Mulliner et al., 2016). Furthermore, it is significant to emphasize that different decisions can be made based on short or long term predictions and considering this with the complexity of having various goals make MCDM techniques an important asset for decision makers. Stages of MCDM is indicated by Figure 2.9 based on the work of Mulliner et al. (2016).

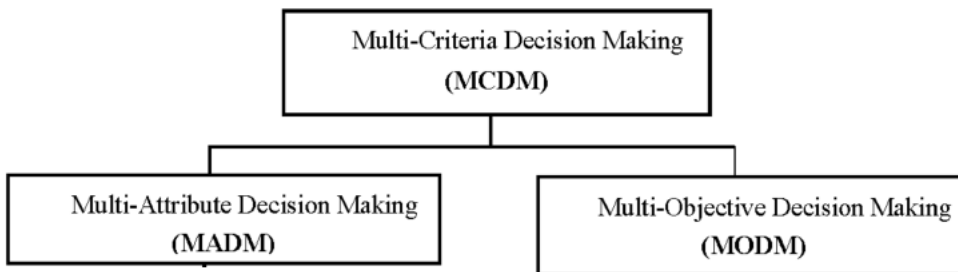


**Figure 2.9.** Stages of MCDM.

### 2.5.1. MCDM Classification

As underlined in the study of Zavadskas et al. (2014), it is not possible to claim that there is a well-defined methodology for decision-making process. A large number of unique multi-criteria decision-making methods have been developed which cover a wide range of approaches. In general, MCDM methods are classified into two categories (Figure 2.10):

- Discrete MADM (multi-attribute decision-making)
- Continuous MODM (multi-objective decision-making)



**Figure 2.10.** Classification of MCDM Methods.

MODM methods are mathematical programming models used for solving problems which have a set of quantifiable objectives and well-defined constraints. MODM methods are associated with problems where alternatives in the problem are in large numbers and not pre-determined. The aim of the method is to decide the optimal alternative among others (Mirjat et al., 2018; Zavadskas et al., 2014). On the other hand a finite number of alternatives are considered in MADM methods. They specify how attribute information is to be processed in order to arrive at a choice.

In addition to the above classification, a different kind of classification based on the characteristics of the criteria, alternatives, or solution set in the structure of the decision problem is indicated by the study of Arslan (2018). In such a selection the MCDM problem to be considered is divided into four different categories which are namely; selection between alternatives, alternatives rating, alternatives classification, and identifying alternatives.

It is imperative to define alternatives, criteria, scale and weights in order to evaluate MCDM techniques. Alternatives are series of activities that are planned to make a selection through a decision-making process. Criteria are factors to be benefited in order to evaluate the properties and performances of alternatives used in the problem. Scale is considered as a standard that is

determined to be used to measure the performance of the alternative, and weights are quantitative expressions for indicating the importance of the criteria (Yılmaz et al., 2020).

### **2.5.2. MCDM Methods**

Numerous MCDM methods such as Analytical Hierarchy Process (AHP), Analytic Network Process (ANP), Technique of Order Preference by Similarity of Ideal Solution (TOPSIS), Elimination Et Choice Translating Reality (ELECTRE), Multi-criteria Optimization and Compromise Solution (VIKOR), Preference Ranking Organization Methods for Enrichment Evaluation (PROMETHEE), Grey Relational Analysis (GRA) and Decision Making Trial and Evaluation Laboratory (DEMATEL) have been used and implemented in different applications (Çelikbilek and Tüysüz, 2016; Gavade, 2014; Velasquez and Hester, 2013). Moreover, Aruldoss et al. (2013) underline the importance of the ongoing researches on exploring more MCDM methods to fill the gap between theory and practice for real world planning as well as designing problems.

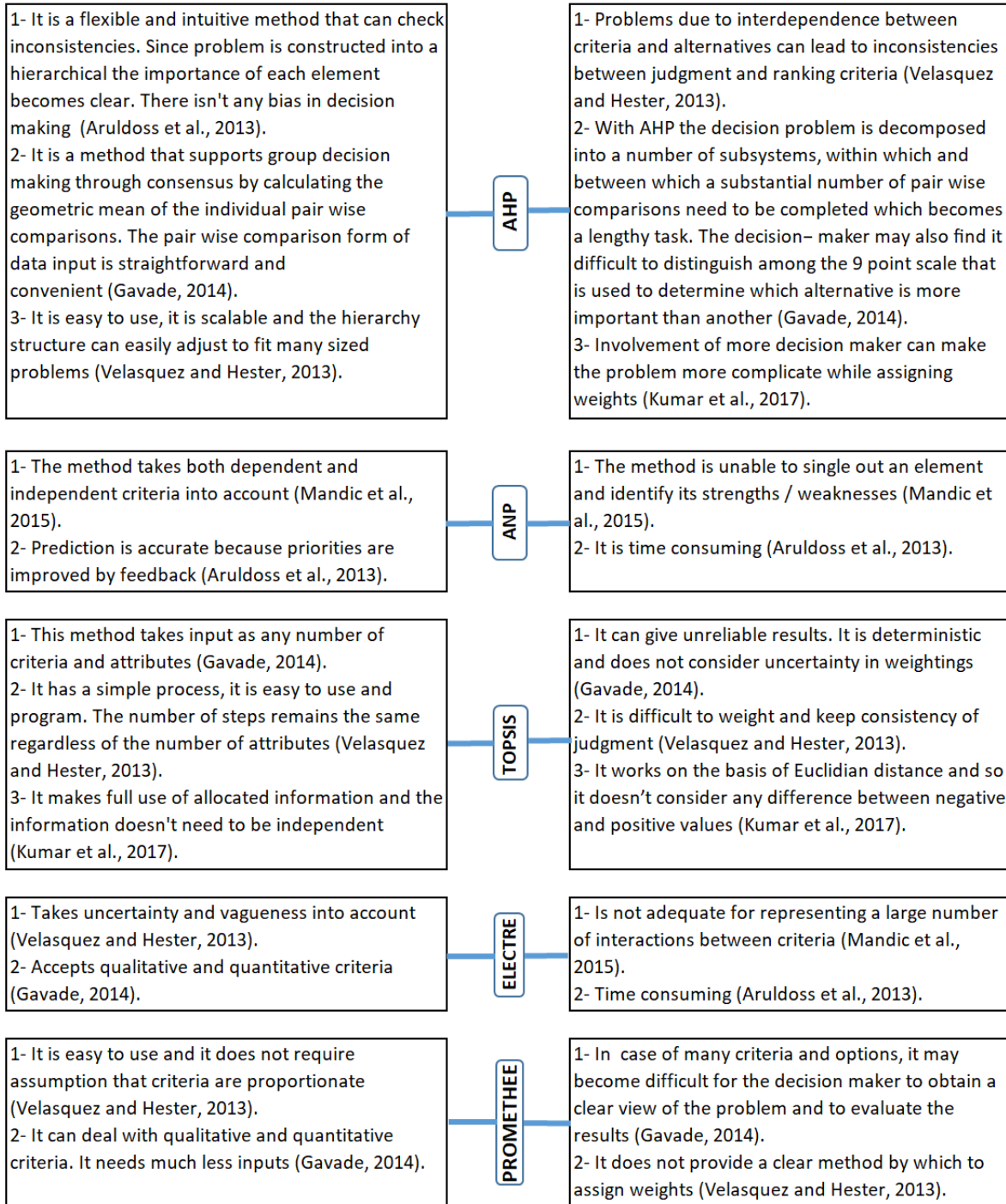
AHP and ANP are methods that benefit from pairwise comparisons to calculate criteria weights or selecting alternatives. The difference between these two methods lies within the modelling of the problem as well as criteria independency issues (Büyüközçü and Sucu, 2002). These models are widely used for dealing with both quantitative and qualitative variables all together and considers the predetermined priorities which were defined by the decision makers (Hodicky et al., 2020). The weights of criteria are determined by pairwise comparisons used in AHP. In such a comparison, the judgements coming from decision makers are used as an input to the AHP model to determine the criteria weights (Chai et al., 2013; De FSM Russo et al., 2015; Tavana et al., 2020). The flexible nature of AHP allows it to be integrated with other methods, which make it possible for a decision maker to benefit from other methods too (Vaidya and Kumar, 2006; Mafakheri et al., 2011; Bhattacharya et al., 2010; Ishizaka et al., 2012).

ELECTRE methods can be considered as a group of decision-making methods, which is based on concordance analysis. In other words, solutions are compared 2 by 2, by considering criteria. ELECTRE methods can solve problems involving qualitative and immeasurable criteria. PROMETHEE methods are also like ELECTRE methods in which similar iterations are used (Velasquez and Hester, 2013).

The methods of TOPSIS and VIKOR are decision-making methods based on calculating the distance between optimal solutions. While both positive ideal solution (the shorter the distance the better the solution) and negative ideal solution (the larger the distance the better the solution) are calculated, only closeness to positive ideal solution is important in VIKOR. Therefore, decision makers who wants to have maximum profit with minimum cost would select TOPSIS, on the other hand VIKOR can be used on cases where the risk of decisions are negligible (Sayadi et al., 2009).

There are studies carried out to determine widely used MCDM methods in the literature. One of the comprehensive study was undertaken by (Aruldoss et al., 2013), which identifies 5 widely used methods as AHP, ELECTRE, TOPSIS, PROMETHEE and Grey Theory. On the other hand Gavade (2014) states that effective MCDM methods are AHP, TOPSIS, ELECTRE, VIKOR and PROMETHEE. Figure 2.11 contains information about the advantages and disadvantages of main MCDM methods.

In addition to traditional MCDM methods which benefits from mathematical operations in order to make approximations, integration of fuzzy logic with MDCM methods have also gained popularity among sustainability researchers. Especially, AHP and TOPSIS have been the most convenient methods to be integrated with fuzzy logic. However, in a world where the systems become more complex, it is not an easy task to benefit from decision-makers to provide input for the fuzzy integrated MCDM methods. Researchers have been trying to solve this issue by developing artificial intelligence (Aruldoss et al., 2013).

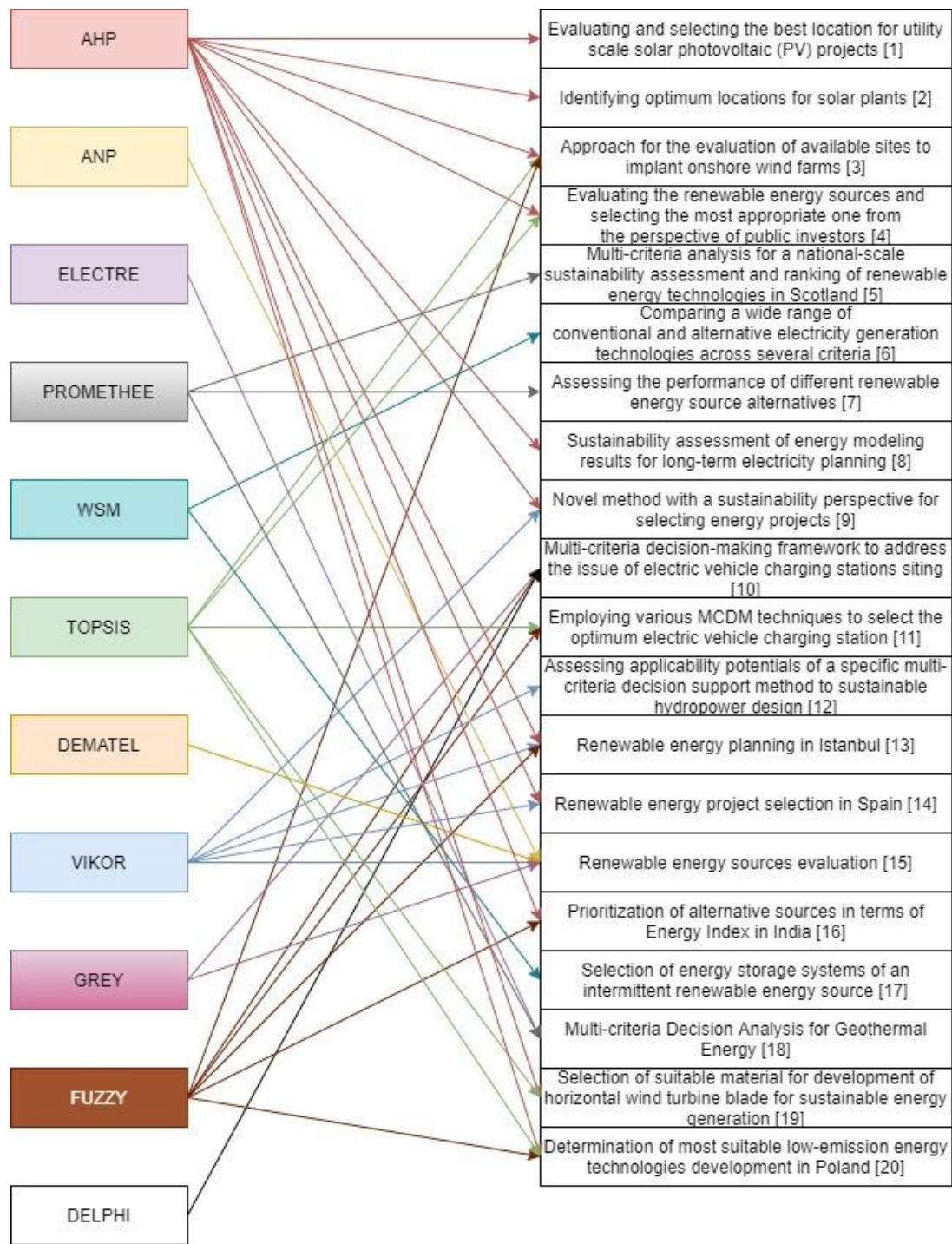


**Figure 2.11.** Advantages & disadvantages of MCDM methods.

Many applications of MCDM methods in the field of sustainability have been introduced in the literature. According to the research undertaken by Stojcic et al. (2019), in which 108 different cases were analyzed, MCDM methods are mainly used for solving problems of selecting the

optimum type of renewable and non-renewable energy sources. Furthermore, the researchers also underline that the most widely used MCDM method in this area is AHP. The researchers state that applying additional theories such as fuzzy, rough, neutrosophic and grey have become popular in order to cope with uncertainty. Moreover, they emphasized the importance of MCDM selection, since each method has its own advantages and disadvantages. The same applies to the selection of additional methods for coping uncertainty issues in a multi-criteria problem. The choice of selection is mostly based on preferences of researchers, analysts, and decision makers. Butkiene et al. (2020) conducted an extensive research on energy technologies in households from MCDM point of view. The main contribution is to make it possible to evaluate the potential for each method for different cases based on available information. Based on these facts, it is vital to consider both convenience and applicability of a MCDM method. In order to achieve to a high-quality decision, it is important to apply multiple methods in a decision-making problem. Such a trend has been observed by the researchers in the literature. Major studies on different MCDM techniques in terms of energy sustainability are shown in Figure 2.12.

The study conducted by Butkiene et al. (2020) also revealed that developing MCDM methods is a continuous process and new methods have been introducing to the literature. One of the comprehensive works in this area is the work of Alinezhad and Khalili (2019). They identified some of the newly developed MCDM techniques that have been used in different applications. They discuss 27 different MCDM methods in detail and provide case studies to further explain how these methods work. Their work is an excellent source for researchers who would like to apply new methods in different application areas.



[1] Garni and Awasthi (2017) / [2] Diaz-Cuevas et al. (2018) / [3] Sanchez-Lozano et al. (2016) / [4] Wu et al. (2018) / [5] Troldborg et al. (2014) / [6] Klein and Whalley (2015) / [7] Tsoutsos et al. (2009) / [8] Mirjat et al. (2018) / [9] Büyüközcan and Karabulut (2017) / [10] Zhao and Li (2016) / [11] Guo and Zhao (2015) / [12] Vujicak et al. (2013) / [13] Kaya and Kahraman (2010) / [14] Cristobal (2011) / [15] Çelikbilek and Tüysüz (2016) / [16] Jha and Puppala (2017) / [17] Raza et al. (2014) / [18] Polatidis et al. (2014) / [19] Okokpuije et al. (2020) / [20] Ligus and Peternek (2018)

**Figure 2.12.** MCDM methods in the sub-area of energy sustainability.

### 3. CASE STUDY

#### 3.1. Research Methodology

The case study includes two MCDM methods; fuzzy AHP is used for determining criteria weights and GRA is used for comparing alternatives. The GRA method used is also revised and extended. The indicators determined in the index have been selected based on academic sources (Table 3.6) and criteria (Table 3.2). The relevance of each indicator to OESI has been also presented with Table 3.5.

##### 3.1.1. OESI

The first step in constructing the OESI is to define the objective of the index and determine the issues relevant in this context. Following table shows the issues to be addressed in order to calculate OESI.

**Table 3.1.** Issues to be addressed in 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 <sup>1</sup>
Social	The level of quality, affordability, and accessibility of energy services

<sup>1</sup> Stringency and enforcement of environmental legislations

The selection of indicators plays a major role in addressing any index to be constructed, however there is no commonly accepted methodology despite existing guidelines or frameworks in the literature (Kemmler and Spreng, 2007). There have been studies that focus on identifying necessities that should be met by selected indicators (Cîrstea et al., 2018; Lee and Zhong, 2015; Afgan et al., 2000; Harger and Meyer, 1996; Reisi et al., 2014; Haghshenas and Vaziri, 2012). Based on these studies, these requirements can be summarized as accessibility, sensitivity, relevance, interpretability, and timeliness (indicated in Table 3.2).

**Table 3.2.** Criteria for indicator selection.

Criteria	Brief Description
Sensitivity	Indicators should be sensitive to any change in the system in order to reflect the changes (Reisi et al., 2014; Haghshenas and Vaziri, 2012; Li et al., 2019).
Interpretability	Indicators should be clearly defined. They must be understandable and measurable (Lee and Zhong, 2015; Afgan et al., 2000; Reisi et al., 2014; Haghshenas and Vaziri, 2012; Li et al., 2019).
Relevance	Indicators should have relevancy to the sustainability (Afgan et al., 2000).
Accessibility	Relevant data must be available (Lee and Zhong, 2015; Reisi et al., 2014; Haghshenas and Vaziri, 2012; Li et al., 2019).
Timeliness	Indicators should be based on timely information (Lee and Zhong, 2015).

The hierarchical structure of the OESI is presented in 3.3, while units and brief descriptions are indicated in Table 3.4.

**Table 3.3.** 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 <sub>2</sub> O and CH <sub>4</sub> emissions	N <sub>2</sub> O emissions from energy processes	IEN1
		CH <sub>4</sub> emissions from energy processes	IEN2
	CO <sub>2</sub> emissions	CO <sub>2</sub> emissions from solid fuel combustion	IEN3
		CO <sub>2</sub> emissions from liquid fuel combustion	IEN4
		CO <sub>2</sub> 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”, sub-criteria at the second level are referred to as “criteria”, and sub-criteria at the third level are referred to as “indicators” for simplifying the representation

**Table 3.4.** Units and brief descriptions of indicators.

Code	Unit	Description
IEC1	kgoe <sup>1</sup> per capita	primary energy consumption <sup>2</sup> on a per capita basis
IEC2	kgoe per GDP <sup>3</sup>	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 <sup>4</sup>
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 <sub>2</sub> equivalent per capita	N <sub>2</sub> O emissions from energy-related processes on a per capita basis
IEN2	ton of CO <sub>2</sub> equivalent per capita	CH <sub>4</sub> emissions from energy-related processes on a per capita basis
IEN3	ton of CO <sub>2</sub> per capita	CO <sub>2</sub> emissions from solid fuel combustion on a per capita basis
IEN4	ton of CO <sub>2</sub> per capita	CO <sub>2</sub> emissions from liquid fuel combustion on a per capita basis
IEN5	ton of CO <sub>2</sub> per capita	CO <sub>2</sub> 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

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

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

<sup>3</sup> GDP is converted to USD by using 2011 rates of purchasing power parity.

<sup>4</sup> pilferage is included.

As mentioned before, although there are no guidelines for indicator selection, it is important that indicators are related with overall energy sustainability. The relevance of indicators and the academic sources used for determining indicators have been provided by Tables 3.5 and 3.6 respectively.

**Table 3.5.** Relevance of indicators.

Code	Relevance
IEC1	Plays a role in aggregating energy intensity (IAEA, 2005).
IEC2	Reflects the relationship between economic development and energy use (IAEA, 2005).
IEC3	The mixture of energy supply is considered as a key determinant of energy security (IAEA, 2005).
IEC4	Taking steps to improve the efficiency of energy supplies and to reduce losses during
IEC5	transmission contributes to effective utilization of energy resources (IAEA, 2005).
IEC6	Macroeconomic stability plays an important role in economic growth, as instability creates
IEC7	uncertainty about future values of economic variables. Since economic development
IEC8	enables the provision of better energy services, macroeconomic conditions of an economy
IEC9	influence the economic dimension (Chirwa and Odhiambo, 2016).
IEN1	The amount of N <sub>2</sub> O and CH <sub>4</sub> emissions per capita is considered as an indicator for
IEN2	environmental sustainability (World Economic Forum, 2017).
IEN3	CO <sub>2</sub> emissions from combustion of fuels for energy contribute heavily to global warming
IEN4	
IEN5	
IEN6	Developing environmental legislation is an important step for the international community to organize itself to take environmental action [49]. Not only the design but also the enforcement of legislation plays an important role for it to “work” (Gunningham, 2011).
IEN7	
ISO1	Access to modern energy services is required to avoid poverty as well as deprivation (IAEA, 2005).
ISO2	The level of access to electricity supply is considered as an indicator of environmental energy equity (World Energy Council, 2016).
ISO3	For social development, affordability of modern energy services across the population
ISO4	should be examined (IAEA, 2005).
ISO5	

**Table 3.6.** Academic sources used for determining indicators for OESI.

Code(s)	Sources
IEC1, IEC2, IEC3	(IAEA, 2005)
IEC4	(IAEA, 2005; Evans et al., 2009)
IEC5	(IAEA, 2005)
IEC6	(Cîrstea et al., 2018; World Energy Council, 2016; Chirwa and Odhiambo, 2016)
IEC7, IEC9	(World Energy Council, 2016; Schwab & Sala-i-Martin, 2017; Chirwa and Odhiambo, 2016)
IEC8	(Cîrstea et al., 2018; World Energy Council, 2016; Chirwa and Odhiambo, 2016)
IEN1, IEN2	(World Economic Forum, 2017)
IEN3, IEN4, IEN5	(Iddrisu and Bhattacharyya, 2015)
IEN6, IEN7	(Bleicher, 1972; Gunningham, 2011; Crotti and Misrahi, 2017; Evans et al., 2009)
ISO1	(IAEA, 2005)
ISO2	(World Energy Council, 2016)
ISO3, ISO4, ISO5	(World Energy Council, 2016; IAEA, 2005)

It is vital to underline that each indicator has an impact on OESI and the effect is either the larger the better, smaller the better, closer to the desired value the better or closer to the desired set of values the better. The impacts of indicators on OESI are indicated by Table 3.7. The desired set of values is determined as the values lying between 0.5% and 2.9% based on the study of Schwab and Sala-i-Martin (2017).

**Table 3.7.** Impact of each indicator value on OESI.

Larger the better	Smaller the better	Closer to the desired value or set of values the better
IEC1	IEC5	IEC8 <sup>1</sup>
IEC2	IEC9	
IEC3	IEN1	
IEC4	IEN2	
IEC6	IEN3	
IEC7	IEN4	
IEN6	IEN5	
IEN7	ISO3	
ISO1	ISO4	
ISO2	ISO5	

<sup>1</sup> The desired set of values is determined as the values lying between 0.5% and 2.9%.

GRA method was applied to indicators as given in Table 3.8 with equal weights for calculating the value of IEC3. The desired value was determined to be 16.667% valid for all indicators depending on authors' projection based on World Bank data. Waste to energy has been excluded from the list due to data unavailability and unreliable information coming from the power plants such as the rate of organic material that have been incinerated in these facilities. Furthermore, World Bank also recognizes as 6 different sources for electricity generation as shown in the following table.

**Table 3.8.** Sub-indicators for calculating IEC3 (closer to the desired value the better).

Indicators	Code
Electricity generation from coal sources <sup>1</sup>	ISE1
Electricity generation from oil sources <sup>1</sup>	ISE2
Electricity generation from natural gas sources <sup>1</sup>	ISE3
Electricity generation from nuclear sources <sup>1</sup>	ISE4
Electricity generation from hydroelectric sources <sup>1</sup>	ISE5
Electricity generation from renewable sources (except hydroelectric) <sup>1</sup>	ISE6

<sup>1</sup> The desired value was determined to be 16.667% (authors' projection based on World Bank data).

### **3.1.2. Fuzzy AHP**

Forman and Gass (2001) state that AHP is a popular MCDM method that can be used to deal with complex problematic situations such as allocation of scarce resources, ranking alternatives in a multi-objective environment, and forecasting. The weights of criteria are determined by making pairwise comparisons in this method. In such a comparison, the judgements coming from decision makers are used as an input to the AHP model to determine the criteria weights (Chai et al., 2013; De FSM Russo and Carmanho, 2015). The flexible nature of AHP allows it to be integrated with other methods, which make it possible for a decision maker to benefit from other methods too (Vaidya and Kumar, 2006; Mafakheri et al., 2011; Bhattacharya et al., 2010; Ishizaka et al., 2012).

AHP is a technique in which judgements from experts are based on crisp logic and it is commonly used for prioritizing different alternatives, by using complex criteria. When applying AHP it is assumed that the expert judgment is exact, so uncertainties occur due to human nature are neglected. A nine-point numerical scale is used for comparing criteria which belong to the same level in a hierarchical structure (Benitez et al., 2011; Wang and Chin, 2011).

Kilincci and Onal (2011) emphasize the importance of benefiting a much comprehensive tool instead of a nine-point numerical scale, since there is vagueness in personal judgments in real-life applications. Fuzzy integrated AHP is a method that is commonly used in the literature to deal with the uncertainties of a decision problem (Haq and Kannan, 2006; Chamodrakas et al., 2010; Chan et al., 2008; Lu et al., 2007).

Criteria weights which will be used in GRA calculations are determined by using a fuzzy AHP method. In our method, linguistic variables received from decision makers are transformed into triangular fuzzy numbers to determine fuzzy weights by using geometric mean approach. Table 3.9 provides information on linguistic terms and corresponding fuzzy triangular numbers.

**Table 3.9.** 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.

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. Following equations demonstrate the mathematical notation of a fuzzy number and algebraic operations between two fuzzy numbers are indicated by the following equations (Kahraman et al., 2003).

$$\tilde{M} = (l, m, u) \quad 3.1$$

$$(\tilde{M})^{-1} = (l, m, u)^{-1} = \left( \frac{1}{u}, \frac{1}{m}, \frac{1}{l} \right) \quad 3.2$$

$$\tilde{M}_1 \oplus \tilde{M}_2 = (l_1, m_1, u_1) \oplus (l_2, m_2, u_2) = (l_1 + l_2, m_1 + m_2, u_1 + u_2) \quad 3.3$$

$$\tilde{M}_1 - \tilde{M}_2 = (l_1, m_1, u_1) - (l_2, m_2, u_2) = (l_1 - l_2, m_1 - m_2, u_1 - u_2) \quad 3.4$$

$$\tilde{M}_1 \otimes \tilde{M}_2 = (l_1, m_1, u_1) \otimes (l_2, m_2, u_2) = (l_1 l_2, m_1 m_2, u_1 u_2) \quad 3.5$$

With respect to Equation (3.3) and Equation (3.5), following equations are created for multiplication and addition of fuzzy numbers:

$$\prod_{i=1}^n \tilde{M}_i = \left( \prod_{i=1}^n l_i, \prod_{i=1}^n m_i, \prod_{i=1}^n u_i \right) \quad 3.6$$

$$\sum_{i=1}^n \tilde{M}_i = \left( \sum_{i=1}^n l_i, \sum_{i=1}^n m_i, \sum_{i=1}^n u_i \right) \quad 3.7$$

The first step of the method is about receiving feedback from decision makers. Then, a judgement matrix is formed which indicate the fuzzy triangular numbers corresponding to the linguistic terms, as shown by Equation 3.8.

$$\tilde{M}_{ij} = \begin{bmatrix} \tilde{M}_{11} & \tilde{M}_{12} & \dots & \tilde{M}_{1n} \\ \tilde{M}_{21} & \tilde{M}_{22} & \dots & \tilde{M}_{2n} \\ \vdots & \vdots & \dots & \vdots \\ \tilde{M}_{n1} & \tilde{M}_{n2} & \dots & \tilde{M}_{nn} \end{bmatrix} = \begin{bmatrix} l_{11}m_{11}u_{11} & l_{12}m_{12}u_{12} & \dots & l_{1n}m_{1n}u_{1n} \\ l_{21}m_{21}u_{21} & l_{22}m_{22}u_{22} & \dots & l_{2n}m_{2n}u_{2n} \\ \vdots & \vdots & \dots & \vdots \\ l_{n1}m_{n1}u_{n1} & l_{n2}m_{n2}u_{n2} & \dots & l_{nn}m_{nn}u_{nn} \end{bmatrix} \text{ for } \begin{matrix} i = 1, 2, \dots, n \\ j = 1, 2, \dots, n \end{matrix} \quad 3.8$$

The next step is to convert the geometric mean of fuzzy comparison values into crisp values and perform normalization by considering following equation:

$$\tilde{F}_i = \tilde{R} \otimes \tilde{G}_i = \left( \sum_{i=1}^n \sqrt[n]{\prod_{j=1}^n \tilde{M}_{ij}} \right)^{-1} \otimes \sqrt[n]{\prod_{j=1}^n \tilde{M}_{ij}} \quad 3.9$$

$\tilde{G}_i$  represents the geometric mean value of triangular fuzzy numbers for  $C_i$  criterion,

$\tilde{R}$  represents the reciprocal of the sum of the geometric mean of fuzzy comparison values, and

$\tilde{F}_i$  represents the fuzzy weight for  $C_i$  criterion.

The last steps of the fuzzy AHP process include taking arithmetic mean of fuzzy weights and perform normalization. This is done to ensure that the sum of the weights is equal to 1. In the case of multiple decision makers the arithmetic mean of the final criteria weights is calculated for each decision maker.

### 3.1.3. GRA

The method of GRA is based on determining existing correlation between sequences by using the information available to the decision makers. To achieve this, an ideal sequence is defined, and comparative sequences are created based on the performances of alternatives. This allows to determine the trend correlation between the ideal sequence and comparative sequences. The comparative sequence that leans more toward concordance with the ideal sequence has the highest grey relational degree. Therefore, related alternative is considered as the optimum choice (Mohamed et al., 2009; Lin et al., 2009; Wei, 2010).

#### 3.1.3.1. Overview of GRA

The concept of GRA is based on a mathematical approach depending on the correlation between the series that compose a set space. It uses a specific algorithm to determine the distance between the pre-determined reference series (developed based on the set) and each of the series of the set (comparative series). By applying the algorithm, the ranking of the different alternatives can be obtained.

The available information within a system may contain uncertainties due to different kind of reasons such as linguistic ambiguity, inaccuracy or inadequacy of received information, conflicting nature of data, undetermined system behavior, lack of data about parameters, boundary and structure of the system. This triggered researchers to work on theories and methodologies to overcome uncertainty. Fuzzy systems theory, grey systems theory and rough set theory are some of the important examples for such efforts. The grey systems theory is a methodology, which is able to deal with systems that contain small sample size and partially known information by excavating and extracting any useful data to solve complex problems (Sifeng et al., 2011).

The grey relational analysis (GRA) shapes a major proportion of grey theory, since the goal is to investigate whether two information curves are related considering their geometric similarity. The more similar the curves are, the high is the grey relational degree. Therefore, it is not required to have a large sample size or a pre-determined distribution (Javanmardi et al., 2020).

GRA benefits from the correlation between a pre-determined reference (ideal) sequence and comparative sequences. Each comparative sequence is compared with the reference sequence to determine the grey relational degree. The aim is to determine the comparative sequence which leans more toward concordance with the ideal sequence (Altintas et al., 2020).

A literature review was conducted to explore GRA-based methods used in sustainability energy studies and their impacts on such studies. Databases such as ScienceDirect, Scopus, and Web of Science (WoS) have been used to find publications between the years 2010 – 2020. The keywords are selected as "Grey Relational Analysis" and "Energy Sustainability". Table 3.10 shows the publications:

Ebrahimi and Rahmani (2019) revealed major limitations and drawbacks of current GRA methods as a MCDM tool and proposed a hybrid method by combining Shannon entropy technique for criteria weighting. Iran's energy producers have been assessed and ranked by considering 27 different criteria along with 5 major dimensions. Dimensions were identified as; environmental, social, economic, technical, and institutional.

In another study (Wu et al., 2018) a hybrid MCDM model is introduced for assessing the

sustainability levels of coal-fired power units in China. The hybrid model benefits from areal grey relational analysis, fuzzy rough sets and analytic hierarchy process. According to the authors, this method is superior in its capability of determining the relationships between adjacent indicators, and also provides more satisfying results in criteria weighting since it uses both subjective and objective criteria weighting techniques.

A modified version of TOPSIS with grey incidence analysis was introduced by Niu et al. (2018) for evaluating the level of sustainability for electric power construction projects. The grey incidence analysis was used to improve the traditional TOPSIS, so that the evaluation of the objects in the aspect of nearness and similarity becomes possible. The relative closeness scores were calculated with this approach and alternatives were ranked accordingly.

**Table 3.10.** GRA studies between 2010 – 2020.

<b>Energy Sustainability</b>	
<i>STUDY</i>	<i>REFERENCE</i>
An Extended GRA Method Integrated with Fuzzy AHP to Construct a Multidimensional Index for Ranking Overall Energy Sustainability Performances	Altintas et al. (2020)
A five-dimensional approach to sustainability for prioritizing energy production systems using a revised GRA method: A case study	Ebrahimi and Rahmani (2019)
An Integrated Multi-Criteria Decision Making Model and AHP Weighting Uncertainty Analysis for Sustainability Assessment of Coal-Fired Power Units	Wu et al. (2018)
External Benefit Evaluation of Renewable Energy Power in China for Sustainability	Zhao and Guo (2015)
A grey-based group decision-making methodology for the selection of hydrogen technologies in life cycle sustainability perspective	Manzardo et al. (2012)
General sustainability indicator of renewable energy system based on grey relational analysis	Liu et al. (2013)
A multi-criterion decision making for sustainability assessment of hydrogen production technologies based on objective grey relational analysis	Li et al. (2020)
Polygeneration system and sustainability: Multi-attribute decision support framework for comprehensive assessment under uncertainties	Wang et al. (2017)
Technology selection for photovoltaic cell from sustainability perspective: An integrated approach	Fang et al. (2020)
Multi-criteria decision making for the prioritization of energy systems under uncertainties after life cycle sustainability assessment	Ren (2018)
Integrated grey relational analysis and multi objective grey linear programming for sustainable electricity generation planning	Malekpoor et al. (2018)

The first step of GRA procedure is to create the decision matrix for a MCDM problem that consists of a set of alternatives ( $A_1, A_2, \dots, A_m$ ) and criteria ( $C_1, C_2, \dots, C_n$ ) formed as shown in Equation (3.10). Afterwards, the ideal sequence should be identified and added to the decision matrix as a reference.

$$X_{ij} = \begin{bmatrix} X_{11} & X_{12} & \dots & X_{1n} \\ X_{21} & X_{22} & \dots & X_{2n} \\ \vdots & \vdots & \dots & \vdots \\ X_{m1} & X_{m2} & \dots & X_{mn} \end{bmatrix} \text{ for } \begin{matrix} i = 1, 2, \dots, m \\ j = 1, 2, \dots, n \end{matrix} \quad 3.10$$

$X_{ij}$  represents the performance of alternative  $A_i$  for criterion  $C_j$ .

With respect to the existing literature, the ideal sequence may consist of “larger the better” criteria, “smaller the better” criteria, and “closer to the desired value the better” criteria. The normalization step (grey relational generating), which is required to transform input data into a comparable form, is performed by using one of the following equations depending on the type of the criteria. Equation (3.11) is used for larger the better criteria, Equation (3.12) is used for smaller the better criteria, and Equation (3.13) is used for closer to the desired value the better criteria (Kuo et al., 2018; Malekpoor et al., 2018).

$$X_{ij}^* = \frac{X_{ij} - \min(X_{ij}, i = 1, 2, \dots, m)}{\max(X_{ij}, i = 1, 2, \dots, m) - \min(X_{ij}, i = 1, 2, \dots, m)} \text{ for } \begin{matrix} i = 1, 2, \dots, m \\ j = 1, 2, \dots, n \end{matrix} \quad 3.11$$

$$X_{ij}^* = \frac{\max(X_{ij}, i = 1, 2, \dots, m) - X_{ij}}{\max(X_{ij}, i = 1, 2, \dots, m) - \min(X_{ij}, i = 1, 2, \dots, m)} \text{ for } \begin{matrix} i = 1, 2, \dots, m \\ j = 1, 2, \dots, n \end{matrix} \quad 3.12$$

$$X_{ij}^* = 1 - \frac{|X_{ij} - X_{d_{vj}}|}{\max\{\max(X_{ij}, i = 1, 2, \dots, m) - X_{d_{vj}}, X_{d_{vj}} - \min(X_{ij}, i = 1, 2, \dots, m)\}} \text{ for } \begin{matrix} i = 1, 2, \dots, m \\ j = 1, 2, \dots, n \end{matrix} \quad 3.13$$

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

$X_{d_{vj}}$  is the desired value for criterion  $C_j$ .

After applying the normalization process, data is adjusted in a way so that each value falls within the range of [0,1]. If this value is equal to 1 or is the closest value to 1 compared to others, the

performance of that alternative is considered as the best for that criterion. In contrast, if this value is equal to 0 or is the closest value to 0 compared to others, the performance of that alternative is considered as the worst one for that criterion.

After the normalization process, the grey relational coefficient is calculated by using Equations 3.14 and 3.15. This is performed to identify how close the normalized sequence is to the corresponding reference sequence.

$$\Delta_{ij} = |X_{ij}^* - X_{oj}| \quad \text{for } i = 1, 2, \dots, m \quad j = 1, 2, \dots, n \quad 3.14$$

$$\gamma(X_{oj}, X_{ij}^*) = \frac{\min(\Delta_{ij}, i = 1, 2, \dots, m; j = 1, 2, \dots, n) + \zeta \max(\Delta_{ij}, i = 1, 2, \dots, m; j = 1, 2, \dots, n)}{\Delta_{ij} + \zeta \max(\Delta_{ij}, i = 1, 2, \dots, m; j = 1, 2, \dots, n)} \quad \text{for } \begin{matrix} i = 1, 2, \dots, m \\ j = 1, 2, \dots, n \end{matrix} \quad 3.15$$

$\gamma(X_{oj}, X_{ij}^*)$  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,

$\zeta$  is defined as the identification coefficient (for compressing or expanding the range of the grey relational coefficient to be calculated, identified as 0.5 based on the literature available (Sofyalioğlu and Öztürk, Ş., 2012; Mohamed et al., 2009; Lin et al., 2009; Kuo et al., 2008; Malekpoor et al, 2018)).

The final correlation between the comparative and reference sequences is represented by grey relational grade and it is calculated by Equation 3.16. The lower the value of the grey relational grade, the worse is the performance of the corresponding alternative.

$$\Gamma(X_i) = \sum_{j=1}^n W_j \gamma(X_{oj}, X_{ij}^*) \quad \text{for } i = 1, 2, \dots, m \quad 3.16$$

$\Gamma(X_i)$  represents the grey relational grade for alternative  $A_i$ , and

$W_j$  is the weight of  $C_j$  obtained with fuzzy AHP.

### 3.1.3.2. The Discussion for GRA

The concept of GRA is based on a mathematical approach depending on the correlation between the series that compose a set space. It uses a specific algorithm to determine the distance between the pre-determined reference series (developed based on the set) and the each of the series of the set (comparative series). By applying the algorithm, the ranking of the different alternatives can be obtained.

Many MCDM methods have been introduced to the literature so far, which all have different strength and weaknesses. Some advantages and disadvantages have been discussed in the previous chapter. Furthermore, it is important to decide on the MCDM method from the application point of view. It is possible to claim that each none of the MCDM methods would be able to provide 100% satisfying results, and there is always room for arguments. This makes MCDM an attractive research area that continuously grows.

In the case study, the aim is to rank the overall energy sustainability performances of 35 OECD member countries. The model is based on a hierarchical structure that is composed of 3 levels of criteria. Since, there were challenges in data gathering due to reasons such as large number of countries to be compared and large number of criteria to be used, different data sources have been used which made the data accuracy questionable. From that point of view, GRA provides the superior solution among other MCDM methods. Based on the study of Lu and Wevers (2017), the clear advantage of the GRA method is the requirement of only relative accuracy of attribute values within each attribute vector, and not absolute accuracy for every attribute value, which provides an essential difference of this method with other presented methods. As far as the attributes used are expressed in physical measurement units, other methods require absolute accuracy for each attribute value on its own. The advantage of using GRA in energy sustainability applications due to the lack of accurate information on attributes have been emphasized by different studies. For instance, Ebrahimi and Rahmani (2017) claimed that many MCDM methods are incompatible with real-world applications in evaluating energy producers, which led them to use GRA in their research to prioritize energy production systems.

Another reason why using GRA is superior to others lie in its the normalization model. As shown by the study of Lu and Wevers (2017), the application of different normalization methods may

have an influence on the obtained ranking. In its standard normalization approach, GRA provides a method of linear normalization which is slightly more sophisticated than what is normally called linear normalization. They state that this procedure does not affect the interrelationships between the data series and therefore provides a more robust result. This claim can be supported with the work of Lie et al. (2020) which has used GRA in sustainability assessment of hydrogen production technologies. They claimed that the advantage of being simple, robust, and practical made GRA an attractive method to be used.

### 3.1.3.3. Revised and Extended GRA Normalization Procedure

In MCDM problems one of the challenges that needs to be faced is to bring attributes with different character to a common denominator, so that deriving an adequate ranking is possible. Different procedures of normalization may be used based on the method and the application. For instance, linear normalization for benefit type attributes divides the attribute value by the maximum value of the attribute range, whereas vector normalization divides the attribute value by the square root of the sum of the squares of all attribute values in the range.

Although, the normalization procedure for the closer to the desired value the better criteria represented in the literature works in cases where the value of at least one of the alternatives is equal to the desired value, it does not align with the concept of the procedures applied for the larger the better and the smaller the better criteria in cases where there none of the values is equal to the desired value. The procedure should include assigning 1 to the best alternative and 0 the worst one considering the Equations 3.11 and 3.12.

The proposed solution is to add another normalization step to solve this problem by introducing a pre-normalization step indicated by Equation (3.17) and a normalization step indicated by Equation (3.18).

$$Y_{ij} = \frac{|X_{ij} - X_{advj}|}{\max(X_{ij}, i = 1, 2, \dots, m) - \min(X_{ij}, i = 1, 2, \dots, m)} \quad \text{for } \begin{matrix} i = 1, 2, \dots, m \\ j = 1, 2, \dots, n \end{matrix} \quad 3.17$$

$$X_{ij}^* = \frac{\max(Y_{ij}, i = 1, 2, \dots, m) - Y_{ij}}{\max(Y_{ij}, i = 1, 2, \dots, m) - \min(Y_{ij}, i = 1, 2, \dots, m)} \quad \text{for } \begin{matrix} i = 1, 2, \dots, m \\ j = 1, 2, \dots, n \end{matrix} \quad 3.18$$

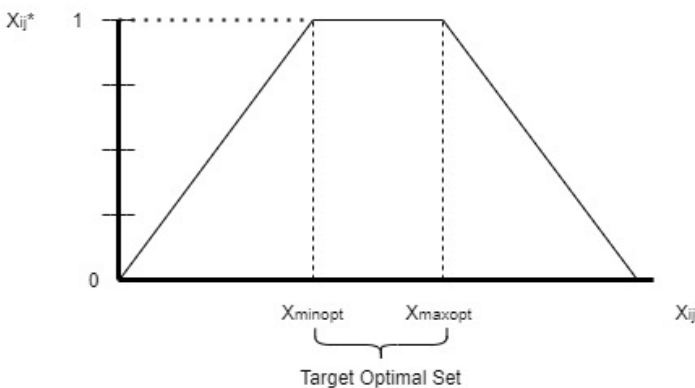
$Y_{ij}$  is the pre-normalization value.

In sustainability applications, it is possible to encounter cases where a set of values is considered optimum instead of a single value. In total 4 different scenarios may be possible; all the optimal values are greater than the highest alternative value, all the optimal values are lower than the lowest alternative value, all the optimal values lie between the maximum and minimum alternative values, the set of optimal values includes the minimum or maximum alternative value and not the other. Table 3.11 shows the equations to be used for each different scenario.

**Table 3.11.** Different scenarios and equations to be applied.

Scenario	Equations to be applied
All the optimal values are greater than the highest alternative value	Equation 3.11
All the optimal values are lower than the lowest alternative value	Equation 3.12
All the optimal values lie between the maximum and minimum alternative values	Equation 3.18 for normalization & 3.19 for pre-normalization
The set of optimal values includes the minimum or maximum alternative value and not the other	Equation 3.18 for normalization & 3.20 for pre-normalization

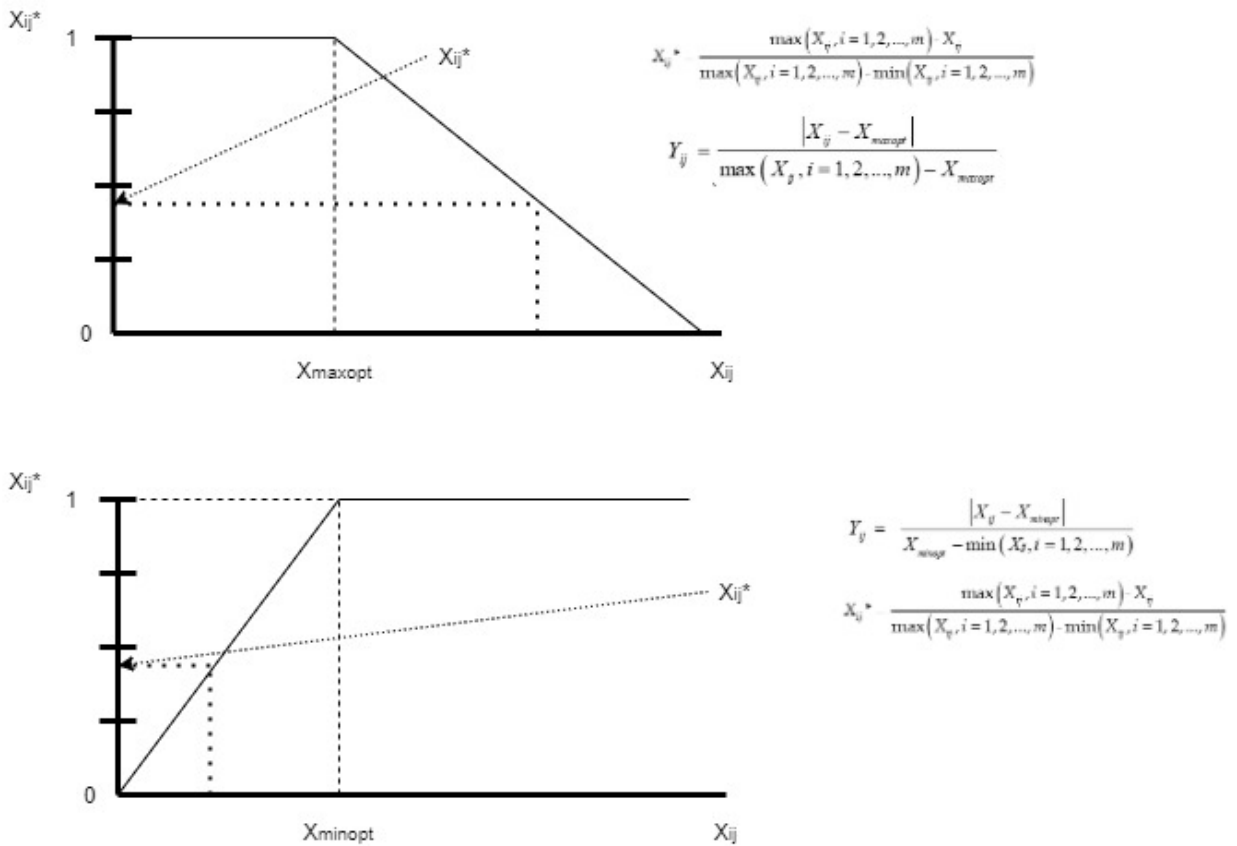
In case of the all the optimal values lie between the maximum and minimum alternative values, the value or  $X_{ij}^*$  will be 1 if it lies between those values. On the other hand, values for  $X_{ij}^*$  will decrease linearly, as its value moves away from the optimal set (Figure 3.1).



**Figure 3.1.** Graphical representation of normalization procedure for all the optimal values lies between the maximum and minimum alternative values.

$$Y_{ij} = \begin{cases} \frac{|X_{ij} - X_{maxopt}|}{\max(X_{ij}, i = 1, 2, \dots, m) - \min(X_{ij}, i = 1, 2, \dots, m)}, & \text{where } X_{maxopt} < X_{ij} \leq \max(X_{ij}, i = 1, 2, \dots, m) \\ 0 & \text{, where } X_{minopt} \leq X_{ij} \leq X_{maxopt} \\ \frac{|X_{ij} - X_{minopt}|}{\max(X_{ij}, i = 1, 2, \dots, m) - \min(X_{ij}, i = 1, 2, \dots, m)}, & \text{where } \min(X_{ij}, i = 1, 2, \dots, m) \leq X_{ij} < X_{minopt} \end{cases} \quad 3.19$$

If the set of optimal values includes the minimum alternative value and not the maximum,  $X_{ij}^*$  will equal to 1 where, its value is higher than the minimum alternative value. On the other hand,  $X_{ij}^*$  will equal to 1 where, its value is smaller than the maximum alternative value (Figure 3.2).



**Figure 3.2.** Graphical representation of normalization procedure for the set of optimal values includes the minimum or maximum alternative value and not the other.

$$Y_{ij} = \begin{cases} \frac{|X_{ij} - X_{minopt}|}{X_{minopt} - \min(X_{ij}, i = 1, 2, \dots, m)}, \text{ where } \min(X_{ij}, i = 1, 2, \dots, m) < X_{minopt} < \max(X_{ij}, i = 1, 2, \dots, m) < X_{maxopt} \\ X_{ij} < X_{minopt} \end{cases} \quad 3.20$$

$$\begin{cases} \frac{|X_{ij} - X_{maxopt}|}{\max(X_{ij}, i = 1, 2, \dots, m) - X_{maxopt}}, \text{ where } X_{minopt} < \min(X_{ij}, i = 1, 2, \dots, m) < X_{maxopt} < \max(X_{ij}, i = 1, 2, \dots, m) \\ X_{ij} > X_{maxopt} \end{cases}$$

The approach given in this dissertation also provides promising opportunities not just in linear but also non-linear applications. It is possible to apply current GRA procedure by modifying the normalization procedure step. For instance, Table 3.12 is created to demonstrate different functions for a specific criterion, square root function, linear function, and square function. In this case, there are 11 alternatives, and the maximum value is considered as 100 and minimum is 0. As indicated from the table, there is a huge difference based on the function to be used. The reason to use different functions can be explained by the difference in the effect based on the value of alternative for a specific criterion.

**Table 3.12.** Representation of different functions (max is better)

	1	2	3	4	5	6	7	8	9	10	11
<i>Criteria Values</i>	0	10	20	30	40	50	60	70	80	90	100
<i>Linear Function</i>	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
<i>Square Root Function</i>	0	0.32	0.45	0.55	0.63	0.71	0.77	0.84	0.89	0.95	1
<i>Square Function</i>	0	0.01	0.04	0.09	0.16	0.25	0.36	0.49	0.64	0.81	1

Thus, such a function can be represented as Equation 3.21 and 3.22 for larger the better and smaller the better criteria, respectively.

$$X_{ij}^* = \left( \frac{X_{ij} - \min(X_{ij}, i = 1, 2, \dots, m)}{\max(X_{ij}, i = 1, 2, \dots, m) - \min(X_{ij}, i = 1, 2, \dots, m)} \right)^n \quad \text{for } \begin{matrix} i = 1, 2, \dots, m \\ j = 1, 2, \dots, k \end{matrix} \quad 3.21$$

$$X_{ij}^* = \left( \frac{\max(X_{ij}, i = 1, 2, \dots, m) - X_{ij}}{\max(X_{ij}, i = 1, 2, \dots, m) - \min(X_{ij}, i = 1, 2, \dots, m)} \right)^n \quad \text{for } \begin{matrix} i = 1, 2, \dots, m \\ j = 1, 2, \dots, k \end{matrix} \quad 3.22$$

Where n can be any number depending on the function to be used. As indicated in the previous chapters, each sub-indicator used for creating the diversification of sources for electricity generation criterion has a weight of 16.667% based on Author's projection. However, if this criterion was evaluated from the perspective of energy security, many different factors would also influence the weight of these sub-indicators such as resource estimates, reserves to production ratios, diversity indices, import dependence, political stability, the energy price, mean variance portfolio theory and share of zero-carbon fuels and market liquidity (Kruyt et al., 2009).

An additional scenario was created based on the claim that the sources must be diverse and there is too much dependence on a specific source. Based on the author's projection a scenario that is based on two different functions are created. According to this scenario, if the dependence of a specific source is more than 50% than square root function is used for 50% to 100%.

### 3.2. Representation and Analysis of Results

As mentioned in the previous section, calculating the weights for each indicator is necessary before applying GRA procedures. Following Tables 3.13 and 3.14 show the weights of criteria and indicators, which are found out by applying fuzzy AHP procedures. As observed in the following tables, while the economic and security dimension have the greatest impact on OESI, the environmental and social dimensions have similar impacts. In Table 3.13, weights are calculated out of 1. However, the sum may not be exactly equal to 1 since fractional rounding has been applied during calculations. The same also applies for Table 3.14.

**Table 3.13.** 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

**Table 3.14.** Criteria weights.

Dimensions	Weights (%)	Criteria	Weights (%)
<b>Economic and Security</b>	50.33	Energy use patterns and diversification	24.06
		Supply efficiency	20.81
		Macroeconomic context	5.46
<b>Environmental</b>	27.61	N <sub>2</sub> O and CH <sub>4</sub> emissions	9.70
		CO <sub>2</sub> emissions	14.84
		Environmental regulations	3.06
<b>Social</b>	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.

By taking other energy sustainability indices into account, it is possible to claim that there are similarities between the results. Even though each index is different from each other in terms of objective and may consider 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 (World Economic Forum, 2017), and World Energy Trilemma Index (World Energy Council, 2016). The results are presented in Table 3.15.

**Table 3.15.** Results of OESI.

Countries	Score (Total)	Rank (Total)	Score (Ec. and Se.) <sup>1</sup>	Rank (Ec. and Se.) <sup>1</sup>	Score (Env.) <sup>2</sup>	Rank (Env.) <sup>2</sup>	Score (Soc.) <sup>3</sup>	Rank (Soc.) <sup>3</sup>
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

<sup>1</sup> Ec. and Se. refers to Economic and Security.

<sup>2</sup> Env. refers to Environmental.

<sup>3</sup> Soc. refers to Social.

It is important to emphasize that a snapshot of overall energy sustainability performances of countries on a comparative scale is provided by the Overall Energy Sustainability Index and therefore the results must be interpreted with circumspection. In order to obtain a more comprehensive insight into overall energy sustainability, a disaggregated evaluation at the sub-

criteria level is useful. It will allow policy makers to focus on areas that needs to be improved.

Tables 3.16, 3.17 and 3.18 present weighted indicator values.

**Table 3.16.** Weighted indicator values (economic and security dimension).

<b>Countries</b>	<b>IEC1</b>	<b>IEC2</b>	<b>IEC3</b>	<b>IEC4</b>	<b>IEC5</b>	<b>IEC6</b>	<b>IEC7</b>	<b>IEC8</b>	<b>IEC9</b>
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 3.17.** Weighted indicator values (environmental dimension).

<b>Countries</b>	<b>IEN1</b>	<b>IEN2</b>	<b>IEN3</b>	<b>IEN4</b>	<b>IEN5</b>	<b>IEN6</b>	<b>IEN7</b>
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.

**Table 3.18.** Weighted indicator values (social dimension).

**Table 14.** Weighted indicator values (social dimension)

<b>Countries</b>	<b>ISO1</b>	<b>ISO2</b>	<b>ISO3</b>	<b>ISO4</b>	<b>ISO5</b>
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

Based on the results, it is possible to claim that countries which performed high performance in OESI are the ones that could manage to link various aspects of energy sustainability. The overall scores are distributed between 0.807 and 0.518 out of 1. The reason of the absence of scores under 0.5 can be explained by the consideration of OECD countries in the research. Since OECD member countries are considered as alternatives in the study.

From the dimension point of view, economic and security dimension has much more effect on the OESI compared to environmental and social dimensions. It is observed that, the countries,

which benefit from various energy resources, are efficient in energy use, and have high productive uses of energy benefit from various energy resources achieved high points in this dimension. Thus, improving those areas would help maximizing overall energy sustainability.

With respect to environmental dimension, carbon dioxide, nitrous oxide, and methane emissions are the main drivers of environmental problems. Moreover, creating environmental awareness and promoting environmental education are important means for ensuring pressure on governments to trigger developing legislation and regulations useful to protect the environment.

The last place in the list is the social dimension. Policies aimed to implement a transition towards energy sustainability are required to be evaluated based on their effect on accessibility, quality, and affordability of energy services.

In case of applying the alternative model, two different functions are considered for calculating the diversification of sources for electricity generation indicator. As mentioned in the previous section, calculating the weights for each indicator is necessary before applying GRA procedures. Following Table 3.19 shows the weights of criteria and indicators, which have been calculated with two functions. In this case a linear function has been applied until reaching the value of 50%. However, if the value exceeds 50%, then it means that a country is too dependent on a specific source, and an additional square root function has been applied.

**Table 3.19.** Results of OESI (with two functions).

Countries	Score (Total)	Rank (Total)	Score (Ec. and Se.) <sup>1</sup>	Rank (Ec. and Se.) <sup>1</sup>	Score (Env.) <sup>2</sup>	Rank (Env.) <sup>2</sup>	Score (Soc.) <sup>3</sup>	Rank (Soc.) <sup>3</sup>
Australia	0.5467	31	0.2462	16	0.1387	35	0.1617	22
Austria	0.6522	6	0.265	7	0.2085	11	0.1787	15
Belgium	0.6077	20	0.2357	23	0.1956	24	0.1763	17
Canada	0.6151	17	0.2527	10	0.1685	33	0.1938	6
Chile	0.6006	24	0.2511	13	0.2214	4	0.1281	32
Czechia	0.5883	26	0.2363	21	0.199	21	0.153	25
Denmark	0.6317	10	0.2203	31	0.2163	6	0.195	5
Estonia	0.5647	29	0.2321	24	0.1902	27	0.1424	28
Finland	0.6607	5	0.2746	4	0.198	22	0.188	9
France	0.612	18	0.2192	32	0.2026	17	0.1902	7
Germany	0.6188	14	0.2512	12	0.2005	19	0.1671	20
Greece	0.6244	12	0.2798	3	0.2101	9	0.1346	30
Hungary	0.5496	30	0.2117	34	0.2083	12	0.1296	31
Iceland	0.8061	1	0.3767	1	0.2393	1	0.1901	8
Ireland	0.5767	27	0.218	33	0.1892	28	0.1696	19
Israel	0.6179	15	0.2475	15	0.1997	20	0.1707	18
Italy	0.6021	23	0.2425	18	0.2036	14	0.1559	24
Japan	0.637	8	0.2537	9	0.2032	15	0.1801	13
Korea	0.6283	11	0.2651	6	0.1843	29	0.1789	14
Latvia	0.544	33	0.2252	29	0.197	23	0.1217	33
Luxembourg	0.6076	21	0.2412	20	0.1713	31	0.1951	4
Mexico	0.5167	35	0.2223	30	0.2096	10	0.0848	35
Netherlands	0.6164	16	0.2359	22	0.1945	26	0.186	11
New Zealand	0.6425	7	0.2501	14	0.1952	25	0.1972	3
Norway	0.6749	3	0.2856	2	0.1686	32	0.2207	1
Poland	0.5458	32	0.2295	25	0.1804	30	0.1359	29
Portugal	0.594	25	0.2283	27	0.2214	5	0.1443	26
Slovakia	0.6191	13	0.2727	5	0.2037	13	0.1426	27
Slovenia	0.6066	22	0.2416	19	0.2018	18	0.1633	21
Spain	0.632	9	0.259	8	0.2137	7	0.1594	23
Sweden	0.6759	2	0.2514	11	0.2374	3	0.1871	10
Switzerland	0.6711	4	0.2277	28	0.2379	2	0.2055	2
Turkey	0.5337	34	0.2034	35	0.2101	8	0.1203	34
United Kingdom	0.6097	19	0.2289	26	0.2029	16	0.1779	16
United States	0.5677	28	0.2435	17	0.1415	34	0.1827	12

<sup>1</sup> Ec. and Se. refers to Economic and Security.

<sup>2</sup> Env. refers to Environmental.

<sup>3</sup> Soc. refers to Social.

Since a square root function has been used for the values between 50% and 100%, the difference between higher values is much low compared to the difference between lower values. If this was a squared function, then the opposite would be valid. Sub-indicator values for “Diversification of sources for electricity generation” can be seen in Tables 20 and 21.

**Table 3.20.** Sub-indicator values (single function case).

<b>Countries</b>	<b>IES1</b>	<b>IES2</b>	<b>IES3</b>	<b>IES4</b>	<b>IES5</b>	<b>IES6</b>
Australia	0.4151	0.3787	0.8542	0.6482	0.7834	0.7242
Austria	0.7982	0.3647	0.8576	0.6482	0.4783	1
Belgium	0.7626	0.3366	0.6113	0.579	0.7115	0.8618
Canada	0.8056	0.3565	0.738	1	0.4776	0.6672
Chile	0.6437	0.5382	0.9979	0.6482	0.7342	0.7801
Czechia	0.4716	0.3349	0.6306	0.66	0.7182	0.763
Denmark	0.8163	0.3527	0.8315	0.6482	0.7066	0.3333
Estonia	0.3333	0.3449	0.5963	0.6482	0.7091	0.9032
Finland	0.9098	0.3395	0.7348	0.6404	0.8393	0.9067
France	0.6972	0.3404	0.6437	0.3333	0.8549	0.6791
Germany	0.5521	0.3523	0.7676	0.9297	0.745	0.6744
Greece	0.5303	1	0.8903	0.6482	0.8897	0.9654
Hungary	0.9212	0.3367	1	0.4607	0.7158	0.7633
Iceland	0.6665	0.3337	0.5875	0.6482	0.4116	0.6905
Ireland	0.7787	0.3541	0.455	0.6482	0.7436	0.7338
Israel	0.5398	0.3649	0.4051	0.6482	0.7061	0.6043
Italy	1	0.4733	0.5223	0.6482	0.9798	0.7698
Japan	0.6581	0.7465	0.5128	0.6613	0.8313	0.7185
Korea	0.5556	0.4096	0.8267	0.694	0.7112	0.586
Latvia	0.6671	0.3339	0.4511	0.6482	0.6431	0.9678
Luxembourg	0.8925	0.334	0.3333	0.6482	0.8153	0.7666
Mexico	0.8553	0.9003	0.3541	0.7047	0.8601	0.6587
Netherlands	0.618	0.3591	0.4633	0.7005	0.7069	0.8389
New Zealand	0.7285	0.3333	0.9588	0.6482	0.5056	0.7387
Norway	0.6679	0.3337	0.6151	0.6482	0.3333	0.6001
Poland	0.3412	0.362	0.6497	0.6482	0.7203	0.8523
Portugal	0.7311	0.4178	0.8729	0.6482	1	0.6201
Slovakia	0.8751	0.3563	0.6898	0.424	0.9721	0.7058
Slovenia	0.7205	0.3361	0.6297	0.588	0.8172	0.6311
Spain	0.9171	0.5046	0.932	0.8877	0.8604	0.7308
Sweden	0.6835	0.3421	0.5951	0.6279	0.5744	0.9914
Switzerland	0.6665	0.3345	0.5982	0.6253	0.4894	0.6425
Turkey	0.7409	0.3515	0.5195	0.6482	0.8164	0.6827
United Kingdom	0.8417	0.3447	0.6451	0.8795	0.7305	0.7816
United States	0.6533	0.3527	0.6077	0.923	0.7891	0.702

**Table 3.21.** Sub-indicator values (two functions case).

<b>Countries</b>	<b>IES1</b>	<b>IES2</b>	<b>IES3</b>	<b>IES4</b>	<b>IES5</b>	<b>IES6</b>
Australia	0.3842	0.3787	0.8811	0.6805	0.7877	0.7712
Austria	0.815	0.3647	0.8839	0.6805	0.4222	1
Belgium	0.7814	0.3366	0.6654	0.614	0.7167	0.8889
Canada	0.8218	0.3565	0.7808	1	0.4217	0.7201
Chile	0.6679	0.5382	0.9983	0.6805	0.7392	0.8199
Czechia	0.4387	0.3349	0.6834	0.6918	0.7233	0.8052
Denmark	0.8319	0.3527	0.8619	0.6805	0.7119	0.3333
Estonia	0.3333	0.3449	0.6513	0.6805	0.7143	0.9229
Finland	0.9182	0.3395	0.7779	0.6732	0.8427	0.9258
France	0.7194	0.3404	0.6955	0.3333	0.858	0.7309
Germany	0.5784	0.3523	0.8068	0.9386	0.7498	0.7267
Greece	0.5569	1	0.9112	0.6805	0.8922	0.9728
Hungary	0.9286	0.3367	1	0.443	0.7209	0.8054
Iceland	0.6899	0.3337	0.643	0.6805	0.3758	0.7412
Ireland	0.7966	0.3541	0.5135	0.6805	0.7484	0.7796
Israel	0.5663	0.3649	0.4176	0.6805	0.7113	0.6621
Italy	1	0.4733	0.5803	0.6805	0.9803	0.811
Japan	0.6818	0.7465	0.571	0.6931	0.8348	0.7662
Korea	0.5819	0.4096	0.8578	0.724	0.7164	0.645
Latvia	0.6905	0.3339	0.5096	0.6805	0.6489	0.9747
Luxembourg	0.9024	0.334	0.3333	0.6805	0.8191	0.8083
Mexico	0.8681	0.9003	0.3501	0.734	0.8631	0.7124
Netherlands	0.643	0.3591	0.5219	0.7301	0.7122	0.8699
New Zealand	0.7492	0.3333	0.9671	0.6805	0.449	0.7839
Norway	0.6912	0.3337	0.6689	0.6805	0.3333	0.6583
Poland	0.3377	0.362	0.7011	0.6805	0.7254	0.881
Portugal	0.7517	0.4178	0.8968	0.6805	1	0.6768
Slovakia	0.8863	0.3563	0.7377	0.3973	0.9728	0.7549
Slovenia	0.7416	0.3361	0.6826	0.6227	0.821	0.687
Spain	0.9249	0.5046	0.9454	0.9014	0.8635	0.777
Sweden	0.7062	0.3421	0.6502	0.6612	0.5806	0.9933
Switzerland	0.6899	0.3345	0.6531	0.6587	0.4322	0.6976
Turkey	0.7609	0.3515	0.5776	0.6805	0.8202	0.7342
United Kingdom	0.8555	0.3447	0.6969	0.8941	0.7355	0.8212
United States	0.6772	0.3527	0.662	0.9327	0.7933	0.7514

Being able to use multiple functions makes it possible to benefit from multiple linear functions too. With respect to the pre-determined criteria, weights and functions, different slopes can be used for each function. The application area for using multiple functions reach far beyond than only energy security dimension. This may be helpful to understand the mathematical relation between all dimensions. An example would be to highlight the correlation between environmental problems and its effect on human well-being. The identification of function changing points would be the most important step when benefiting from such functions.

## 4. CONCLUSION

To define a country's position among others from sustainability point of view can be done by determining a quantitative basis to measure sustainability. As provided, the main assumption of this thesis is that sustainability assessment requires a set of multi-dimensional indicators to accomplish this goal. However, this leads to the question of how to aggregate indicators. The use of a multi-criteria framework (GRA based approach) for measuring energy sustainability has been discussed here.

It is obvious that the decision-making and selection of an appropriate method to achieve pre-determined objective is vital. It is possible to reconcile contradictory questions by using MCDM methods and choose the optimum solution based on criteria. This explains the reason of high popularity of MCDM methods dealing with energy policy or any other sustainability issue.

A framework has been built to develop the index for measuring the overall energy sustainability of various countries in this thesis. The objective of introducing such an index was to provide a benchmark for policy makers to assess energy sustainability performances with the help of a new underlying model. This model also can be used in different applications of sustainability. Such an approach contributes to efforts of researchers working on decision-making methods to deal with sustainability issues. However, the main objective of this work was the GRA methodology that has been developed for measuring overall energy sustainability of OECD countries.

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.

#### **4.1. Managerial Implications of the Research**

Grey Relational Analysis can be regarded as a popular method with easy calculations and being straightforward for analyzing relations between the discrete data sets. As indicated in the previous sections, the calculations are based on creating comparative sequences and comparing them with the ideal one (correlation degree of factors). To achieve this goal, performing normalization is an important process. The goal of normalization is to change the values of variables in the dataset to a common scale, without distorting differences in the ranges of values. It refers to rescaling by the minimum and range of the vector, to make all the elements lie between 0 and 1, so that all the values lie in a common scale. In other words, normalization makes sure that all data looks and reads the same way across all records.

Although, the normalization procedure for the closer to the desired value the better criteria represented in the literature works in cases where the value of at least one of the alternatives is equal to the desired value, it does not align with the concept of the procedures applied for the larger the better and the smaller the better criteria in cases where none of the values is equal to the desired value. The procedure should include assigning 1 to the best alternative and 0 the worst one. The proposed solution ensures that the normalization process has been performed in a way that the range for all values are between 0 and 1 (worst alternative taking 0 and best alternative taking 1 as values). By using this approach, it is also possible to normalize the values which have not one but more optimum values. Therefore, such revisions and extensions can be useful in sustainability applications. Furthermore, it has been shown that normalization with different functions can be also performed with the approach introduced in this thesis. This can be a useful technique especially for energy security dimension in energy sustainability.

Developing such a technique may represent a worldwide monitoring mechanism that points out the strengths and weaknesses of a country from the renewable energy sustainability point of view. The index provides required information to policy makers to increase the level of energy sustainability by improving positive impact indicators and by minimizing the values of negative impact indicators. By indicating the level of development of a country, it can also motivate governments to take the necessary steps for increasing the level of energy sustainability.

## **4.2. Limitations of the Research**

Diversification of sources for electricity generation is one of the most significant indicators in terms of criteria weights and other factors such as political stability, energy resource availability, energy dependence, and reserve-to-production ratio should influence its value. Those factors should be dependent on each other and their weights must be arranged on a country basis. However, this also brings new issues that needs to be dealt with. First, the method to be used for calculating criteria weights and how these criteria can affect each other must be determined. Secondly, the functions to be used must be identified. Lastly, the values for changing functions must be identified. Despite the problems, creating an extra energy security dimension provides a more comprehensive approach to determine the overall energy sustainability for different countries.

## **4.3. Further Research**

In terms of future research, taking steps to include future projection data for all dimensions can contribute to the efforts of developing the OESI. Furthermore, 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. Furthermore, it is also important to add an additional energy security dimension to adequately capture overall energy sustainability. This has gained popularity especially in recent studies such as Azzuni et al. (2020), Soleymani (2020) and Karatayev and Hall (2020). Therefore, by determining the set of indicators and applying the principles introduced in this thesis a more comprehensive index can be constructed. The issues regarding weight determination can be undertaken by considering objective weighting methods instead of subjective ones due to the complex decision process in which qualitative feedback can be misleading. Since the selection of functions are also an important issue to be solved, multiple models benefiting from a different combination of functions can be introduced.

## REFERENCES

- Abouelnaga, A. E., Metwally, A., Aly, N., Nagy, M., Agamy, S. (2010) Assessment of nuclear energy sustainability index using fuzzy logic. *Nuclear Engineering and Design*, 240(7), 1928-1933.
- Afgan, N. H., Carvalho, M. G. (2004) Sustainability assessment of hydrogen energy systems. *International Journal of Hydrogen Energy*, 29(13), 1327-1342.
- Afgan, N. H., Carvalho, M. G. (2008) Sustainability assessment of a hybrid energy system. *Energy Policy*, 36(8), 2903-2910.
- Afgan, N. H., Carvalho, M. G., & Hovanov, N. V. (2000). Energy system assessment with sustainability indicators. *Energy policy*, 28(9), 603-612.
- Alinezhad, A., Khalili, J. (2019) *New Methods and Applications in Multiple Attribute Decision Making*, Springer, Worcester, MA, USA.
- Al Garni, H. Z., Awasthi, A. (2017) Solar PV power plant site selection using a GIS-AHP based approach with application in Saudi Arabia. *Applied energy*, 206, 1225-1240.
- Altintas, K., Vayvay, O., Apak, S., Cobanoglu, E. (2020) An Extended GRA Method Integrated with Fuzzy AHP to Construct a Multidimensional Index for Ranking Overall Energy Sustainability Performances. *Sustainability*, 12, 1602.
- Arslan, H. M. (2018) Current Classification of Multi Criteria Decision Analysis Methods And Public Sector Implementations. *Current Debates in Public Finance Public Administration & Environmental Studies: Volume 13*, 242.
- Aruldoss, M., Lakshmi, T. M., Venkatesan, V. P. (2013) A survey on multi criteria decision making methods and its applications. *American Journal of Information Systems*, 1(1), 31-43.
- Azzuni, A., Aghahosseini, A., Ram, M., Bogdanov, D., Caldera, U., Breyer, C. (2020) Energy Security Analysis for a 100% Renewable Energy Transition in Jordan by 2050. *Sustainability*, 12(12), 4921.
- Begić, F., Afgan, N. H. (2007) Sustainability assessment tool for the decision making in selection of energy system—Bosnian case. *Energy*, 32(10), 1979-1985.

- Benítez, J., Delgado-Galván, X., Gutiérrez, J. A., Izquierdo, J. (2011) Balancing consistency and expert judgment in AHP. *Mathematical and Computer Modelling*, 54(7-8), 1785-1790.
- Berry, D. (2008) The impact of energy efficiency programs on the growth of electricity sales. *Energy Policy*, 36(9), 3620-3625.
- Bertoni, M. (2019) Multi-criteria decision making for sustainability and value assessment in early PSS design. *Sustainability*, 11(7), 1952.
- Bhattacharya, A., Geraghty, J., Young, P. (2010) Supplier selection paradigm: An integrated hierarchical QFD methodology under multiple-criteria environment. *Applied Soft Computing*, 10(4), 1013-1027.
- Bleicher, S. A. (1972) An Overview of International Environmental Regulation. *Ecology*, 2, 1-90.
- Bocca, R., & Mehlum, E. (2012) The global energy architecture performance index report 2013. World Economic Forum USA.
- Bossel, H. (1999) Indicators for sustainable development: Theory, method, applications A Report to the Balaton Group, International Institute for Sustainable Development, Winnipeg, Canada.
- Brown, M. A., Sovacool, B. K. (2007) Developing an 'energy sustainability index' to evaluate energy policy. *Interdisciplinary Science Reviews*, 32(4), 335-349.
- Butkiene, I., Zavadskas, E. K., Streimikiene, D. (2020) Multi-criteria decision-making (MCDM) for the assessment of renewable energy technologies in a household: a review. *Energies*, 13(5), 1164.
- Büyüközkan, G., Karabulut, Y. (2017) Energy project performance evaluation with sustainability perspective. *Energy*, 119, 549-560.
- Büyük yazıcı, M., Sucu, M. (2003) The analytic hierarchy and analytic network processes. *Hacettepe Journal of Mathematics and Statistics*, 32, 65-73.
- Candido, G. A., Cavalcanti, R. F. R. M. M. (2016) Energy Sustainability: presentation and discussion of the indicators. *Holos*, 32(8), 3-23. 3.

- Cîrstea, S.; Moldovan-Teselios, C.; Cîrstea, A.; Turcu, A.; Darab, C. (2018) Evaluating renewable energy sustainability by composite index. *Sustainability*, 10, 811.
- Chai, J., Liu, J. N., Ngai, E. W. (2013) Application of decision-making techniques in supplier selection: A systematic review of literature. *Expert systems with applications*, 40(10), 3872-3885. 48.
- Chamodrakas, I., Batis, D., Martakos, D. (2010) Supplier selection in electronic marketplaces using satisficing and fuzzy AHP. *Expert Systems with Applications*, 37(1), 490-498.
- Chan, F. T., Kumar, N., Tiwari, M. K., Lau, H. C., Choy, K. (2008) Global supplier selection: a fuzzy-AHP approach. *International Journal of production research*, 46(14), 3825-3857.
- Chirwa, T. G., Odhiambo, N. M. (2016) Macroeconomic determinants of economic growth: A review of international literature. *South East European Journal of Economics and Business* 2016, 11, 33-47.
- Cristóbal, J. R. (2011) Multi-criteria decision-making in the selection of a renewable energy project in Spain: The Vikor method. *Renewable energy*, 36(2), 498-502.
- Crotti, R., Misrahi, T. (2017) The Travel & Tourism Competitiveness Report 2017 Paving the way for a more sustainable and inclusive future. World Economic Forum: Cologny/Geneva, Switzerland.
- Çelikbilek, Y., Tüysüz, F. (2016) An integrated grey based multi-criteria decision making approach for the evaluation of renewable energy sources. *Energy*, 115, 1246-1258.
- Davidson, O., Sparks, D. (Eds.). (2002) *Developing Energy Solutions for Climate Change: South African Research at EDRC*. Energy and Development Research Centre, University of Cape Town.
- De FSM Russo, R., Camanho, R. (2015) Criteria in AHP: a systematic review of literature. *Procedia Computer Science*, 55, 1123-1132.
- Díaz-Cuevas, P., Camarillo-Naranjo, J. M., Pérez-Alcántara, J. P. (2018) Relational spatial database and multi-criteria decision methods for selecting optimum locations for photovoltaic power plants in the province of Seville (southern Spain). *Clean Technologies and Environmental Policy*, 20(8), 1889-1902.

- Dzoga, M., Simatele, D. M., Munga, C., and Yonge, S. (2020) Application of the DPSIR Framework to Coastal and Marine Fisheries Management in Kenya. *Ocean Science*, 55(2), 193-201.
- Ebrahimi, M., Rahmani, D. (2019) A five-dimensional approach to sustainability for prioritizing energy production systems using a revised GRA method: A case study. *Renewable Energy*, 135, 345-354.
- Evans, A., Strezov, V., Evans, T. J. (2009) Assessment of sustainability indicators for renewable energy technologies. *Renewable and Sustainable Energy Reviews*, 13, 1082-1088.
- Fang, H., Wang, X., Song, W. (2020) Technology selection for photovoltaic cell from sustainability perspective: An integrated approach. *Renewable Energy*, 153, 1029-1041.
- Forman, E. H., Gass, S. I. (2001) The analytic hierarchy process—an exposition. *Operations research*, 49(4), 469-486.
- Gavade, R. K. (2014) Multi-Criteria Decision Making: An overview of different selection problems and methods. *International Journal of Computer Science and Information Technologies*, 5(4), 5643-5646.
- Goldblatt, D., Pachauri, S., Scheller, A. (2000) Einsichten in die Konstruktion von Indikatoren. *ETH-Bulletin*, 276, 20-22.
- Goldrath, T., Ayalon, O., Shechter, M. (2015) A combined sustainability index for electricity efficiency measures. *Energy Policy*, 86, 574-584. 50.
- Gunningham, N. (2011) Enforcing environmental regulation. *Journal of Environmental Law*. 23, 169-201.
- Guo, S., Zhao, H. (2015) Optimal site selection of electric vehicle charging station by using fuzzy TOPSIS based on sustainability perspective. *Applied Energy*, 158, 390-402.
- Haghshenas, H. Vaziri, M. (2012) Urban sustainable transportation indicators for global comparison. *Ecological Indicators*, 15, 115-121.
- Haq, A. N., Kannan, G. (2006) Fuzzy analytical hierarchy process for evaluating and selecting a vendor in a supply chain model. *The International Journal of Advanced Manufacturing*

Technology, 29(7-8), 826-835.

Hardi, P., Zdan, T. (1997) *Assessing Sustainable Development: Principles in Practice*, International Institute for Sustainable Development, Winnipeg, Canada.

Harger, J. R. E., Meyer, F. M. (1996) Definition of indicators for environmentally sustainable development. *Chemosphere*, 33(9), 1749-1775.

Hodicky, J., Özkan, G., Özdemir, H., Stodola, P., Drozd, J., and Buck, W. (2020) Analytic Hierarchy Process (AHP)-Based Aggregation Mechanism for Resilience Measurement: NATO Aggregated Resilience Decision Support Model. *Entropy*, 22(9), 1037.

Ibrahim, H., Ilinca, A., Perron, J. (2008) Energy storage systems—characteristics and comparisons. *Renewable and sustainable energy reviews*, 12(5), 1221-1250.

Iddrisu, I., & Bhattacharyya, S. C. (2015). Sustainable Energy Development Index: A multi-dimensional indicator for measuring sustainable energy development. *Renewable and Sustainable Energy Reviews*, 50, 513-530. 62.

International Atomic Energy Agency (IAEA); United Nations Department of Economic and Social Affairs (UNDESA); International Energy Agency (IEA); Eurostat; European Environment Agency (EEA) (2005) *Energy Indicators for Sustainable Development: Methodologies and Guidelines*; International Atomic Energy Agency (IAEA): Vienna, Austria.

International Energy Agency (IEA) (2012). *World Energy Outlook*. Paris: IEA.

Ishizaka, A., Nemery, P., Lidouh, K. (2013) Location selection for the construction of a casino in the Greater London region: a triple multi-criteria approach. *Tourism Management*, 34, 211-220.

Ishizaka, A., Pearman, C., Nemery, P. (2012). AHPSort: an AHP-based method for sorting problems. *International Journal of Production Research*, 50(17), 4767-4784.

Javanmardi, E., Liu, S., Xie N. (2020) Exploring Grey Systems Theory-Based Methods and Applications in Sustainability Studies: A Systematic Review Approach. *Sustainability*, 12, 4437. 17.

- Jha, S. K., Puppala, H. (2017) Prospects of renewable energy sources in India: Prioritization of alternative sources in terms of Energy Index. *Energy*, 127, 116-127.
- Kahraman, C., Cebeci, U., Ulukan, Z. (2003) Multi-criteria supplier selection using fuzzy AHP. *Logistics Information Management*, 16, 382-394.
- Karatayev, M., Hall, S. (2020) Establishing and comparing energy security trends in resource-rich exporting nations (Russia and the Caspian Sea region). *Resources Policy*, 68, 101746.
- Kaya, T., Kahraman, C. (2010) Multicriteria renewable energy planning using an integrated fuzzy VIKOR & AHP methodology: The case of Istanbul. *Energy*, 35(6), 2517-2527.
- Kemmler, A., Spreng, D. (2007) Energy indicators for tracking sustainability in developing countries. *Energy Policy*, 35(4), 2466-2480.
- Kilincci, O., Onal, S. A. (2011) Fuzzy AHP approach for supplier selection in a washing machine company. *Expert systems with Applications*, 38(8), 9656-9664.
- Klein, S. J., Whalley, S. (2015) Comparing the sustainability of US electricity options through multi-criteria decision analysis. *Energy Policy*, 79, 127-149.
- Kristensen, P. (2004) The DPSIR Framework, workshop on a comprehensive/detailed assessment of the vulnerability of water resources to environmental change in Africa using river basin approach. UNEP Headquarters, Nairobi, Kenya.
- Kruyt, B., van Vuuren, D. P., De Vries, H. J. M., Groenenberg, H. (2009) Indicators for energy security. *Energy policy*, 37(6), 2166-2181.
- Kumar, A., Sah, B., Singh, A. R., Deng, Y., He, X., Kumar, P., Bansal, R. C. (2017) A review of multi criteria decision making (MCDM) towards sustainable renewable energy development. *Renewable and Sustainable Energy Reviews*, 69, 596-609. 68.
- Kuo, Y., Yang, T., Huang, G. W. (2008) The use of grey relational analysis in solving multiple attribute decision-making problems. *Computers & Industrial Engineering* 2008, 55, 80-93.
- Lee, C. W.; Zhong, J. (2015) Construction of a responsible investment composite index for renewable energy industry. *Renewable and Sustainable Energy Reviews*, 51, 288-303.

- Levrel, H., Kerbiriou, C., Couvet, D., Weber, J. (2009) OECD pressure–state–response indicators for managing biodiversity: a realistic perspective for a French biosphere reserve. *Biodiversity and Conservation*, 18(7), 1719-1732.
- Li, F.; Liu, X.; Hu, D.; Wang, R.; Yang, W.; Li, D.; Zhao, D. (2019) Measurement indicators and an evaluation approach for assessing urban sustainable development: A case study for China's Jining City. *Landscape and Urban Planning*, 90, 134-142.
- Li, W., Ren, X., Ding, S., Dong, L. (2020) A multi-criterion decision making for sustainability assessment of hydrogen production technologies based on objective grey relational analysis. *International Journal of Hydrogen Energy*.
- Liu, G., Baniyounes, A. M., Rasul, M. G., Amanullah, M. T. O., & Khan, M. M. K. (2013). General sustainability indicator of renewable energy system based on grey relational analysis. *International journal of energy research*, 37(14), 1928-1936.
- Ligus, M., Peternek, P. (2018) Determination of most suitable low-emission energy technologies development in Poland using integrated fuzzy AHP-TOPSIS method.
- Lin, Y. H., Lee, P. C., Chang, T. P. (2009) Practical expert diagnosis model based on the grey relational analysis technique. *Expert Systems with Applications*, 36, 1523-1528.
- Linster, M., Fletcher, J. (2001) Using the Pressure-State-Response Model to Develop Indicators of Sustainability: OECD Framework for Environmental Indicators, Organisation for Economic Co-operation and Development, Paris, France.
- Liu, G. (2014) Development of a general sustainability indicator for renewable energy systems: A review. *Renewable and Sustainable Energy Reviews*, 31, 611-621.
- Lu, L. Y., Wu, C. H., Kuo, T. C. (2007) Environmental principles applicable to green supplier evaluation by using multi-objective decision analysis. *International journal of production research*, 45(18-19), 4317-4331.
- Lu, M., Wevers, K. (2007) Application of grey relational analysis for evaluating road traffic safety measures: advanced driver assistance systems against infrastructure redesign. *IET Intelligent Transport Systems*, 1(1), 3-14.
- Lu, Y., Khan, Z. A., Alvarez-Alvarado, M. S., Zhang, Y., Huang, Z., Imran, M. (2020) A critical

- review of sustainable energy policies for the promotion of renewable energy sources. *Sustainability*, 12(12), 5078.
- Luthra, S., Mangla, S. K., Kharb, R. K. (2015) Sustainable assessment in energy planning and management in Indian perspective. *Renewable and Sustainable Energy Reviews*, 47, 58-73.
- Mainali, B., Silveira, S. (2015) Using a sustainability index to assess energy technologies for rural electrification. *Renewable and Sustainable Energy Reviews*, 41, 1351-1365.
- Mafakheri, F., Breton, M., Ghoniem, A. (2011) Supplier selection-order allocation: A two-stage multiple criteria dynamic programming approach. *International Journal of Production Economics*, 132(1), 52-57.
- Malekpoor, H., Chalvatzis, K., Mishra, N., Mehlawat, M. K., Zafirakis, D., Song, M. (2018) Integrated grey relational analysis and multi objective grey linear programming for sustainable electricity generation planning. *Annals of Operations Research*, 269(1-2), 475-503.
- Mandic, K., Bobar, V., Delibašić, B. (2015) Modeling interactions among criteria in MCDM methods: a review. In *International Conference on Decision Support System Technology* (pp. 98-109). Springer, Cham.
- Manzardo, A., Ren, J., Mazzi, A., Scipioni, A. (2012) A grey-based group decision-making methodology for the selection of hydrogen technologies in life cycle sustainability perspective. *International journal of hydrogen energy*, 37(23), 17663-17670.
- Martchamadol, J., Kumar, S. (2013) An aggregated energy security performance indicator. *Applied energy*, 103, 653-670.
- Martins, J. H., Camanho, A. S., Gaspar, M. B. (2012) A review of the application of driving forces–pressure–state–impact–response framework to fisheries management. *Ocean & coastal management*, 69, 273-281.
- Maxim, A. (2014) Sustainability assessment of electricity generation technologies using weighted multi-criteria decision analysis. *Energy Policy*, 65, 284-297.
- Mirjat, N., Uqaili, M. A., Harijan, K., Mustafa, M. W., Rahman, M., Khan, M. (2018) Multi-

- criteria analysis of electricity generation scenarios for sustainable energy planning in Pakistan. *Energies*, 11(4), 757.
- Mog, J. M. (2004) Struggling with sustainability—a comparative framework for evaluating sustainable development programs. *World development*, 32(12), 2139-2160.
- Mohamed, S. A. N., Zainudin, E. S., Sapuan, S. M., Deros, M. A. M., Arifin, A. M. T. (2009) Integration of taguchi-grey relational analysis technique in parameter process optimization for rice husk composite. *BioResources*, 14, 1110-1126.
- Mulliner, E., Malys, N., Maliene, V. (2016) Comparative analysis of MCDM methods for the assessment of sustainable housing affordability. *Omega*, 59, 146-156.
- Narula, K., Reddy, B. S. (2016) A SES (sustainable energy security) index for developing countries. *Energy*, 94, 326-343.
- Nathan, H. S. K., Reddy, B. S. (2008) A conceptual framework for development of sustainable development indicators. Indira Gandhi Institute of Development Research (IGIDR), Working Paper, WP-2008-003.
- Neri, A. C., Dupin, P., Sánchez, L. E. (2016) A pressure–state–response approach to cumulative impact assessment. *Journal of Cleaner Production*, 126, 288-298.
- Neves, A. R., Leal, V. (2010) Energy sustainability indicators for local energy planning: review of current practices and derivation of a new framework. *Renewable and Sustainable Energy Reviews*, 14(9), 2723-2735.
- Niu, D., Li, Y., Dai, S., Kang, H., Xue, Z., Jin, X., Song, Y. (2018) Sustainability evaluation of power grid construction projects using improved TOPSIS and least square support vector machine with modified fly optimization algorithm. *Sustainability*, 10(1), 231.
- Nussbaumer, P., Bazilian, M., Modi, V. (2012) Measuring energy poverty: Focusing on what matters. *Renewable and Sustainable Energy Reviews*, 16(1), 231-243.
- Okokpujie, I. P., Okonkwo, U. C., Bolu, C. A., Ohunakin, O. S., Agboola, M. G., Atayero, A. A. (2020) Implementation of multi-criteria decision method for selection of suitable material for development of horizontal wind turbine blade for sustainable energy generation. *Heliyon*, 6(1), e03142.

- Olsson, J. A., Hilding-Rydevik, T., Aalbu, H., Bradley, K. (2004) Indicators for sustainable development. Paper for Discussion at the European Regional Network on Sustainable Development, 23-24 March, Cardiff, UK.
- Onat, N., Bayar, H. (2010). The sustainability indicators of power production systems. *Renewable and Sustainable Energy Reviews*, 14(9), 3108-3115.
- Organisation for Economic Co-operation and Development (1993) OECD Core Set of Indicators for Environmental Performance Reviews: A Synthesis Report by the Group on the State of the Environment (Environment Monographs Report No. 83). Paris: OECD.
- Organisation for Economic Co-operation and Development (2001) OECD Environmental Indicators towards Sustainable Development. Paris: OECD.
- Organisation for Economic Co-operation and Development (OECD) (2008) Handbook on Constructing Composite Indicators Methodology and User Guide. Paris: OECD.
- Overturf, M. C., McKnight, D. (2012) Managing Energy Productivity with a Sustainable Energy Index (ENDX). *Energy Engineering*, 109(1), 36-51.
- Oyedepo, S. O. (2012) On energy for sustainable development in Nigeria. *Renewable and Sustainable Energy Reviews*, 16(5), 2583-2598.
- Patlitzianas, K. D., Doukas, H., Kagiannas, A. G., Psarras, J. (2008) Sustainable energy policy indicators: Review and recommendations. *Renewable Energy*, 33(5), 966-973. 39.
- Polatidis, H., Haralambidou, K., Haralambopoulos, D. (2015) Multi-criteria decision analysis for geothermal energy: A comparison between the ELECTRE III and the PROMETHEE II methods. *Energy Sources, Part B: Economics, Planning, and Policy*, 10(3), 241-249.
- Radovanović, M., Filipović, S., & Pavlović, D. (2017). Energy security measurement—A sustainable approach. *Renewable and Sustainable Energy Reviews*, 68, 1020-1032.
- Raza, S. S., Janajreh, I., Ghenai, C. (2014) Sustainability index approach as a selection criteria for energy storage system of an intermittent renewable energy source. *Applied Energy*, 136, 909-920.
- Razmjoo, A. A., Sumper, A., and Davarpanah, A. (2019) Development of sustainable energy

- indexes by the utilization of new indicators: A comparative study. *Energy Reports*, 5, 375-383.
- Reisi, M.; Aye, L.; Rajabifard, A.; Ngo, T. (2014) Transport sustainability index: Melbourne case study. *Ecological Indicators*, 43, 288-296.
- Ren, J. (2018) Multi-criteria decision making for the prioritization of energy systems under uncertainties after life cycle sustainability assessment. *Sustainable Production and Consumption*, 16, 45-57.
- Rennings, K., Wiggering, H. (1997) Steps towards indicators of sustainable development: linking economic and ecological concepts. *Ecological economics*, 20(1), 25-36.
- Rosen, M. A. (2009) Energy sustainability: A pragmatic approach and illustrations. *Sustainability*, 1(1), 55-80.
- Sahin, M. (2020) A comprehensive analysis of weighting and multicriteria methods in the context of sustainable energy. *International Journal of Environmental Science and Technology*, 1-26.
- Sánchez-Lozano, J. M., García-Cascales, M. S., Lamata, M. T. (2016) GIS-based onshore wind farm site selection using Fuzzy Multi-Criteria Decision Making methods. Evaluating the case of Southeastern Spain. *Applied Energy*, 171, 86-102.
- Sayadi, M. K., Heydari, M., Shahanaghi, K. (2009) Extension of VIKOR method for decision making problem with interval numbers. *Applied Mathematical Modelling*, 33(5), 2257-2262.
- Schlör, H., Fischer, W., Hake, J. F. (2013) Methods of measuring sustainable development of the German energy sector. *Applied Energy*, 101, 172-181. 44.
- Schwab, K., Sala-i-Martin, X. (2017) *The Global Competitiveness Report 2017–2018*; World Economic Forum: Cologny/Geneva, Switzerland.
- Shah, R. (2000, April) International frameworks of environmental statistics and indicators. In *Inception Workshop on the Institutional Strengthening and Collection of Environment Statistics*.

- Sifeng, L., Forrest, J., Yingjiel, Y. (2011) A Brief Introduction to Grey Systems Theory. Proceedings of 2011 IEEE International Conference on Grey Systems and Intelligent Services, 15-18 September, Nanjing, China.
- Singh, R. K., Murty, H. R., Gupta, S. K., Dikshit, A. K. (2009) An overview of sustainability assessment methodologies. *Ecological indicators*, 9(2), 189-212.
- Shortall, R., Davidsdottir, B. (2017) How to measure national energy sustainability performance: An Icelandic case-study. *Energy for Sustainable Development*, 39, 29-47.
- Škobalj, P., Kijevčanin, M., Jovanović, M., Afgan, N., Erić, M. (2017). Energy indicators impact in multicriteria sustainability analyse of thermal power plant unit. *Thermal Science*, 21(2), 1143-1151.
- Sofyalioğlu, Ç., Öztürk, Ş. (2012) Application of grey relational analysis with fuzzy AHP to FMEA method. *Doğuş Üniversitesi Dergisi*, 13, 114-130.
- Soleymani, S. A demand-side assessment of sustainable energy security in Iran. *International Journal of Energy and Water Resources*, 4, 307-320.
- Stojčić, M., Zavadskas, E. K., Pamučar, D., Stević, Ž., Mardani, A. (2019) Application of MCDM methods in sustainability engineering: A literature review 2008–2018. *Symmetry*, 11(3), 350.
- Streimikiene, D., & Sarvutyte, M. (2010) Sustainability Assessment of Energy Technologies. *Economics & Management*.
- Tavana, M., Shaabani, A., Javier Santos-Arteaga, F., Raeesi Vanani, I. (2020) A Review of Uncertain Decision-Making Methods in Energy Management Using Text Mining and Data Analytics. *Energies*, 13(15), 3947.
- The Department of Economic and Social Affairs of the United Nations (2007) Indicators of sustainable development: Guidelines and methodologies (3rd ed.), United Nations Publications. New York, USA.
- Troldborg, M., Heslop, S., Hough, R. L. (2014) Assessing the sustainability of renewable energy technologies using multi-criteria analysis: Suitability of approach for national-scale assessments and associated uncertainties. *Renewable and sustainable energy reviews*, 39,

1173-1184.

- Tsai, W. T. (2010) Energy sustainability from analysis of sustainable development indicators: A case study in Taiwan. *Renewable and Sustainable Energy Reviews*, 14(7), 2131-2138.
- Tsoutsos, T., Drandaki, M., Frantzeskaki, N., Iosifidis, E., Kiosses, I. (2009) Sustainable energy planning by using multi-criteria analysis application in the island of Crete. *Energy policy*, 37(5), 1587-1600.
- U.S. Chamber of Commerce's Institute for 21st Century Energy (2012) International Index of Energy Security Risk. Assessing Risk in a Global Market. Washington DC: Institute for 21st Century Energy.
- U.S. Chamber of Commerce's Institute for 21st Century Energy (2016). International Index of Energy Security Risk. Assessing Risk in a Global Market. Washington DC: Institute for 21st Century Energy.
- Vaidya, O. S., Kumar, S. (2006) Analytic hierarchy process: An overview of applications. *European Journal of operational research*, 169(1), 1-29.
- Velasquez, M., Hester, P. T. (2013) An analysis of multi-criteria decision making methods. *International journal of operations research*, 10(2), 56-66.
- Vera, I., Langlois, L. (2007) Energy indicators for sustainable development. *Energy*, 32(6), 875-882.
- Vidadili, N., Suleymanov, E., Bulut, C., Mahmudlu, C. (2017) Transition to renewable energy and sustainable energy development in Azerbaijan. *Renewable and Sustainable Energy Reviews*, 80, 1153-1161.
- Vučijak, B., Kupusović, T., Midžić-Kurtagić, S., Čerić, A. (2013) Applicability of multicriteria decision aid to sustainable hydropower. *Applied Energy*, 101, 261-267.
- Wang, Y. M., Chin, K. S. (2011) Fuzzy analytic hierarchy process: A logarithmic fuzzy preference programming methodology. *International journal of approximate reasoning*, 52(4), 541-553.
- Wang, Z., Xu, G., Ren, J., Li, Z., Zhang, B., Ren, X. (2017) Polygeneration system and

sustainability: multi-attribute decision-support framework for comprehensive assessment under uncertainties. *Journal of cleaner production*, 167, 1122-1137.

Wei, G. W. (2010) GRA method for multiple attribute decision making with incomplete weight information in intuitionistic fuzzy setting. *Knowledge-Based Systems*, 23, 243-247.

World Economic Forum (2017) *Global Energy Architecture Performance Index Report* World Economic Forum: Geneva, Switzerland.

World Energy Council (2016). *Energy Trilemma Index Benchmarking the sustainability of national energy systems*. London: World Energy Council.

Winzer, C. (2012) Conceptualizing energy security. *Energy policy*, 46, 36-48.

Wu, C. C., Tsai, H. M. (2014) A capital-based framework for assessing coastal and marine social–ecological dynamics and natural resource management: A case study of Penghu archipelago. *Journal of Marine and Island Cultures*, 3(2), 60-68.

Wu, D., Yang, Z., Wang, N., Li, C., Yang, Y. (2018) An Integrated Multi-Criteria Decision Making Model and AHP Weighting Uncertainty Analysis for Sustainability Assessment of Coal-Fired Power Units. *Sustainability*, 10(6), 1700.

Yılmaz, B. Ö., Tozan, H., Karadayı, M. A. (2020) Multi-Criteria Decision Making (MCDM) Applications in Military Healthcare Field. *Journal of Health Systems and Policies*, 2(2), 149-181.

Zavadskas, E. K., Turskis, Z., Kildienė, S. (2014) State of art surveys of overviews on MCDM/MADM methods. *Technological and economic development of economy*, 20(1), 165-179.

Zhao, H., Guo, S. (2015) External benefit evaluation of renewable energy power in China for sustainability. *Sustainability*, 7(5), 4783-4805.

Zhao, H., Li, N. (2016) Optimal siting of charging stations for electric vehicles based on fuzzy Delphi and hybrid multi-criteria decision making approaches from an extended sustainability perspective. *Energies*, 9(4), 270.

## **APPENDICES**

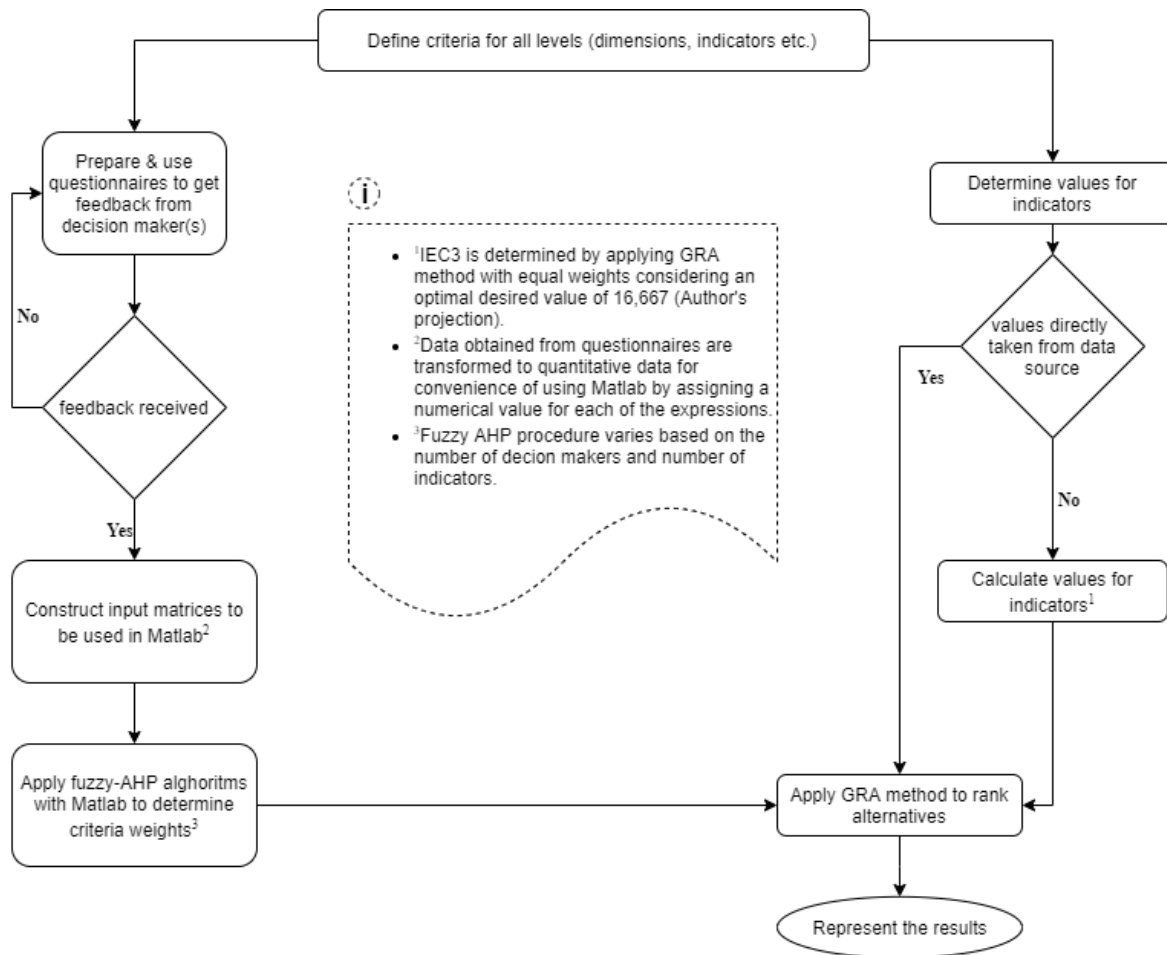
### **APPENDIX A**

The first step for developing the framework was defining objective, criteria, and sub-criteria in order to demonstrate the issue as clearly as possible. This has been done accordingly to the principles that have been presented in Chapter 3. It was vital to address the issues that have been highly considered in the definition of energy sustainability.

As highlighted in the previous chapters, instead of benefiting only mathematical approximations, the system has used input from decision makers to calculate criteria weights. Due to the fuzziness in the feedback of decision makers, a fuzzy integrated approach has been selected. Based on the selected method a questionnaire has been developed and sent to decision makers to get their feedback. The fuzzy feedback provided has been transformed to quantitative variables and fuzzy AHP has been applied. The results are the input for GRA process.

Matlab (R2018b) was used for calculating weights with fuzzy AHP. Matlab is a high-performance language that allows a user to benefit from numeric computing for analyzing data and developing algorithms. It is a popular platform among engineers and scientists to solve complex problems. Due to the multidimensional and complexity of sustainability issues, Matlab has been considered as a useful tool.

In the case of sub-indicators, a direct GRA application approach has been applied. The reason to use such a process is about the same criteria weights that were assigned to the sub-indicators. After applying a separate GRA method to find the scores of the indicator, a total GRA method has been applied. All GRA processes have been calculated with Microsoft Excel (2016). While Figure A.1 provides the flow chart that represents the overall process, the flow chart shown by Figure A.2 provides all the steps of extended and revised GRA process that has been introduced by the author.



**Figure A1.** Flow chart of the overall procedure.

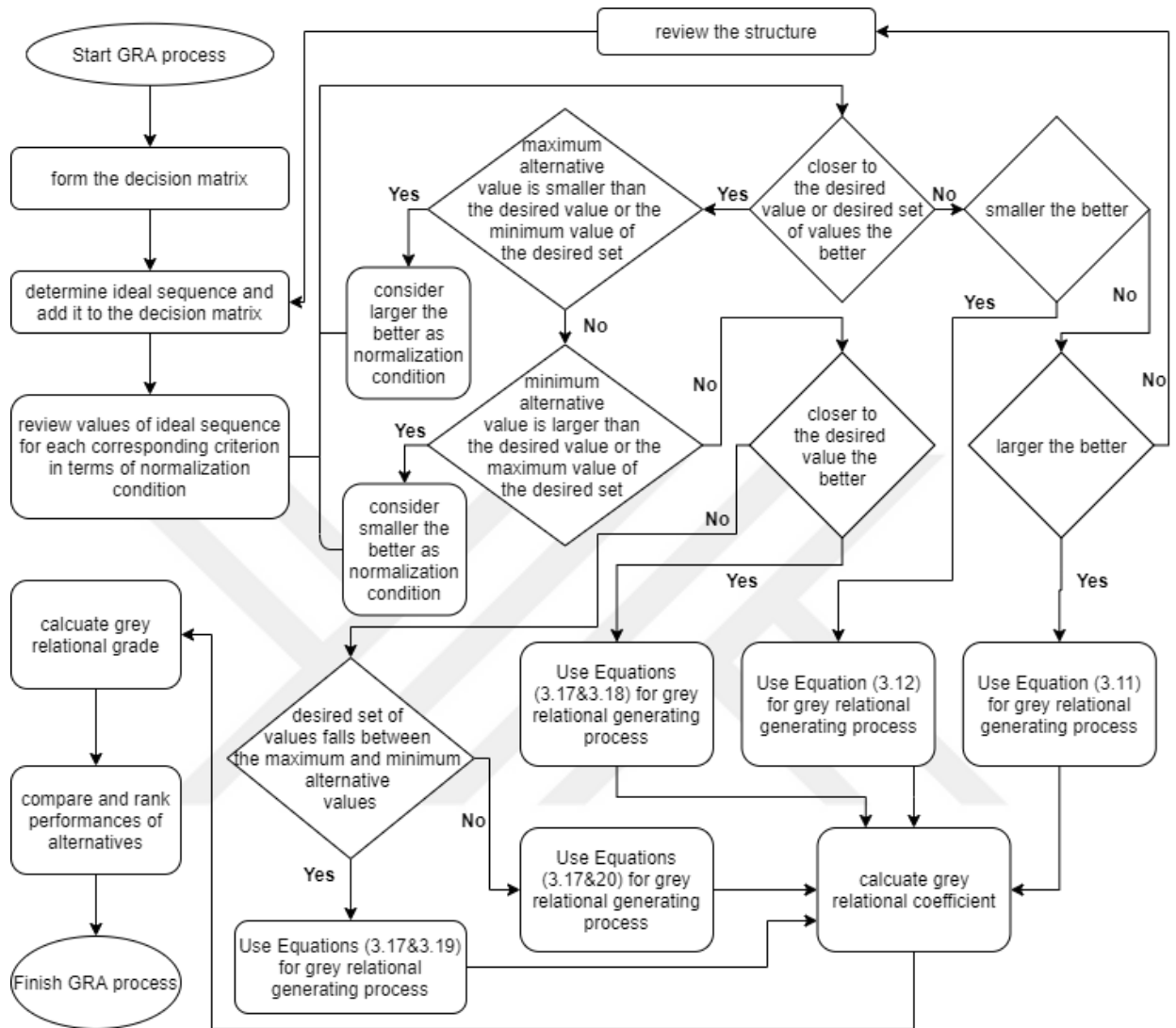


Figure A2. Flow chart of the revised and extended GRA procedure.

## APPENDIX B

Following questionnaires have been used for feedback. The feedback from decision makers have been also provided:

<b>1. CRITERIA GROUP (DIMENSIONS)</b>			
<b>CRITERIA</b>	<b>IMPORTANCE</b>	<b>IMPORTANCE</b>	<b>CRITERIA</b>
Economic & Security			Environmental
Economic & Security			Social
Environmental			Social
<b>2. CRITERIA GROUP (SUB - DIMENSION // Economic &amp; Security)</b>			
<b>CRITERIA</b>	<b>IMPORTANCE</b>	<b>IMPORTANCE</b>	<b>CRITERIA</b>
Energy Use Patterns			Supply Efficiency
Energy Use Patterns			Macroeconomic Context
Supply Efficiency			Macroeconomic Context
<b>3. CRITERIA GROUP (SUB - DIMENSION // Environmental)</b>			
<b>CRITERIA</b>	<b>IMPORTANCE</b>	<b>IMPORTANCE</b>	<b>CRITERIA</b>
N2O & CH4 Emissions			CO2 Emissions
N2O & CH4 Emissions			Environmental Regulations
CO2 Emissions			Environmental Regulations
<b>4. CRITERIA GROUP (SUB - DIMENSIONS // Social)</b>			
<b>CRITERIA</b>	<b>IMPORTANCE</b>	<b>IMPORTANCE</b>	<b>CRITERIA</b>
Quality of Supply and Equity			Affordability
<b>5. CRITERIA GROUP (Indicators // Energy Use Patterns - Economic)</b>			
<b>CRITERIA</b>	<b>IMPORTANCE</b>	<b>IMPORTANCE</b>	<b>CRITERIA</b>
Energy use per capita			Energy use per GDP

Energy use per capita			Diversification of sources for power production
Energy use per GDP			Diversification of sources for power production
<b>6. CRITERIA GROUP (Indicators // Supply Efficiency - Economic)</b>			
<b>CRITERIA</b>	<b>IMPORTANCE</b>	<b>IMPORTANCE</b>	<b>CRITERIA</b>
Supply Efficiency of Electricity Generation			Electric Power Transmission and Distribution Losses
<b>7. CRITERIA GROUP (Indicators // Macroeconomic Context &amp; Foreign Investments - Economic)</b>			
<b>CRITERIA</b>	<b>IMPORTANCE</b>	<b>IMPORTANCE</b>	<b>CRITERIA</b>
Economic Growth Rate			Government Budget Balance
Economic Growth Rate			Inflation Rate
Economic Growth Rate			Government Debt
Government Budget Balance			Inflation Rate
Government Budget Balance			Government Debt
Inflation Rate			Government Debt
<b>8. CRITERIA GROUP (Indicators // N<sub>2</sub>O &amp; CH<sub>4</sub> Emissions - Environmental)</b>			
<b>CRITERIA</b>	<b>IMPORTANCE</b>	<b>IMPORTANCE</b>	<b>CRITERIA</b>
N <sub>2</sub> O emissions from energy processes			CH <sub>4</sub> emissions from energy processes
<b>9. CRITERIA GROUP (Indicators // CO<sub>2</sub> Emissions - Environmental)</b>			
<b>CRITERIA</b>	<b>IMPORTANCE</b>	<b>IMPORTANCE</b>	<b>CRITERIA</b>
CO <sub>2</sub> emissions from solid fuel combustion			CO <sub>2</sub> emissions from liquid fuel combustion
CO <sub>2</sub> emissions from solid fuel combustion			CO <sub>2</sub> emissions from gaseous fuel combustion
CO <sub>2</sub> emissions from liquid fuel combustion			CO <sub>2</sub> emissions from gaseous fuel combustion
<b>10. CRITERIA GROUP (Indicators // Environmental Regulations - Environmental)</b>			

CRITERIA	IMPORTANCE	IMPORTANCE	CRITERIA
Stringency of environmental regulations			Enforcement of environmental regulations
<b>11. CRITERIA GROUP (Indicators // Equity - Social)</b>			
CRITERIA	IMPORTANCE	IMPORTANCE	CRITERIA
Access to electricity			Quality of electricity supply
<b>12. CRITERIA GROUP (Indicators // Affordability - Social)</b>			
CRITERIA	IMPORTANCE	IMPORTANCE	CRITERIA
Affordability of electricity price for household consumers			Affordability of pump price for diesel fuel
Affordability of electricity price for household consumers			Affordability of pump price for gasoline fuel
Affordability of pump price for diesel fuel			Affordability of pump price for gasoline fuel

<b>1. CRITERIA GROUP (DIMENSIONS) - ALTINTAŞ</b>			
CRITERIA	IMPORTANCE	IMPORTANCE	CRITERIA
Economic & Security	Weakly Important		Environmental
Economic & Security	Weakly Important		Social
Environmental	Equally Important		Social
<b>2. CRITERIA GROUP (SUB - DIMENSION // Economic &amp; Security)</b>			
CRITERIA	IMPORTANCE	IMPORTANCE	CRITERIA
Energy Use Patterns	Weakly Important		Supply Efficiency
Energy Use Patterns	Fairly Important		Macroeconomic Context
Supply Efficiency	Weakly Important		Macroeconomic Context
<b>3. CRITERIA GROUP (SUB - DIMENSION // Environmental)</b>			
CRITERIA	IMPORTANCE	IMPORTANCE	CRITERIA
N2O & CH4 Emissions		Weakly Important	CO2 Emissions

N2O & CH4 Emissions	Weakly Important		Environmental Regulations
CO2 Emissions	Fairly Important		Environmental Regulations
<b>4. CRITERIA GROUP (SUB - DIMENSIONS // Social)</b>			
<b>CRITERIA</b>	<b>IMPORTANCE</b>	<b>IMPORTANCE</b>	<b>CRITERIA</b>
Quality of Supply and Equity	Equally Important		Affordability
<b>5. CRITERIA GROUP (Indicators // Energy Use Patterns - Economic)</b>			
<b>CRITERIA</b>	<b>IMPORTANCE</b>	<b>IMPORTANCE</b>	<b>CRITERIA</b>
Energy use per capita	Equally Important		Energy use per GDP
Energy use per capita	Equally Important		Diversification of sources for power production
Energy use per GDP	Equally Important		Diversification of sources for power production
<b>6. CRITERIA GROUP (Indicators // Supply Efficiency - Economic)</b>			
<b>CRITERIA</b>	<b>IMPORTANCE</b>	<b>IMPORTANCE</b>	<b>CRITERIA</b>
Supply Efficiency of Electricity Generation	Equally Important		Electric Power Transmission and Distribution Losses
<b>7. CRITERIA GROUP (Indicators // Macroeconomic Context &amp; Foreign Investments - Economic)</b>			
<b>CRITERIA</b>	<b>IMPORTANCE</b>	<b>IMPORTANCE</b>	<b>CRITERIA</b>
Economic Growth Rate	Equally Important		Government Budget Balance
Economic Growth Rate	Equally Important		Inflation Rate
Economic Growth Rate	Equally Important		Government Debt
Government Budget Balance	Equally Important		Inflation Rate
Government Budget Balance	Equally Important		Government Debt
Inflation Rate	Equally Important		Government Debt
<b>8. CRITERIA GROUP (Indicators // N<sub>2</sub>O &amp; CH<sub>4</sub> Emissions - Environmental)</b>			
<b>CRITERIA</b>	<b>IMPORTANCE</b>	<b>IMPORTANCE</b>	<b>CRITERIA</b>

N <sub>2</sub> O emissions from energy processes		Fairly Important	CH <sub>4</sub> emissions from energy processes
<b>9. CRITERIA GROUP (Indicators // CO<sub>2</sub> Emissions - Environmental)</b>			
<b>CRITERIA</b>	<b>IMPORTANCE</b>	<b>IMPORTANCE</b>	<b>CRITERIA</b>
CO <sub>2</sub> emissions from solid fuel combustion	Equally Important		CO <sub>2</sub> emissions from liquid fuel combustion
CO <sub>2</sub> emissions from solid fuel combustion	Equally Important		CO <sub>2</sub> emissions from gaseous fuel combustion
CO <sub>2</sub> emissions from liquid fuel combustion	Equally Important		CO <sub>2</sub> emissions from gaseous fuel combustion
<b>10. CRITERIA GROUP (Indicators // Environmental Regulations - Environmental)</b>			
<b>CRITERIA</b>	<b>IMPORTANCE</b>	<b>IMPORTANCE</b>	<b>CRITERIA</b>
Stringency of environmental regulations	Equally Important		Enforcement of environmental regulations
<b>11. CRITERIA GROUP (Indicators // Equity - Social)</b>			
<b>CRITERIA</b>	<b>IMPORTANCE</b>	<b>IMPORTANCE</b>	<b>CRITERIA</b>
Access to electricity	Equally Important		Quality of electricity supply
<b>12. CRITERIA GROUP (Indicators // Affordability - Social)</b>			
<b>CRITERIA</b>	<b>IMPORTANCE</b>	<b>IMPORTANCE</b>	<b>CRITERIA</b>
Affordability of electricity price for household consumers	Absolutely Important		Affordability of pump price for diesel fuel
Affordability of electricity price for household consumers	Strongly Important		Affordability of pump price for gasoline fuel
Affordability of pump price for diesel fuel	Weakly Important		Affordability of pump price for gasoline fuel

<b>1. CRITERIA GROUP (DIMENSIONS) - KAVAKLIOGLU</b>			
<b>CRITERIA</b>	<b>IMPORTANCE</b>	<b>IMPORTANCE</b>	<b>CRITERIA</b>
Economic & Security	Weakly Important		Environmental
Economic & Security	Fairly Important		Social
Environmental	Weakly Important		Social

<b>2. CRITERIA GROUP (SUB - DIMENSION // Economic &amp; Security)</b>			
<b>CRITERIA</b>	<b>IMPORTANCE</b>	<b>IMPORTANCE</b>	<b>CRITERIA</b>
Energy Use Patterns		Weakly Important	Supply Efficiency
Energy Use Patterns	Weakly Important		Macroeconomic Context
Supply Efficiency	Fairly Important		Macroeconomic Context
<b>3. CRITERIA GROUP (SUB - DIMENSION // Environmental)</b>			
<b>CRITERIA</b>	<b>IMPORTANCE</b>	<b>IMPORTANCE</b>	<b>CRITERIA</b>
N2O & CH4 Emissions		Weakly Important	CO2 Emissions
N2O & CH4 Emissions	Weakly Important		Environmental Regulations
CO2 Emissions	Fairly Important		Environmental Regulations
<b>4. CRITERIA GROUP (SUB - DIMENSIONS // Social)</b>			
<b>CRITERIA</b>	<b>IMPORTANCE</b>	<b>IMPORTANCE</b>	<b>CRITERIA</b>
Quality of Supply and Equity	Equally Important		Affordability
<b>5. CRITERIA GROUP (Indicators // Energy Use Patterns - Economic)</b>			
<b>CRITERIA</b>	<b>IMPORTANCE</b>	<b>IMPORTANCE</b>	<b>CRITERIA</b>
Energy use per capita	Equally Important		Energy use per GDP
Energy use per capita		Weakly Important	Diversification of sources for power production
Energy use per GDP		Weakly Important	Diversification of sources for power production
<b>6. CRITERIA GROUP (Indicators // Supply Efficiency - Economic)</b>			
<b>CRITERIA</b>	<b>IMPORTANCE</b>	<b>IMPORTANCE</b>	<b>CRITERIA</b>
Supply Efficiency of Electricity Generation	Equally Important		Electric Power Transmission and Distribution Losses
<b>7. CRITERIA GROUP (Indicators // Macroeconomic Context &amp; Foreign Investments - Economic)</b>			
<b>CRITERIA</b>	<b>IMPORTANCE</b>	<b>IMPORTANCE</b>	<b>CRITERIA</b>

Economic Growth Rate	Weakly Important		Government Budget Balance
Economic Growth Rate	Weakly Important		Inflation Rate
Economic Growth Rate	Fairly Important		Government Debt
Government Budget Balance	Equally Important		Inflation Rate
Government Budget Balance	Weakly Important		Government Debt
Inflation Rate	Weakly Important		Government Debt
<b>8. CRITERIA GROUP (Indicators // N<sub>2</sub>O &amp; CH<sub>4</sub> Emissions - Environmental)</b>			
<b>CRITERIA</b>	<b>IMPORTANCE</b>	<b>IMPORTANCE</b>	<b>CRITERIA</b>
N <sub>2</sub> O emissions from energy processes		Fairly Important	CH <sub>4</sub> emissions from energy processes
<b>9. CRITERIA GROUP (Indicators // CO<sub>2</sub> Emissions - Environmental)</b>			
<b>CRITERIA</b>	<b>IMPORTANCE</b>	<b>IMPORTANCE</b>	<b>CRITERIA</b>
CO <sub>2</sub> emissions from solid fuel combustion	Equally Important		CO <sub>2</sub> emissions from liquid fuel combustion
CO <sub>2</sub> emissions from solid fuel combustion		Fairly Important	CO <sub>2</sub> emissions from gaseous fuel combustion
CO <sub>2</sub> emissions from liquid fuel combustion		Fairly Important	CO <sub>2</sub> emissions from gaseous fuel combustion
<b>10. CRITERIA GROUP (Indicators // Environmental Regulations - Environmental)</b>			
<b>CRITERIA</b>	<b>IMPORTANCE</b>	<b>IMPORTANCE</b>	<b>CRITERIA</b>
Stringency of environmental regulations	Fairly Important		Enforcement of environmental regulations
<b>11. CRITERIA GROUP (Indicators // Equity - Social)</b>			
<b>CRITERIA</b>	<b>IMPORTANCE</b>	<b>IMPORTANCE</b>	<b>CRITERIA</b>
Access to electricity		Weakly Important	Quality of electricity supply
<b>12. CRITERIA GROUP (Indicators // Affordability - Social)</b>			
<b>CRITERIA</b>	<b>IMPORTANCE</b>	<b>IMPORTANCE</b>	<b>CRITERIA</b>
Affordability of electricity price for household consumers	Absolutely Important		Affordability of pump price for diesel fuel

Affordability of electricity price for household consumers		Fairly Important	Affordability of pump price for gasoline fuel
Affordability of pump price for diesel fuel		Fairly Important	Affordability of pump price for gasoline fuel

<b>1. CRITERIA GROUP (DIMENSIONS) - KAVAKLIOGLU</b>			
<b>CRITERIA</b>	<b>IMPORTANCE</b>	<b>IMPORTANCE</b>	<b>CRITERIA</b>
Economic & Security	Weakly Important		Environmental
Economic & Security	Fairly Important		Social
Environmental	Weakly Important		Social
<b>2. CRITERIA GROUP (SUB - DIMENSION // Economic &amp; Security)</b>			
<b>CRITERIA</b>	<b>IMPORTANCE</b>	<b>IMPORTANCE</b>	<b>CRITERIA</b>
Energy Use Patterns		Weakly Important	Supply Efficiency
Energy Use Patterns	Weakly Important		Macroeconomic Context
Supply Efficiency	Fairly Important		Macroeconomic Context
<b>3. CRITERIA GROUP (SUB - DIMENSION // Environmental)</b>			
<b>CRITERIA</b>	<b>IMPORTANCE</b>	<b>IMPORTANCE</b>	<b>CRITERIA</b>
N2O & CH4 Emissions		Weakly Important	CO2 Emissions
N2O & CH4 Emissions	Weakly Important		Environmental Regulations
CO2 Emissions	Fairly Important		Environmental Regulations
<b>4. CRITERIA GROUP (SUB - DIMENSIONS // Social)</b>			
<b>CRITERIA</b>	<b>IMPORTANCE</b>	<b>IMPORTANCE</b>	<b>CRITERIA</b>
Quality of Supply and Equity	Equally Important		Affordability
<b>5. CRITERIA GROUP (Indicators // Energy Use Patterns - Economic)</b>			
<b>CRITERIA</b>	<b>IMPORTANCE</b>	<b>IMPORTANCE</b>	<b>CRITERIA</b>
Energy use per capita	Equally Important		Energy use per GDP

Energy use per capita		Weakly Important	Diversification of sources for power production
Energy use per GDP		Weakly Important	Diversification of sources for power production
<b>6. CRITERIA GROUP (Indicators // Supply Efficiency - Economic)</b>			
<b>CRITERIA</b>	<b>IMPORTANCE</b>	<b>IMPORTANCE</b>	<b>CRITERIA</b>
Supply Efficiency of Electricity Generation	Equally Important		Electric Power Transmission and Distribution Losses
<b>7. CRITERIA GROUP (Indicators // Macroeconomic Context &amp; Foreign Investments - Economic)</b>			
<b>CRITERIA</b>	<b>IMPORTANCE</b>	<b>IMPORTANCE</b>	<b>CRITERIA</b>
Economic Growth Rate	Weakly Important		Government Budget Balance
Economic Growth Rate	Weakly Important		Inflation Rate
Economic Growth Rate	Fairly Important		Government Debt
Government Budget Balance	Equally Important		Inflation Rate
Government Budget Balance	Weakly Important		Government Debt
Inflation Rate	Weakly Important		Government Debt
<b>8. CRITERIA GROUP (Indicators // N<sub>2</sub>O &amp; CH<sub>4</sub> Emissions - Environmental)</b>			
<b>CRITERIA</b>	<b>IMPORTANCE</b>	<b>IMPORTANCE</b>	<b>CRITERIA</b>
N <sub>2</sub> O emissions from energy processes		Fairly Important	CH <sub>4</sub> emissions from energy processes
<b>9. CRITERIA GROUP (Indicators // CO<sub>2</sub> Emissions - Environmental)</b>			
<b>CRITERIA</b>	<b>IMPORTANCE</b>	<b>IMPORTANCE</b>	<b>CRITERIA</b>
CO <sub>2</sub> emissions from solid fuel combustion	Equally Important		CO <sub>2</sub> emissions from liquid fuel combustion
CO <sub>2</sub> emissions from solid fuel combustion		Fairly Important	CO <sub>2</sub> emissions from gaseous fuel combustion
CO <sub>2</sub> emissions from liquid fuel combustion		Fairly Important	CO <sub>2</sub> emissions from gaseous fuel combustion
<b>10. CRITERIA GROUP (Indicators // Environmental Regulations - Environmental)</b>			

CRITERIA	IMPORTANCE	IMPORTANCE	CRITERIA
Stringency of environmental regulations	Fairly Important		Enforcement of environmental regulations
<b>11. CRITERIA GROUP (Indicators // Equity - Social)</b>			
CRITERIA	IMPORTANCE	IMPORTANCE	CRITERIA
Access to electricity		Weakly Important	Quality of electricity supply
<b>12. CRITERIA GROUP (Indicators // Affordability - Social)</b>			
CRITERIA	IMPORTANCE	IMPORTANCE	CRITERIA
Affordability of electricity price for household consumers	Absolutely Important		Affordability of pump price for diesel fuel
Affordability of electricity price for household consumers		Fairly Important	Affordability of pump price for gasoline fuel
Affordability of pump price for diesel fuel		Fairly Important	Affordability of pump price for gasoline fuel

<b>1. CRITERIA GROUP (DIMENSIONS) - GÜRBÜZ</b>			
CRITERIA	IMPORTANCE	IMPORTANCE	CRITERIA
Economic & Security	Equally Important		Environmental
Economic & Security	Equally Important		Social
Environmental	Equally Important		Social
<b>2. CRITERIA GROUP (SUB - DIMENSION // Economic &amp; Security)</b>			
CRITERIA	IMPORTANCE	IMPORTANCE	CRITERIA
Energy Use Patterns	Weakly Important		Supply Efficiency
Energy Use Patterns	Strongly Important		Macroeconomic Context
Supply Efficiency	Fairly Important		Macroeconomic Context
<b>3. CRITERIA GROUP (SUB - DIMENSION // Environmental)</b>			
CRITERIA	IMPORTANCE	IMPORTANCE	CRITERIA
N2O & CH4 Emissions	Equally Important		CO2 Emissions

N2O & CH4 Emissions	Fairly Important		Environmental Regulations
CO2 Emissions	Fairly Important		Environmental Regulations
<b>4. CRITERIA GROUP (SUB - DIMENSIONS // Social)</b>			
<b>CRITERIA</b>	<b>IMPORTANCE</b>	<b>IMPORTANCE</b>	<b>CRITERIA</b>
Quality of Supply and Equity	Weakly Important		Affordability
<b>5. CRITERIA GROUP (Indicators // Energy Use Patterns - Economic)</b>			
<b>CRITERIA</b>	<b>IMPORTANCE</b>	<b>IMPORTANCE</b>	<b>CRITERIA</b>
Energy use per capita	Equally Important		Energy use per GDP
Energy use per capita		Weakly Important	Diversification of sources for power production
Energy use per GDP		Weakly Important	Diversification of sources for power production
<b>6. CRITERIA GROUP (Indicators // Supply Efficiency - Economic)</b>			
<b>CRITERIA</b>	<b>IMPORTANCE</b>	<b>IMPORTANCE</b>	<b>CRITERIA</b>
Supply Efficiency of Electricity Generation	Equally Important		Electric Power Transmission and Distribution Losses
<b>7. CRITERIA GROUP (Indicators // Macroeconomic Context &amp; Foreign Investments - Economic)</b>			
<b>CRITERIA</b>	<b>IMPORTANCE</b>	<b>IMPORTANCE</b>	<b>CRITERIA</b>
Economic Growth Rate	Equally Important		Government Budget Balance
Economic Growth Rate	Fairly Important		Inflation Rate
Economic Growth Rate	Fairly Important		Government Debt
Government Budget Balance	Fairly Important		Inflation Rate
Government Budget Balance	Fairly Important		Government Debt
Inflation Rate			Government Debt
<b>8. CRITERIA GROUP (Indicators // N<sub>2</sub>O &amp; CH<sub>4</sub> Emissions - Environmental)</b>			
<b>CRITERIA</b>	<b>IMPORTANCE</b>	<b>IMPORTANCE</b>	<b>CRITERIA</b>

N <sub>2</sub> O emissions from energy processes	Equally Important		CH <sub>4</sub> emissions from energy processes
<b>9. CRITERIA GROUP (Indicators // CO<sub>2</sub> Emissions - Environmental)</b>			
<b>CRITERIA</b>	<b>IMPORTANCE</b>	<b>IMPORTANCE</b>	<b>CRITERIA</b>
CO <sub>2</sub> emissions from solid fuel combustion	Equally Important		CO <sub>2</sub> emissions from liquid fuel combustion
CO <sub>2</sub> emissions from solid fuel combustion	Equally Important		CO <sub>2</sub> emissions from gaseous fuel combustion
CO <sub>2</sub> emissions from liquid fuel combustion	Equally Important		CO <sub>2</sub> emissions from gaseous fuel combustion
<b>10. CRITERIA GROUP (Indicators // Environmental Regulations - Environmental)</b>			
<b>CRITERIA</b>	<b>IMPORTANCE</b>	<b>IMPORTANCE</b>	<b>CRITERIA</b>
Stringency of environmental regulations	Equally Important		Enforcement of environmental regulations
<b>11. CRITERIA GROUP (Indicators // Equity - Social)</b>			
<b>CRITERIA</b>	<b>IMPORTANCE</b>	<b>IMPORTANCE</b>	<b>CRITERIA</b>
Access to electricity	Equally Important		Quality of electricity supply
<b>12. CRITERIA GROUP (Indicators // Affordability - Social)</b>			
<b>CRITERIA</b>	<b>IMPORTANCE</b>	<b>IMPORTANCE</b>	<b>CRITERIA</b>
Affordability of electricity price for household consumers	Equally Important		Affordability of pump price for diesel fuel
Affordability of electricity price for household consumers	Equally Important		Affordability of pump price for gasoline fuel
Affordability of pump price for diesel fuel	Equally Important		Affordability of pump price for gasoline fuel

## APPENDIX C

The steps of GRA for calculating the value for IEC3 has been provided in the following tables step by step:

**Table C.1** Subindicator values

<b>Countries</b>	<b>IES1</b>	<b>IES2</b>	<b>IES3</b>	<b>IES4</b>	<b>IES5</b>	<b>IES6</b>
Australia	63.57	1.95	20.81	0	5.54	8.14
Austria	8.24	1.4	12.63	0	59.94	16.49
Belgium	6.29	0.1581	31.77	38.94	0.443	20.36
Canada	8.62	1.06	8.18	16.81	60.06	5.55
Chile	35.1	6.19	16.84	0	31.17	10.31
Czechia	53.96	0.0799	2.74	32.49	0.9623	9.68
Denmark	24.17	0.8945	11.77	0	0.0626	60.7
Estonia	83.23	0.5472	0.5952	0	0.2592	14.14
Finland	13.35	0.2988	8.04	33.9	24.44	19.1
France	2.2	0.3377	3.5	77.69	9.75	6.13
Germany	43.68	0.8756	9.41	14.22	2.94	27.43
Greece	46.15	10.84	13.64	0	11.56	17.63
Hungary	19.53	0.1646	16.79	52.45	0.7751	9.69
Iceland	0	0.0213	0	0	73.31	26.67
Ireland	26.14	0.9551	45.01	0	2.84	24.8
Israel	45.05	1.41	51.39	0	0.0199	2.13
Italy	16.65	4.81	38.34	0	15.64	23.4
Japan	33.97	9	39.17	0.9354	8.44	7.9
Korea	43.3	3.03	21.73	30.23	0.4185	1
Latvia	0.0483	0.0322	45.46	0	38.79	15.76
Luxembourg	20.69	0.0363	63.91	0	7.51	23.52
Mexico	11.02	10.24	59.77	3.77	10.03	5.13
Netherlands	37.25	1.17	44.08	3.51	0.0845	12.28
New Zealand	4.25	0.0023	15.53	0	55.49	24.6
Norway	0.1046	0.0201	1.8	0	95.84	1.88
Poland	80.94	1.29	3.84	0	1.12	12.69
Portugal	28.92	3.29	20.22	0	16.88	30.28
Slovakia	11.9	1.05	5.95	58.16	15.32	7.35
Slovenia	29.59	0.1351	2.69	38.14	25.71	3.67
Spain	19.69	5.52	18.51	20.66	10.05	24.92
Sweden	1.24	0.4194	0.5148	34.85	46.13	16.3
Switzerland	0.0016	0.0577	0.7195	35.05	58.07	4.29
Turkey	28.32	0.8433	38.58	0	25.76	6.3
United Kingdom	22.94	0.5399	29.75	20.98	1.89	22.97
United States	34.34	0.8942	32	19.35	5.9	7.18

**Table C.2** Pre-normalization step

<b>Countries</b>	<b>IES1</b>	<b>IES2</b>	<b>IES3</b>	<b>IES4</b>	<b>IES5</b>	<b>IES6</b>
Australia	0.5635	1.3579	0.0648	0.2145	0.1161	0.1428
Austria	0.1012	1.4087	0.0632	0.2145	0.4516	0.003
Belgium	0.1247	1.5232	0.2363	0.2867	0.1693	0.0619
Canada	0.0967	1.44	0.1328	0.0018	0.4529	0.1862
Chile	0.2215	0.9667	0.0027	0.2145	0.1514	0.1065
Czechia	0.4481	1.5305	0.2179	0.2037	0.1639	0.117
Denmark	0.0902	1.4553	0.0766	0.2145	0.1733	0.7376
Estonia	0.7998	1.4873	0.2515	0.2145	0.1712	0.0423
Finland	0.0398	1.5103	0.135	0.2218	0.0811	0.0408
France	0.1738	1.5067	0.206	0.7855	0.0722	0.1765
Germany	0.3246	1.457	0.1135	0.0315	0.1433	0.1803
Greece	0.3542	0.5376	0.0474	0.2145	0.0533	0.0161
Hungary	0.0344	1.5226	0.0019	0.4606	0.1658	0.1169
Iceland	0.2002	1.5359	0.2608	0.2145	0.5911	0.1676
Ireland	0.1138	1.4497	0.4435	0.2145	0.1443	0.1362
Israel	0.341	1.4077	0.5433	0.2145	0.1737	0.2435
Italy	0.0002	1.094	0.3391	0.2145	0.0107	0.1128
Japan	0.2079	0.7074	0.3521	0.2025	0.0859	0.1468
Korea	0.32	1.2583	0.0792	0.1746	0.1696	0.2624
Latvia	0.1997	1.5349	0.4505	0.2145	0.2309	0.0152
Luxembourg	0.0483	1.5345	0.7392	0.2145	0.0956	0.1148
Mexico	0.0678	0.593	0.6744	0.166	0.0693	0.1932
Netherlands	0.2473	1.4299	0.4289	0.1693	0.1731	0.0735
New Zealand	0.1492	1.5376	0.0178	0.2145	0.4052	0.1329
Norway	0.199	1.536	0.2326	0.2145	0.8263	0.2477
Poland	0.7722	1.4188	0.2007	0.2145	0.1622	0.0666
Portugal	0.1472	1.2343	0.0556	0.2145	0.0022	0.228
Slovakia	0.0573	1.441	0.1677	0.5341	0.0141	0.1561
Slovenia	0.1553	1.5254	0.2187	0.2764	0.0944	0.2177
Spain	0.0363	1.0285	0.0288	0.0514	0.0691	0.1382
Sweden	0.1853	1.4991	0.2527	0.234	0.3075	0.0061
Switzerland	0.2002	1.5325	0.2495	0.2366	0.4321	0.2073
Turkey	0.14	1.46	0.3429	0.2145	0.0949	0.1736
United Kingdom	0.0754	1.488	0.2047	0.0555	0.1542	0.1056
United States	0.2123	1.4553	0.2399	0.0345	0.1124	0.1589

**Table C.3** Normalization step

<b>Countries</b>	<b>IES1</b>	<b>IES2</b>	<b>IES3</b>	<b>IES4</b>	<b>IES5</b>	<b>IES6</b>
Australia	0.2954	0.1797	0.9147	0.7286	0.8618	0.8096
Austria	0.8736	0.129	0.9169	0.7286	0.4547	1
Belgium	0.8443	0.0144	0.6821	0.6365	0.7972	0.9198
Canada	0.8793	0.0976	0.8225	1	0.4531	0.7506
Chile	0.7233	0.5709	0.9989	0.7286	0.819	0.8591
Czechia	0.4398	0.0072	0.7071	0.7424	0.8038	0.8447
Denmark	0.8875	0.0823	0.8987	0.7286	0.7924	0
Estonia	0	0.0503	0.6615	0.7286	0.7949	0.9464
Finland	0.9504	0.0274	0.8195	0.7193	0.9043	0.9485
France	0.7829	0.031	0.7232	0	0.9151	0.7638
Germany	0.5943	0.0806	0.8486	0.9622	0.8289	0.7586
Greece	0.5572	1	0.9384	0.7286	0.938	0.9821
Hungary	0.9572	0.015	1	0.4146	0.8014	0.8449
Iceland	0.7498	0.0018	0.6489	0.7286	0.2853	0.7759
Ireland	0.8579	0.0879	0.4011	0.7286	0.8276	0.8186
Israel	0.5737	0.1299	0.2657	0.7286	0.7919	0.6726
Italy	1	0.4436	0.5427	0.7286	0.9897	0.8505
Japan	0.7402	0.8302	0.525	0.744	0.8985	0.8041
Korea	0.6	0.2794	0.8952	0.7796	0.7969	0.6468
Latvia	0.7505	0.0028	0.3916	0.7286	0.7225	0.9834
Luxembourg	0.9398	0.0031	0	0.7286	0.8867	0.8478
Mexico	0.9154	0.9446	0.0879	0.7905	0.9187	0.741
Netherlands	0.6909	0.1077	0.4208	0.7862	0.7927	0.904
New Zealand	0.8137	0	0.9785	0.7286	0.511	0.8231
Norway	0.7514	0.0016	0.6871	0.7286	0	0.6669
Poland	0.0344	0.1188	0.7304	0.7286	0.8058	0.9134
Portugal	0.8161	0.3034	0.9272	0.7286	1	0.6936
Slovakia	0.9286	0.0967	0.7752	0.3208	0.9856	0.7916
Slovenia	0.8061	0.0123	0.706	0.6496	0.8882	0.7077
Spain	0.9548	0.5091	0.9635	0.9368	0.9189	0.8158
Sweden	0.7684	0.0385	0.6598	0.7037	0.6296	0.9957
Switzerland	0.7498	0.0051	0.6642	0.7004	0.4783	0.7218
Turkey	0.8251	0.0776	0.5376	0.7286	0.8875	0.7677
United Kingdom	0.906	0.0496	0.725	0.9315	0.8156	0.8603
United States	0.7347	0.0823	0.6772	0.9583	0.8663	0.7877

**Table C.4** Absolute value of the difference

<b>Countries</b>	<b>IES1</b>	<b>IES2</b>	<b>IES3</b>	<b>IES4</b>	<b>IES5</b>	<b>IES6</b>
Australia	0.7046	0.8203	0.0853	0.2714	0.1382	0.1904
Austria	0.1264	0.871	0.0831	0.2714	0.5453	0
Belgium	0.1557	0.9856	0.3179	0.3635	0.2028	0.0802
Canada	0.1207	0.9024	0.1775	0	0.5469	0.2494
Chile	0.2767	0.4291	0.0011	0.2714	0.181	0.1409
Czechia	0.5602	0.9928	0.2929	0.2576	0.1962	0.1553
Denmark	0.1125	0.9177	0.1013	0.2714	0.2076	1
Estonia	1	0.9497	0.3385	0.2714	0.2051	0.0536
Finland	0.0496	0.9726	0.1805	0.2807	0.0957	0.0515
France	0.2171	0.969	0.2768	1	0.0849	0.2362
Germany	0.4057	0.9194	0.1514	0.0378	0.1711	0.2414
Greece	0.4428	0	0.0616	0.2714	0.062	0.0179
Hungary	0.0428	0.985	0	0.5854	0.1986	0.1551
Iceland	0.2502	0.9982	0.3511	0.2714	0.7147	0.2241
Ireland	0.1421	0.9121	0.5989	0.2714	0.1724	0.1814
Israel	0.4263	0.8701	0.7343	0.2714	0.2081	0.3274
Italy	0	0.5564	0.4573	0.2714	0.0103	0.1495
Japan	0.2598	0.1698	0.475	0.256	0.1015	0.1959
Korea	0.4	0.7206	0.1048	0.2204	0.2031	0.3532
Latvia	0.2495	0.9972	0.6084	0.2714	0.2775	0.0166
Luxembourg	0.0602	0.9969	1	0.2714	0.1133	0.1522
Mexico	0.0846	0.0554	0.9121	0.2095	0.0813	0.259
Netherlands	0.3091	0.8923	0.5792	0.2138	0.2073	0.096
New Zealand	0.1863	1	0.0215	0.2714	0.489	0.1769
Norway	0.2486	0.9984	0.3129	0.2714	1	0.3331
Poland	0.9656	0.8812	0.2696	0.2714	0.1942	0.0866
Portugal	0.1839	0.6966	0.0728	0.2714	0	0.3064
Slovakia	0.0714	0.9033	0.2248	0.6792	0.0144	0.2084
Slovenia	0.1939	0.9877	0.294	0.3504	0.1118	0.2923
Spain	0.0452	0.4909	0.0365	0.0632	0.0811	0.1842
Sweden	0.2316	0.9615	0.3402	0.2963	0.3704	0.0043
Switzerland	0.2502	0.9949	0.3358	0.2996	0.5217	0.2782
Turkey	0.1749	0.9224	0.4624	0.2714	0.1125	0.2323
United Kingdom	0.094	0.9504	0.275	0.0685	0.1844	0.1397
United States	0.2653	0.9177	0.3228	0.0417	0.1337	0.2123

**Table C.5.** Grey Relational Grade

<b>Countries</b>	<b>IES1</b>	<b>IES2</b>	<b>IES3</b>	<b>IES4</b>	<b>IES5</b>	<b>IES6</b>
Australia	0.4151	0.3787	0.8542	0.6482	0.7834	0.7242
Austria	0.7982	0.3647	0.8576	0.6482	0.4783	1
Belgium	0.7626	0.3366	0.6113	0.579	0.7115	0.8618
Canada	0.8056	0.3565	0.738	1	0.4776	0.6672
Chile	0.6437	0.5382	0.9979	0.6482	0.7342	0.7801
Czechia	0.4716	0.3349	0.6306	0.66	0.7182	0.763
Denmark	0.8163	0.3527	0.8315	0.6482	0.7066	0.3333
Estonia	0.3333	0.3449	0.5963	0.6482	0.7091	0.9032
Finland	0.9098	0.3395	0.7348	0.6404	0.8393	0.9067
France	0.6972	0.3404	0.6437	0.3333	0.8549	0.6791
Germany	0.5521	0.3523	0.7676	0.9297	0.745	0.6744
Greece	0.5303	1	0.8903	0.6482	0.8897	0.9654
Hungary	0.9212	0.3367	1	0.4607	0.7158	0.7633
Iceland	0.6665	0.3337	0.5875	0.6482	0.4116	0.6905
Ireland	0.7787	0.3541	0.455	0.6482	0.7436	0.7338
Israel	0.5398	0.3649	0.4051	0.6482	0.7061	0.6043
Italy	1	0.4733	0.5223	0.6482	0.9798	0.7698
Japan	0.6581	0.7465	0.5128	0.6613	0.8313	0.7185
Korea	0.5556	0.4096	0.8267	0.694	0.7112	0.586
Latvia	0.6671	0.3339	0.4511	0.6482	0.6431	0.9678
Luxembourg	0.8925	0.334	0.3333	0.6482	0.8153	0.7666
Mexico	0.8553	0.9003	0.3541	0.7047	0.8601	0.6587
Netherlands	0.618	0.3591	0.4633	0.7005	0.7069	0.8389
New Zealand	0.7285	0.3333	0.9588	0.6482	0.5056	0.7387
Norway	0.6679	0.3337	0.6151	0.6482	0.3333	0.6001
Poland	0.3412	0.362	0.6497	0.6482	0.7203	0.8523
Portugal	0.7311	0.4178	0.8729	0.6482	1	0.6201
Slovakia	0.8751	0.3563	0.6898	0.424	0.9721	0.7058
Slovenia	0.7205	0.3361	0.6297	0.588	0.8172	0.6311
Spain	0.9171	0.5046	0.932	0.8877	0.8604	0.7308
Sweden	0.6835	0.3421	0.5951	0.6279	0.5744	0.9914
Switzerland	0.6665	0.3345	0.5982	0.6253	0.4894	0.6425
Turkey	0.7409	0.3515	0.5195	0.6482	0.8164	0.6827
United Kingdom	0.8417	0.3447	0.6451	0.8795	0.7305	0.7816
United States	0.6533	0.3527	0.6077	0.923	0.7891	0.702

## APPENDIX D

Data sources used for calculating indicator values have been provided in this section:

**Table D.1** Data source for indicators

<b>Indicators</b>	<b>Data Source</b>
IEC1	World Bank
IEC2	World Bank
IEC3	Trading Economics
IEC4	Evans et al. (2009) Brighthub Engineering
IEC5	World Bank
IEC6	World Bank
IEC7	The Global Competitiveness Report 2017–2018
IEC8	The Global Competitiveness Report 2017–2018
IEC9	The Global Competitiveness Report 2017–2018
IEN1	World Bank
IEN2	World Bank
IEN3	World Bank
IEN4	World Bank
IEN5	World Bank
IEN6	The Travel & Tourism Competitiveness Report 2017
IEN7	The Travel & Tourism Competitiveness Report 2017
ISO1	World Bank
ISO2	The Global Competitiveness Report 2017–2018
ISO3	Global Petrol Prices (Datasheet)
ISO4	Global Petrol Prices Trading Economics
ISO5	Global Petrol Prices Trading Economics

**Table D.2.** Steps to calculate IEN1

<b>OECD</b>	<b><u>2008 (N<sub>2</sub>O emissions thousand metric tons of CO<sub>2</sub> equivalent per capita)</u></b>	<b><u>2008 {Population (thousand)}</u></b>	<b><u>2008 (N<sub>2</sub>O emissions thousand metric tons of CO<sub>2</sub> equivalent per capita) / 2008 {Population (thousand)}</u></b>
Australia	3746	21249.2	0.176
Austria	709	8321.5	0.085
Belgium	714	10709.97	0.067
Canada	6431	33245.77	0.193
Chile	558	16661.94	0.033
Czechia	1440	10384.6	0.139
Denmark	536	5493.62	0.098
Estonia	131	1337.09	0.098
Finland	1994	5313.4	0.375
France	3884	64374.99	0.060
Germany	5661	82110.1	0.069
Greece	799	11077.84	0.072
Hungary	324	10038.19	0.032
Iceland	15	317.41	0.047
Ireland	315	4489.54	0.070
Israel	275	7308.8	0.038
Italy	3197	58826.73	0.054
Japan	7235	128063	0.056
Korea	3280	49054.71	0.067
Latvia	164	2177.32	0.075
Luxembourg	82	488.65	0.168
Mexico	3695	113661.81	0.033
Netherlands	777	16445.59	0.047
New Zealand	299	4259.8	0.070
Norway	311	4768.21	0.065
Poland	3836	38125.76	0.101
Portugal	532	10558.18	0.050
Slovakia	385	5379.23	0.072
Slovenia	138	2021.32	0.068
Spain	2687	45954.11	0.058
Sweden	1081	9219.64	0.117
Switzerland	390	7647.68	0.051
Turkey	3334	70440.03	0.047
United Kingdom	2330	61807	0.038
United States	65719	304093.97	0.216

**Table D.3.** Steps to calculate IEN2

<b>OECD</b>	<b><i>2008 (CH<sub>4</sub> emissions thousand metric tons of CO<sub>2</sub> equivalent per capita)</i></b>	<b><i>2008 {Population (thousand)}</i></b>	<b><i>2008 (CH<sub>4</sub> emissions thousand metric tons of CO<sub>2</sub> equivalent per capita) / 2008 {Population (thousand)}</i></b>
Australia	39063	21249.2	1.838
Austria	2037	8321.5	0.245
Belgium	1399	10709.97	0.131
Canada	45411	33245.77	1.366
Chile	4263	16661.94	0.256
Czechia	5109	10384.6	0.492
Denmark	1305	5493.62	0.238
Estonia	922	1337.09	0.690
Finland	834	5313.4	0.157
France	35280	64374.99	0.548
Germany	15348	82110.1	0.187
Greece	1849	11077.84	0.167
Hungary	2151	10038.19	0.214
Iceland	3	317.41	0.009
Ireland	1967	4489.54	0.438
Israel	1034	7308.8	0.141
Italy	6245	58826.73	0.106
Japan	3375	128063	0.026
Korea	7014	49054.71	0.143
Latvia	1772	2177.32	0.814
Luxembourg	128	488.65	0.262
Mexico	39540	113661.81	0.348
Netherlands	5453	16445.59	0.332
New Zealand	1122	4259.8	0.263
Norway	13506	4768.21	2.833
Poland	41179	38125.76	1.080
Portugal	1654	10558.18	0.157
Slovakia	923	5379.23	0.172
Slovenia	1132	2021.32	0.560
Spain	3356	45954.11	0.073
Sweden	1255	9219.64	0.136
Switzerland	1069	7647.68	0.140
Turkey	14822	70440.03	0.210
United Kingdom	13833	61807	0.224
United States	219505	304093.97	0.722

**Table D.4.** Steps to calculate IEN3

<b>OECD</b>	<b><u>2014 {CO<sub>2</sub> Emissions from Solid Fuel Combustion (thousand tonnes)}</u></b>	<b><u>2014 {Population (thousand)}</u></b>	<b><u>2014 {CO<sub>2</sub> Emissions from Solid Fuel Combustion (thousand tonnes)} / 2014 {Population (thousand)}</u></b>
Australia	163394	23475.69	6.960
Austria	11474	8546.36	1.343
Belgium	11789	11209.06	1.052
Canada	75786	35437.43	2.139
Chile	25629	17758.96	1.443
Czechia	614	10525.35	0.058
Denmark	905	5643.38	0.160
Estonia	17481	1314.55	13.298
Finland	17151	5461.21	3.141
France	34539	66316.1	0.521
Germany	308387	80982.5	3.808
Greece	26413	10892.41	2.425
Hungary	8801	9866.47	0.892
Iceland	330	327.39	1.008
Ireland	7752	4657.64	1.664
Israel	24844	8215.7	3.024
Italy	49622	60789.14	0.816
Japan	449064	127276	3.528
Korea	308618	50746.66	6.082
Latvia	227	1993.78	0.114
Luxembourg	202	556.32	0.363
Mexico	48984	120355.13	0.407
Netherlands	3326	16865.01	0.197
New Zealand	5519	4509.7	1.224
Norway	3223	5137.23	0.627
Poland	191395	38011.74	5.035
Portugal	10125	10401.06	0.973
Slovakia	13289	5418.65	2.452
Slovenia	4166	2061.98	2.020
Spain	43461	46480.88	0.935
Sweden	8005	9696.11	0.826
Switzerland	543	8188.65	0.066
Turkey	138888	77231.91	1.798
United Kingdom	113974	64613.16	1.764
United States	1650322	318386.42	5.183

**Table D.5.** Steps to calculate IEN4

<b>OECD</b>	<b><u>2014 {CO2 Emissions from Liquid Fuel Combustion (thousand tonnes)}</u></b>	<b><u>2014 {CO2 Emissions from Liquid Fuel Combustion (thousand tonnes)} / 2014 {Population (thousand)}</u></b>
Australia	120197	5.12
Austria	30286	3.54
Belgium	49662	4.43
Canada	248318	7.01
Chile	46241	2.60
Czechia	19076	1.81
Denmark	16890	2.99
Estonia	818	0.62
Finland	23769	4.35
France	185605	2.80
Germany	250320	3.09
Greece	32658	3.00
Hungary	16248	1.65
Iceland	1654	5.05
Ireland	16795	3.61
Israel	22050	2.68
Italy	143985	2.37
Japan	489159	3.84
Korea	156273	3.08
Latvia	3674	1.84
Luxembourg	6978	12.54
Mexico	269062	2.24
Netherlands	67003	3.97
New Zealand	18386	4.08
Norway	31324	6.10
Poland	55962	1.47
Portugal	24232	2.33
Slovakia	7085	1.31
Slovenia	6557	3.18
Spain	129038	2.78
Sweden	32350	3.34
Switzerland	26512	3.24
Turkey	79435	1.03
United Kingdom	162353	2.51
United States	2114139	6.64

**Table D.6.** Steps to calculate IEN5

<b>OECD</b>	<b><u>2014 {CO<sub>2</sub> Emissions from Gaseous Fuel Combustion (thousand tonnes)}</u></b>	<b><u>2014 {CO<sub>2</sub> Emissions from Gaseous Fuel Combustion (thousand tonnes)} / 2014 {Population (thousand)}</u></b>
Australia	72607	3.09
Austria	14760	1.73
Belgium	28856	2.57
Canada	23284	0.66
Chile	8152	0.46
Czechia	14158	1.35
Denmark	6443	1.14
Estonia	997	0.76
Finland	5757	1.05
France	74653	1.13
Germany	145147	1.79
Greece	5691	0.52
Hungary	15992	1.62
Iceland	0	0.00
Ireland	8526	1.83
Israel	14411	1.75
Italy	116134	1.91
Japan	246943	1.94
Korea	98796	1.95
Latvia	2479	1.24
Luxembourg	1933	3.47
Mexico	138616	1.15
Netherlands	66043	3.92
New Zealand	10062	2.23
Norway	11313	2.20
Poland	30700	0.81
Portugal	7954	0.76
Slovakia	8639	1.59
Slovenia	1434	0.70
Spain	54202	1.17
Sweden	1819	0.19
Switzerland	6117	0.75
Turkey	92082	1.19
United Kingdom	136926	2.12
United States	1432767	4.50

**Table D.7. Steps to calculate IEC3**

Countries	A <sup>1</sup>	B <sup>2</sup>	C <sup>3</sup>	D <sup>4</sup>	E <sup>5</sup>	F <sup>6</sup>	G <sup>7</sup>	H <sup>8</sup>	I <sup>9</sup>	J <sup>10</sup>	K <sup>11</sup>	L <sup>12</sup>	M <sup>13</sup>
Australia	52.54	63.57	5.54	20.81	0	1.95	8.14	54.5	90	49	33	38.5	24.125
Austria	69.14	8.24	59.94	12.63	0	1.4	16.49	54.5	90	49	33	38.5	24.125
Belgium	37.22	6.29	0.443	31.77	38.94	0.1581	20.36	54.5	90	49	33	38.5	24.125
Canada	70.05	8.62	60.06	8.18	16.81	1.06	5.55	54.5	90	49	33	38.5	24.125
Chile	60.30	35.1	31.17	16.84	0	6.19	10.31	54.5	90	49	33	38.5	24.125
Czechia	44.70	53.96	0.9623	2.74	32.49	0.0799	9.68	54.5	90	49	33	38.5	24.125
Denmark	33.98	24.17	0.0626	11.77	0	0.8945	60.7	54.5	90	49	33	38.5	24.125
Estonia	49.51	83.23	0.2592	0.5952	0	0.5472	14.14	54.5	90	49	33	38.5	24.125
Finland	49.12	13.35	24.44	8.04	33.9	0.2988	19.1	54.5	90	49	33	38.5	24.125
France	38.94	2.2	9.75	3.5	77.69	0.3377	6.13	54.5	90	49	33	38.5	24.125
Germany	42.71	43.68	2.94	9.41	14.22	0.8756	27.43	54.5	90	49	33	38.5	24.125
Greece	50.67	46.15	11.56	13.64	0	10.84	17.63	54.5	90	49	33	38.5	24.125
Hungary	39.28	19.53	0.7751	16.79	52.45	0.1646	9.69	54.5	90	49	33	38.5	24.125
Iceland	72.42	0	73.31	0	0	0.0213	26.67	54.5	90	49	33	38.5	24.125
Ireland	45.21	26.14	2.84	45.01	0	0.9551	24.8	54.5	90	49	33	38.5	24.125
Israel	50.81	45.05	0.0199	51.39	0	1.41	2.13	54.5	90	49	33	38.5	24.125
Italy	49.43	16.65	15.64	38.34	0	4.81	23.4	54.5	90	49	33	38.5	24.125
Japan	50.98	33.97	8.44	39.17	0.9354	9	7.9	54.5	90	49	33	38.5	24.125
Korea	46.01	43.3	0.4185	21.73	30.23	3.03	1	54.5	90	49	33	38.5	24.125
Latvia	61.03	0.0483	38.79	45.46	0	0.0322	15.76	54.5	90	49	33	38.5	24.125
Luxembourg	55.04	20.69	7.51	63.91	0	0.0363	23.52	54.5	90	49	33	38.5	24.125
Mexico	50.74	11.02	10.03	59.77	3.77	10.24	5.13	54.5	90	49	33	38.5	24.125
Netherlands	46.55	37.25	0.0845	44.08	3.51	1.17	12.28	54.5	90	49	33	38.5	24.125
New Zealand	65.80	4.25	55.49	15.53	0	0.0226	24.6	54.5	90	49	33	38.5	24.125
Norway	87.66	0.1046	95.84	1.8	0	0.0201	1.88	54.5	90	49	33	38.5	24.125
Poland	50.56	80.94	1.12	3.84	0	1.29	12.69	54.5	90	49	33	38.5	24.125
Portugal	49.43	28.92	16.88	20.22	0	3.29	30.28	54.5	90	49	33	38.5	24.125
Slovakia	44.56	11.9	15.32	5.95	58.16	1.05	7.35	54.5	90	49	33	38.5	24.125
Slovenia	54.11	29.59	25.71	2.69	38.14	0.1351	3.67	54.5	90	49	33	38.5	24.125
Spain	43.80	19.69	10.05	18.51	20.66	5.52	24.92	54.5	90	49	33	38.5	24.125
Sweden	58.04	1.24	46.13	0.5148	34.85	0.4194	16.3	54.5	90	49	33	38.5	24.125
Switzerland	65.24	0.0016	58.07	0.7195	35.05	0.0577	4.29	54.5	90	49	33	38.5	24.125
Turkey	59.37	28.32	25.76	38.58	0	0.8433	6.3	54.5	90	49	33	38.5	24.125
United Kingdom	41.45	22.94	1.89	29.75	20.98	0.5399	22.97	54.5	90	49	33	38.5	24.125
United States	48.17	34.34	5.9	32	19.35	0.8942	7.18	54.5	90	49	33	38.5	24.125

1\* 2015 (Supply Efficiency of Electricity Generation %) 2\* 2015 (Electricity production from coal sources % of total) 3\* 2015 (Electricity production from hydroelectric sources % of total) 4\* 2015 (Electricity production from natural gas sources % of total) 5\* 2015 (Electricity production from nuclear sources % of total) 6\* 2015 (Electricity production from oil sources % of total) 7\* 2015 (Electricity production from renewable (except hydroelectric) sources % of total) 8\* Efficiency of Electricity production from coal sources % of total 9\* Efficiency of Electricity production from hydroelectric sources % of total 10\* Efficiency of Electricity production from natural gas sources % of total 11\* Efficiency of Electricity production from nuclear sources % of total 12\* Efficiency of Electricity production from oil sources % of total 13\* Efficiency of Electricity production from renewable (except hydroelectric) sources % of total

## APPENDIX E

Codes for calculating fuzzy AHP scores with decision makers are provided as:

```
for z=1:1:12
```

```
    A=xlsread('RESULTS (ALTINTAS).xlsx',z);
```

```
    for i=1:1:size(A,1)
```

```
        for j=1:1:size(A,2)
```

```
            if j == 1
```

```
                k=1;
```

```
            elseif j == 2
```

```
                k=4;
```

```
            elseif j == 3
```

```
                k=7;
```

```
            elseif j == 4
```

```
                k=10;
```

```
            elseif j == 5
```

```
                k=13;
```

```
            elseif j == 6
```

```
                k=16;
```

```
            elseif j == 7
```

```
                k=19;
```

```
            elseif j == 8
```

```
                k=22;
```

```
            elseif j == 9
```

```
                k=25;
```

```
elseif j == 10
    k=28;
elseif j == 11
    k=31;
elseif j == 12
    k=34;
elseif j == 13
    k=37;
elseif j == 14
    k=40;
else
    k=43;
end

if A(i,j) == 1
    B(i,k) = 1;
    B(i,k+1) = 1;
    B(i,k+2) = 1;
elseif A(i,j) == 3
    B(i,k) = 1;
    B(i,k+1) = 3;
    B(i,k+2) = 5;
elseif A(i,j) == 5
    B(i,k) = 3;
    B(i,k+1) = 5;
```

```
B(i,k+2) = 7;
elseif A(i,j) == 7
    B(i,k) = 5;
    B(i,k+1) = 7;
    B(i,k+2) = 9;
elseif A(i,j) == 9
    B(i,k) = 7;
    B(i,k+1) = 9;
    B(i,k+2) = 9;
elseif A(i,j) == 0.333
    B(i,k) = 0.2;
    B(i,k+1) = 0.333;
    B(i,k+2) = 1;
elseif A(i,j) == 0.2
    B(i,k) = 0.143;
    B(i,k+1) = 0.2;
    B(i,k+2) = 0.333;
elseif A(i,j) == 0.143
    B(i,k) = 0.111;
    B(i,k+1) = 0.143;
    B(i,k+2) = 0.2;
else
    B(i,k) = 0.111;
    B(i,k+1) = 0.111;
```

```

        B(i,k+2) = 0.143;
    end
end
end
fuzzy_matrix=B;
A=fuzzy_matrix;
B=rand(size(A,1),3);
for i=1:1:size(A,1)
    mult_k=1;
    for j=1:3:size(A,2)
        k=A(i,j);
        mult_k = k * mult_k;
        B(i,1) = mult_k;
    end
end
for i=1:1:size(A,1)
    mult_k=1;
    for j=2:3:size(A,2)
        k=A(i,j);
        mult_k = k * mult_k;
        B(i,2) = mult_k;
    end
end
for i=1:1:size(A,1)

```

```

mult_k=1;
for j=3:3:size(A,2)
    k=A(i,j);
    mult_k = k * mult_k;
    B(i,3) = mult_k;
end
end
for i=1:1:size(B,1)
    C(i,1)=nthroot(B(i,1),size(A,2)/3);
end
for i=1:1:size(B,1)
    C(i,2)=nthroot(B(i,2),size(A,2)/3);
end
for i=1:1:size(B,1)
    C(i,3)=nthroot(B(i,3),size(A,2)/3);
end
fuzzy_geometric_mean_value = C;
sum_k=0;
for i=1:1:size(fuzzy_geometric_mean_value,1)
    k = fuzzy_geometric_mean_value(i,1);
    sum_k = sum_k + k;
end
sum_fuzzy_geometric_mean_value(1,1) = sum_k;
sum_k=0;

```

```

for i=1:1:size(fuzzy_geometric_mean_value,1)
    k = fuzzy_geometric_mean_value(i,2);
    sum_k = sum_k + k;
end
sum_fuzzy_geometric_mean_value(1,2) = sum_k;
sum_k=0;
for i=1:1:size(fuzzy_geometric_mean_value,1)
    k = fuzzy_geometric_mean_value(i,3);
    sum_k = sum_k + k;
end
sum_fuzzy_geometric_mean_value(1,3) = sum_k;
reciprocal_of_sum_fuzzy_geometric_mean_value = rand(1,3);
reciprocal_of_sum_fuzzy_geometric_mean_value(1,1) =
1/sum_fuzzy_geometric_mean_value(1,3);
reciprocal_of_sum_fuzzy_geometric_mean_value(1,2) =
1/sum_fuzzy_geometric_mean_value(1,2);
reciprocal_of_sum_fuzzy_geometric_mean_value(1,3) =
1/sum_fuzzy_geometric_mean_value(1,1);
fuzzy_weights = rand(size(fuzzy_geometric_mean_value,1),3);
for i=1:1:size(fuzzy_weights,1)
    fuzzy_weights(i,1) = fuzzy_geometric_mean_value(i,1) *
reciprocal_of_sum_fuzzy_geometric_mean_value(1,1);
end
for i=1:1:size(fuzzy_weights,1)

```

```

    fuzzy_weights(i,2)          =          fuzzy_geometric_mean_value(i,2)          *
reciprocal_of_sum_fuzzy_geometric_mean_value(1,2);

end

for i=1:1:size(fuzzy_weights,1)

    fuzzy_weights(i,3)          =          fuzzy_geometric_mean_value(i,3)          *
reciprocal_of_sum_fuzzy_geometric_mean_value(1,3);

end

crisp_weights = rand(size(fuzzy_weights,1),1);

for i=1:1:size(crisp_weights,1)

    crisp_weights(i,1) = (fuzzy_weights(i,1) + fuzzy_weights(i,2) + fuzzy_weights(i,3))/3;

end

sum_k=0;

for i=1:1:size(crisp_weights,1)

    k = crisp_weights(i,1);

    sum_k = sum_k + k;

end

sum_crisp_weights = sum_k;

crisp_weights_with_normalization = rand(size(crisp_weights,1),1);

for i=1:1:size(crisp_weights_with_normalization,1)

    crisp_weights_with_normalization(i,1) = crisp_weights(i,1) / sum_crisp_weights;

end

criteria_weights = crisp_weights_with_normalization;

if z == 1

    G1=criteria_weights;

```

```
elseif z == 2
    G2=criteria_weights;
elseif z == 3
    G3=criteria_weights;
elseif z == 4
    G4=criteria_weights;
elseif z == 5
    G5=criteria_weights;
elseif z == 6
    G6=criteria_weights;
elseif z == 7
    G7=criteria_weights;
elseif z == 8
    G8=criteria_weights;
elseif z == 9
    G9=criteria_weights;
elseif z == 10
    G10=criteria_weights;
elseif z == 11
    G11=criteria_weights;
else
    G12=criteria_weights;
end
A=1;
```

```

B=1;
C=1;
crisp_weights=1;
crisp_weights_with_normalization=1;
criteria_weights=1;
fuzzy_geometric_mean_value=1;
fuzzy_matrix=1;
fuzzy_weights=1;
i=1;
j=1;
mult_k=1;
reciprocal_of_sum_fuzzy_geometric_mean_value=1;
sum_crisp_weights=1;
sum_fuzzy_geometric_mean_value=1;
sum_k=1;
end

Energy_use_per_capita = G5(1,1)*G2(1,1)*G1(1,1);
IEC1 = Energy_use_per_capita;
Energy_use_per_GDP = G5(2,1)*G2(1,1)*G1(1,1);
IEC2 = Energy_use_per_GDP;
Diversification_of_sources_for_power_production = G5(3,1)*G2(1,1)*G1(1,1);
IEC3 = Diversification_of_sources_for_power_production;
Supply_Efficiency_of_Electricity_Generation = G6(1,1)*G2(2,1)*G1(1,1);
IEC4 = Supply_Efficiency_of_Electricity_Generation;

```

Electric\_Power\_Transmission\_and\_Distribution\_Losses =  $G6(2,1)*G2(2,1)*G1(1,1)$ ;

IEC5 = Electric\_Power\_Transmission\_and\_Distribution\_Losses;

Economic\_Growth\_Rate =  $G7(1,1)*G2(3,1)*G1(1,1)$ ;

IEC6 = Economic\_Growth\_Rate;

Government\_Budget\_Balance =  $G7(2,1)*G2(3,1)*G1(1,1)$ ;

IEC7 = Government\_Budget\_Balance;

Inflation\_Rate =  $G7(3,1)*G2(3,1)*G1(1,1)$ ;

IEC8 = Inflation\_Rate;

Government\_Debt =  $G7(4,1)*G2(3,1)*G1(1,1)$ ;

IEC9 = Government\_Debt;

N2O\_emissions\_from\_energy\_processes =  $G8(1,1)*G3(1,1)*G1(2,1)$ ;

IEN1 = N2O\_emissions\_from\_energy\_processes;

CH4\_emissions\_from\_energy\_processes =  $G8(2,1)*G3(1,1)*G1(2,1)$ ;

IEN2 = CH4\_emissions\_from\_energy\_processes;

CO2\_emissions\_from\_coal\_combustion =  $G9(1,1)*G3(2,1)*G1(2,1)$ ;

IEN3 = CO2\_emissions\_from\_coal\_combustion;

CO2\_emissions\_from\_oil\_combustion =  $G9(2,1)*G3(2,1)*G1(2,1)$ ;

IEN4 = CO2\_emissions\_from\_oil\_combustion;

CO2\_emissions\_from\_natural\_gas\_combustion =  $G9(3,1)*G3(2,1)*G1(2,1)$ ;

IEN5 = CO2\_emissions\_from\_natural\_gas\_combustion;

Stringency\_of\_environmental\_regulations =  $G10(1,1)*G3(3,1)*G1(2,1)$ ;

IEN6 = Stringency\_of\_environmental\_regulations;

Enforcement\_of\_environmental\_regulations =  $G10(2,1)*G3(3,1)*G1(2,1)$ ;

IEN7 = Enforcement\_of\_environmental\_regulations;

Access\_to\_electricity = G11(1,1)\*G4(1,1)\*G1(3,1);

ISO1 = Access\_to\_electricity;

Quality\_of\_electricity\_supply = G11(2,1)\*G4(1,1)\*G1(3,1);

ISO2 = Quality\_of\_electricity\_supply;

Affordability\_of\_electricity\_price\_for\_household\_consumers = G12(1,1)\*G4(2,1)\*G1(3,1);

ISO3 = Affordability\_of\_electricity\_price\_for\_household\_consumers;

Affordability\_of\_pump\_price\_for\_diesel\_fuel = G12(2,1)\*G4(2,1)\*G1(3,1);

ISO4 = Affordability\_of\_pump\_price\_for\_diesel\_fuel;

Affordability\_of\_pump\_price\_for\_gasoline\_fuel = G12(3,1)\*G4(2,1)\*G1(3,1);

ISO5 = Affordability\_of\_pump\_price\_for\_gasoline\_fuel;

sum\_of\_criteria\_weights =

IEC1+IEC2+IEC3+IEC4+IEC5+IEC6+IEC7+IEC8+IEC9+IEN1+IEN2+IEN3+IEN4+IEN5+IEN6  
+IEN7+ISO1+ISO2+ISO3+ISO4+ISO5

final\_criteria\_weights = rand(1,21);

final\_criteria\_weights(1,1)=IEC1/sum\_of\_criteria\_weights;

final\_criteria\_weights(1,2)=IEC2/sum\_of\_criteria\_weights;

final\_criteria\_weights(1,3)=IEC3/sum\_of\_criteria\_weights;

final\_criteria\_weights(1,4)=IEC4/sum\_of\_criteria\_weights;

final\_criteria\_weights(1,5)=IEC5/sum\_of\_criteria\_weights;

final\_criteria\_weights(1,6)=IEC6/sum\_of\_criteria\_weights;

final\_criteria\_weights(1,7)=IEC7/sum\_of\_criteria\_weights;

final\_criteria\_weights(1,8)=IEC8/sum\_of\_criteria\_weights;

final\_criteria\_weights(1,9)=IEC9/sum\_of\_criteria\_weights;

final\_criteria\_weights(1,10)=IEN1/sum\_of\_criteria\_weights;

```

final_criteria_weights(1,11)=IEN2/sum_of_criteria_weights;
final_criteria_weights(1,12)=IEN3/sum_of_criteria_weights;
final_criteria_weights(1,13)=IEN4/sum_of_criteria_weights;
final_criteria_weights(1,14)=IEN5/sum_of_criteria_weights;
final_criteria_weights(1,15)=IEN6/sum_of_criteria_weights;
final_criteria_weights(1,16)=IEN7/sum_of_criteria_weights;
final_criteria_weights(1,17)=ISO1/sum_of_criteria_weights;
final_criteria_weights(1,18)=ISO2/sum_of_criteria_weights;
final_criteria_weights(1,19)=ISO3/sum_of_criteria_weights;
final_criteria_weights(1,20)=ISO4/sum_of_criteria_weights;
final_criteria_weights(1,21)=ISO5/sum_of_criteria_weights;
Datatable =
table(IEC1,IEC2,IEC3,IEC4,IEC5,IEC6,IEC7,IEC8,IEC9,IEN1,IEN2,IEN3,IEN4,IEN5,IEN6,IEN
7,ISO1,ISO2,ISO3,ISO4,ISO5)
xlswrite('GRA.xlsx',final_criteria_weights,1,'A4:U4')
clear
for z=1:1:12
    A=xlswread('RESULTS (GURBUZ).xlsx',z);
    for i=1:1:size(A,1)
        for j=1:1:size(A,2)
            if j == 1
                k=1;
            elseif j == 2
                k=4;
            end
        end
    end
end

```

elseif j == 3

    k=7;

elseif j == 4

    k=10;

elseif j == 5

    k=13;

elseif j == 6

    k=16;

elseif j == 7

    k=19;

elseif j == 8

    k=22;

elseif j == 9

    k=25;

elseif j == 10

    k=28;

elseif j == 11

    k=31;

elseif j == 12

    k=34;

elseif j == 13

    k=37;

elseif j == 14

    k=40;

```
else
    k=43;
end
if A(i,j) == 1
    B(i,k) = 1;
    B(i,k+1) = 1;
    B(i,k+2) = 1;
elseif A(i,j) == 3
    B(i,k) = 1;
    B(i,k+1) = 3;
    B(i,k+2) = 5;
elseif A(i,j) == 5
    B(i,k) = 3;
    B(i,k+1) = 5;
    B(i,k+2) = 7;
elseif A(i,j) == 7
    B(i,k) = 5;
    B(i,k+1) = 7;
    B(i,k+2) = 9;
elseif A(i,j) == 9
    B(i,k) = 7;
    B(i,k+1) = 9;
    B(i,k+2) = 9;
elseif A(i,j) == 0.333
```

```

        B(i,k) = 0.2;
        B(i,k+1) = 0.333;
        B(i,k+2) = 1;
    elseif A(i,j) == 0.2
        B(i,k) = 0.143;
        B(i,k+1) = 0.2;
        B(i,k+2) = 0.333;
    elseif A(i,j) == 0.143
        B(i,k) = 0.111;
        B(i,k+1) = 0.143;
        B(i,k+2) = 0.2;
    else
        B(i,k) = 0.111;
        B(i,k+1) = 0.111;
        B(i,k+2) = 0.143;
    end
end
end
end
fuzzy_matrix=B;
A=fuzzy_matrix;
B=rand(size(A,1),3);
for i=1:1:size(A,1)
    mult_k=1;
    for j=1:3:size(A,2)

```

```

    k=A(i,j);
    mult_k = k * mult_k;
    B(i,1) = mult_k;
end
end
for i=1:1:size(A,1)
    mult_k=1;
    for j=2:3:size(A,2)
        k=A(i,j);
        mult_k = k * mult_k;
        B(i,2) = mult_k;
    end
end
end
for i=1:1:size(A,1)
    mult_k=1;
    for j=3:3:size(A,2)
        k=A(i,j);
        mult_k = k * mult_k;
        B(i,3) = mult_k;
    end
end
end
for i=1:1:size(B,1)
    C(i,1)=nthroot(B(i,1),size(A,2)/3);
end
end

```

```

for i=1:1:size(B,1)
    C(i,2)=nthroot(B(i,2),size(A,2)/3);
end
for i=1:1:size(B,1)
    C(i,3)=nthroot(B(i,3),size(A,2)/3);
end
fuzzy_geometric_mean_value = C;
sum_k=0;
for i=1:1:size(fuzzy_geometric_mean_value,1)
    k = fuzzy_geometric_mean_value(i,1);
    sum_k = sum_k + k;
end
sum_fuzzy_geometric_mean_value(1,1) = sum_k;
sum_k=0;
for i=1:1:size(fuzzy_geometric_mean_value,1)
    k = fuzzy_geometric_mean_value(i,2);
    sum_k = sum_k + k;
end
sum_fuzzy_geometric_mean_value(1,2) = sum_k;
sum_k=0;
for i=1:1:size(fuzzy_geometric_mean_value,1)
    k = fuzzy_geometric_mean_value(i,3);
    sum_k = sum_k + k;
end
end

```

```

sum_fuzzy_geometric_mean_value(1,3) = sum_k;
reciprocal_of_sum_fuzzy_geometric_mean_value = rand(1,3);
reciprocal_of_sum_fuzzy_geometric_mean_value(1,1) =
1/sum_fuzzy_geometric_mean_value(1,3);
reciprocal_of_sum_fuzzy_geometric_mean_value(1,2) =
1/sum_fuzzy_geometric_mean_value(1,2);
reciprocal_of_sum_fuzzy_geometric_mean_value(1,3) =
1/sum_fuzzy_geometric_mean_value(1,1);
fuzzy_weights = rand(size(fuzzy_geometric_mean_value,1),3);
for i=1:1:size(fuzzy_weights,1)
    fuzzy_weights(i,1) = fuzzy_geometric_mean_value(i,1) *
reciprocal_of_sum_fuzzy_geometric_mean_value(1,1);
end
for i=1:1:size(fuzzy_weights,1)
    fuzzy_weights(i,2) = fuzzy_geometric_mean_value(i,2) *
reciprocal_of_sum_fuzzy_geometric_mean_value(1,2);
end
for i=1:1:size(fuzzy_weights,1)
    fuzzy_weights(i,3) = fuzzy_geometric_mean_value(i,3) *
reciprocal_of_sum_fuzzy_geometric_mean_value(1,3);
end
end
crisp_weights = rand(size(fuzzy_weights,1),1);
for i=1:1:size(crisp_weights,1)
    crisp_weights(i,1) = (fuzzy_weights(i,1) + fuzzy_weights(i,2) + fuzzy_weights(i,3))/3;
end

```

```

sum_k=0;
for i=1:1:size(crisp_weights,1)
    k = crisp_weights(i,1);
    sum_k = sum_k + k;
end
sum_crisp_weights = sum_k;
crisp_weights_with_normalization = rand(size(crisp_weights,1),1);
for i=1:1:size(crisp_weights_with_normalization,1)
    crisp_weights_with_normalization(i,1) = crisp_weights(i,1) / sum_crisp_weights;
end
criteria_weights = crisp_weights_with_normalization;
if z == 1
    G1=criteria_weights;
elseif z == 2
    G2=criteria_weights;
elseif z == 3
    G3=criteria_weights;
elseif z == 4
    G4=criteria_weights;
elseif z == 5
    G5=criteria_weights;
elseif z == 6
    G6=criteria_weights;
elseif z == 7

```

```
G7=criteria_weights;
elseif z == 8
    G8=criteria_weights;
elseif z == 9
    G9=criteria_weights;
elseif z == 10
    G10=criteria_weights;
elseif z == 11
    G11=criteria_weights;
else
    G12=criteria_weights;
end
A=1;
B=1;
C=1;
crisp_weights=1;
crisp_weights_with_normalization=1;
criteria_weights=1;
fuzzy_geometric_mean_value=1;
fuzzy_matrix=1;
fuzzy_weights=1;
i=1;
j=1;
mult_k=1;
```

```

reciprocal_of_sum_fuzzy_geometric_mean_value=1;

sum_crisp_weights=1;

sum_fuzzy_geometric_mean_value=1;

sum_k=1;

end

Energy_use_per_capita = G5(1,1)*G2(1,1)*G1(1,1);

IEC1 = Energy_use_per_capita;

Energy_use_per_GDP = G5(2,1)*G2(1,1)*G1(1,1);

IEC2 = Energy_use_per_GDP;

Diversification_of_sources_for_power_production = G5(3,1)*G2(1,1)*G1(1,1);

IEC3 = Diversification_of_sources_for_power_production;

Supply_Efficiency_of_Electricity_Generation = G6(1,1)*G2(2,1)*G1(1,1);

IEC4 = Supply_Efficiency_of_Electricity_Generation;

Electric_Power_Transmission_and_Distribution_Losses = G6(2,1)*G2(2,1)*G1(1,1);

IEC5 = Electric_Power_Transmission_and_Distribution_Losses;

Economic_Growth_Rate = G7(1,1)*G2(3,1)*G1(1,1);

IEC6 = Economic_Growth_Rate;

Government_Budget_Balance = G7(2,1)*G2(3,1)*G1(1,1);

IEC7 = Government_Budget_Balance;

Inflation_Rate = G7(3,1)*G2(3,1)*G1(1,1);

IEC8 = Inflation_Rate;

Government_Debt = G7(4,1)*G2(3,1)*G1(1,1);

IEC9 = Government_Debt;

N2O_emissions_from_energy_processes = G8(1,1)*G3(1,1)*G1(2,1);

```

$IEN1 = N2O\_emissions\_from\_energy\_processes;$   
 $CH4\_emissions\_from\_energy\_processes = G8(2,1)*G3(1,1)*G1(2,1);$   
 $IEN2 = CH4\_emissions\_from\_energy\_processes;$   
 $CO2\_emissions\_from\_coal\_combustion = G9(1,1)*G3(2,1)*G1(2,1);$   
 $IEN3 = CO2\_emissions\_from\_coal\_combustion;$   
 $CO2\_emissions\_from\_oil\_combustion = G9(2,1)*G3(2,1)*G1(2,1);$   
 $IEN4 = CO2\_emissions\_from\_oil\_combustion;$   
 $CO2\_emissions\_from\_natural\_gas\_combustion = G9(3,1)*G3(2,1)*G1(2,1);$   
 $IEN5 = CO2\_emissions\_from\_natural\_gas\_combustion;$   
 $Stringency\_of\_environmental\_regulations = G10(1,1)*G3(3,1)*G1(2,1);$   
 $IEN6 = Stringency\_of\_environmental\_regulations;$   
 $Enforcement\_of\_environmental\_regulations = G10(2,1)*G3(3,1)*G1(2,1);$   
 $IEN7 = Enforcement\_of\_environmental\_regulations;$   
 $Access\_to\_electricity = G11(1,1)*G4(1,1)*G1(3,1);$   
 $ISO1 = Access\_to\_electricity;$   
 $Quality\_of\_electricity\_supply = G11(2,1)*G4(1,1)*G1(3,1);$   
 $ISO2 = Quality\_of\_electricity\_supply;$   
 $Affordability\_of\_electricity\_price\_for\_household\_consumers = G12(1,1)*G4(2,1)*G1(3,1);$   
 $ISO3 = Affordability\_of\_electricity\_price\_for\_household\_consumers;$   
 $Affordability\_of\_pump\_price\_for\_diesel\_fuel = G12(2,1)*G4(2,1)*G1(3,1);$   
 $ISO4 = Affordability\_of\_pump\_price\_for\_diesel\_fuel;$   
 $Affordability\_of\_pump\_price\_for\_gasoline\_fuel = G12(3,1)*G4(2,1)*G1(3,1);$   
 $ISO5 = Affordability\_of\_pump\_price\_for\_gasoline\_fuel;$

```

sum_of_criteria_weights =
IEC1+IEC2+IEC3+IEC4+IEC5+IEC6+IEC7+IEC8+IEC9+IEN1+IEN2+IEN3+IEN4+IEN5+IEN6
+IEN7+ISO1+ISO2+ISO3+ISO4+ISO5

final_criteria_weights = rand(1,21);

final_criteria_weights(1,1)=IEC1/sum_of_criteria_weights;
final_criteria_weights(1,2)=IEC2/sum_of_criteria_weights;
final_criteria_weights(1,3)=IEC3/sum_of_criteria_weights;
final_criteria_weights(1,4)=IEC4/sum_of_criteria_weights;
final_criteria_weights(1,5)=IEC5/sum_of_criteria_weights;
final_criteria_weights(1,6)=IEC6/sum_of_criteria_weights;
final_criteria_weights(1,7)=IEC7/sum_of_criteria_weights;
final_criteria_weights(1,8)=IEC8/sum_of_criteria_weights;
final_criteria_weights(1,9)=IEC9/sum_of_criteria_weights;
final_criteria_weights(1,10)=IEN1/sum_of_criteria_weights;
final_criteria_weights(1,11)=IEN2/sum_of_criteria_weights;
final_criteria_weights(1,12)=IEN3/sum_of_criteria_weights;
final_criteria_weights(1,13)=IEN4/sum_of_criteria_weights;
final_criteria_weights(1,14)=IEN5/sum_of_criteria_weights;
final_criteria_weights(1,15)=IEN6/sum_of_criteria_weights;
final_criteria_weights(1,16)=IEN7/sum_of_criteria_weights;
final_criteria_weights(1,17)=ISO1/sum_of_criteria_weights;
final_criteria_weights(1,18)=ISO2/sum_of_criteria_weights;
final_criteria_weights(1,19)=ISO3/sum_of_criteria_weights;
final_criteria_weights(1,20)=ISO4/sum_of_criteria_weights;

```

```

final_criteria_weights(1,21)=ISO5/sum_of_criteria_weights;

Datatable
table(IEC1,IEC2,IEC3,IEC4,IEC5,IEC6,IEC7,IEC8,IEC9,IEN1,IEN2,IEN3,IEN4,IEN5,IEN6,IEN7,ISO1,ISO2,ISO3,ISO4,ISO5)

xlswrite('GRA.xlsx',final_criteria_weights,1,'A5:U5')

clear

for z=1:1:12
    A=xlsread('RESULTS (KAVAKLIOGLU).xlsx',z);
    for i=1:1:size(A,1)
        for j=1:1:size(A,2)
            if j == 1
                k=1;
            elseif j == 2
                k=4;
            elseif j == 3
                k=7;
            elseif j == 4
                k=10;
            elseif j == 5
                k=13;
            elseif j == 6
                k=16;
            elseif j == 7
                k=19;

```

```
elseif j == 8
    k=22;
elseif j == 9
    k=25;
elseif j == 10
    k=28;
elseif j == 11
    k=31;
elseif j == 12
    k=34;
elseif j == 13
    k=37;
elseif j == 14
    k=40;
else
    k=43;
end
if A(i,j) == 1
    B(i,k) = 1;
    B(i,k+1) = 1;
    B(i,k+2) = 1;
elseif A(i,j) == 3
    B(i,k) = 1;
    B(i,k+1) = 3;
```

```
B(i,k+2) = 5;
elseif A(i,j) == 5
    B(i,k) = 3;
    B(i,k+1) = 5;
    B(i,k+2) = 7;
elseif A(i,j) == 7
    B(i,k) = 5;
    B(i,k+1) = 7;
    B(i,k+2) = 9;
elseif A(i,j) == 9
    B(i,k) = 7;
    B(i,k+1) = 9;
    B(i,k+2) = 9;
elseif A(i,j) == 0.333
    B(i,k) = 0.2;
    B(i,k+1) = 0.333;
    B(i,k+2) = 1;
elseif A(i,j) == 0.2
    B(i,k) = 0.143;
    B(i,k+1) = 0.2;
    B(i,k+2) = 0.333;
elseif A(i,j) == 0.143
    B(i,k) = 0.111;
    B(i,k+1) = 0.143;
```

```

        B(i,k+2) = 0.2;
    else
        B(i,k) = 0.111;
        B(i,k+1) = 0.111;
        B(i,k+2) = 0.143;
    end
end
end
fuzzy_matrix=B;
A=fuzzy_matrix;
B=rand(size(A,1),3);
for i=1:1:size(A,1)
    mult_k=1;
    for j=1:3:size(A,2)
        k=A(i,j);
        mult_k = k * mult_k;
        B(i,1) = mult_k;
    end
end
end
for i=1:1:size(A,1)
    mult_k=1;
    for j=2:3:size(A,2)
        k=A(i,j);
        mult_k = k * mult_k;

```

```

        B(i,2) = mult_k;
    end
end
for i=1:1:size(A,1)
    mult_k=1;
    for j=3:3:size(A,2)
        k=A(i,j);
        mult_k = k * mult_k;
        B(i,3) = mult_k;
    end
end
for i=1:1:size(B,1)
    C(i,1)=nthroot(B(i,1),size(A,2)/3);
end
for i=1:1:size(B,1)
    C(i,2)=nthroot(B(i,2),size(A,2)/3);
end
for i=1:1:size(B,1)
    C(i,3)=nthroot(B(i,3),size(A,2)/3);
end
fuzzy_geometric_mean_value = C;
sum_k=0;
for i=1:1:size(fuzzy_geometric_mean_value,1)
    k = fuzzy_geometric_mean_value(i,1);

```

```

    sum_k = sum_k + k;
end
sum_fuzzy_geometric_mean_value(1,1) = sum_k;
sum_k=0;
for i=1:1:size(fuzzy_geometric_mean_value,1)
    k = fuzzy_geometric_mean_value(i,2);
    sum_k = sum_k + k;
end
sum_fuzzy_geometric_mean_value(1,2) = sum_k;
sum_k=0;
for i=1:1:size(fuzzy_geometric_mean_value,1)
    k = fuzzy_geometric_mean_value(i,3);
    sum_k = sum_k + k;
end
sum_fuzzy_geometric_mean_value(1,3) = sum_k;
reciprocal_of_sum_fuzzy_geometric_mean_value = rand(1,3);
reciprocal_of_sum_fuzzy_geometric_mean_value(1,1) =
1/sum_fuzzy_geometric_mean_value(1,3);
reciprocal_of_sum_fuzzy_geometric_mean_value(1,2) =
1/sum_fuzzy_geometric_mean_value(1,2);
reciprocal_of_sum_fuzzy_geometric_mean_value(1,3) =
1/sum_fuzzy_geometric_mean_value(1,1);
fuzzy_weights = rand(size(fuzzy_geometric_mean_value,1),3);
for i=1:1:size(fuzzy_weights,1)

```

```

        fuzzy_weights(i,1)          =          fuzzy_geometric_mean_value(i,1)          *
reciprocal_of_sum_fuzzy_geometric_mean_value(1,1);

    end

    for i=1:1:size(fuzzy_weights,1)

        fuzzy_weights(i,2)          =          fuzzy_geometric_mean_value(i,2)          *
reciprocal_of_sum_fuzzy_geometric_mean_value(1,2);

    end

    for i=1:1:size(fuzzy_weights,1)

        fuzzy_weights(i,3)          =          fuzzy_geometric_mean_value(i,3)          *
reciprocal_of_sum_fuzzy_geometric_mean_value(1,3);

    end

    crisp_weights = rand(size(fuzzy_weights,1),1);
    for i=1:1:size(crisp_weights,1)

        crisp_weights(i,1) = (fuzzy_weights(i,1) + fuzzy_weights(i,2) + fuzzy_weights(i,3))/3;

    end

    sum_k=0;

    for i=1:1:size(crisp_weights,1)

        k = crisp_weights(i,1);

        sum_k = sum_k + k;

    end

    sum_crisp_weights = sum_k;

    crisp_weights_with_normalization = rand(size(crisp_weights,1),1);
    for i=1:1:size(crisp_weights_with_normalization,1)

        crisp_weights_with_normalization(i,1) = crisp_weights(i,1) / sum_crisp_weights;

```

```
end
criteria_weights = crisp_weights_with_normalization;
if z == 1
    G1=criteria_weights;
elseif z == 2
    G2=criteria_weights;
elseif z == 3
    G3=criteria_weights;
elseif z == 4
    G4=criteria_weights;
elseif z == 5
    G5=criteria_weights;
elseif z == 6
    G6=criteria_weights;
elseif z == 7
    G7=criteria_weights;
elseif z == 8
    G8=criteria_weights;
elseif z == 9
    G9=criteria_weights;
elseif z == 10
    G10=criteria_weights;
elseif z == 11
    G11=criteria_weights;
```

```

else
    G12=criteria_weights;
end
A=1;
B=1;
C=1;
crisp_weights=1;
crisp_weights_with_normalization=1;
criteria_weights=1;
fuzzy_geometric_mean_value=1;
fuzzy_matrix=1;
fuzzy_weights=1;
i=1;
j=1;
mult_k=1;
reciprocal_of_sum_fuzzy_geometric_mean_value=1;
sum_crisp_weights=1;
sum_fuzzy_geometric_mean_value=1;
sum_k=1;
end
Energy_use_per_capita = G5(1,1)*G2(1,1)*G1(1,1);
IEC1 = Energy_use_per_capita;
Energy_use_per_GDP = G5(2,1)*G2(1,1)*G1(1,1);
IEC2 = Energy_use_per_GDP;

```

Diversification\_of\_sources\_for\_power\_production =  $G5(3,1)*G2(1,1)*G1(1,1)$ ;

IEC3 = Diversification\_of\_sources\_for\_power\_production;

Supply\_Efficiency\_of\_Electricity\_Generation =  $G6(1,1)*G2(2,1)*G1(1,1)$ ;

IEC4 = Supply\_Efficiency\_of\_Electricity\_Generation;

Electric\_Power\_Transmission\_and\_Distribution\_Losses =  $G6(2,1)*G2(2,1)*G1(1,1)$ ;

IEC5 = Electric\_Power\_Transmission\_and\_Distribution\_Losses;

Economic\_Growth\_Rate =  $G7(1,1)*G2(3,1)*G1(1,1)$ ;

IEC6 = Economic\_Growth\_Rate;

Government\_Budget\_Balance =  $G7(2,1)*G2(3,1)*G1(1,1)$ ;

IEC7 = Government\_Budget\_Balance;

Inflation\_Rate =  $G7(3,1)*G2(3,1)*G1(1,1)$ ;

IEC8 = Inflation\_Rate;

Government\_Debt =  $G7(4,1)*G2(3,1)*G1(1,1)$ ;

IEC9 = Government\_Debt;

N2O\_emissions\_from\_energy\_processes =  $G8(1,1)*G3(1,1)*G1(2,1)$ ;

IEN1 = N2O\_emissions\_from\_energy\_processes;

CH4\_emissions\_from\_energy\_processes =  $G8(2,1)*G3(1,1)*G1(2,1)$ ;

IEN2 = CH4\_emissions\_from\_energy\_processes;

CO2\_emissions\_from\_coal\_combustion =  $G9(1,1)*G3(2,1)*G1(2,1)$ ;

IEN3 = CO2\_emissions\_from\_coal\_combustion;

CO2\_emissions\_from\_oil\_combustion =  $G9(2,1)*G3(2,1)*G1(2,1)$ ;

IEN4 = CO2\_emissions\_from\_oil\_combustion;

CO2\_emissions\_from\_natural\_gas\_combustion =  $G9(3,1)*G3(2,1)*G1(2,1)$ ;

IEN5 = CO2\_emissions\_from\_natural\_gas\_combustion;

Stringency\_of\_environmental\_regulations = G10(1,1)\*G3(3,1)\*G1(2,1);

IEN6 = Stringency\_of\_environmental\_regulations;

Enforcement\_of\_environmental\_regulations = G10(2,1)\*G3(3,1)\*G1(2,1);

IEN7 = Enforcement\_of\_environmental\_regulations;

Access\_to\_electricity = G11(1,1)\*G4(1,1)\*G1(3,1);

ISO1 = Access\_to\_electricity;

Quality\_of\_electricity\_supply = G11(2,1)\*G4(1,1)\*G1(3,1);

ISO2 = Quality\_of\_electricity\_supply;

Affordability\_of\_electricity\_price\_for\_household\_consumers = G12(1,1)\*G4(2,1)\*G1(3,1);

ISO3 = Affordability\_of\_electricity\_price\_for\_household\_consumers;

Affordability\_of\_pump\_price\_for\_diesel\_fuel = G12(2,1)\*G4(2,1)\*G1(3,1);

ISO4 = Affordability\_of\_pump\_price\_for\_diesel\_fuel;

Affordability\_of\_pump\_price\_for\_gasoline\_fuel = G12(3,1)\*G4(2,1)\*G1(3,1);

ISO5 = Affordability\_of\_pump\_price\_for\_gasoline\_fuel;

sum\_of\_criteria\_weights = IEC1+IEC2+IEC3+IEC4+IEC5+IEC6+IEC7+IEC8+IEC9+IEN1+IEN2+IEN3+IEN4+IEN5+IEN6  
+IEN7+ISO1+ISO2+ISO3+ISO4+ISO5

final\_criteria\_weights = rand(1,21);

final\_criteria\_weights(1,1)=IEC1/sum\_of\_criteria\_weights;

final\_criteria\_weights(1,2)=IEC2/sum\_of\_criteria\_weights;

final\_criteria\_weights(1,3)=IEC3/sum\_of\_criteria\_weights;

final\_criteria\_weights(1,4)=IEC4/sum\_of\_criteria\_weights;

final\_criteria\_weights(1,5)=IEC5/sum\_of\_criteria\_weights;

final\_criteria\_weights(1,6)=IEC6/sum\_of\_criteria\_weights;

```
final_criteria_weights(1,7)=IEC7/sum_of_criteria_weights;
final_criteria_weights(1,8)=IEC8/sum_of_criteria_weights;
final_criteria_weights(1,9)=IEC9/sum_of_criteria_weights;
final_criteria_weights(1,10)=IEN1/sum_of_criteria_weights;
final_criteria_weights(1,11)=IEN2/sum_of_criteria_weights;
final_criteria_weights(1,12)=IEN3/sum_of_criteria_weights;
final_criteria_weights(1,13)=IEN4/sum_of_criteria_weights;
final_criteria_weights(1,14)=IEN5/sum_of_criteria_weights;
final_criteria_weights(1,15)=IEN6/sum_of_criteria_weights;
final_criteria_weights(1,16)=IEN7/sum_of_criteria_weights;
final_criteria_weights(1,17)=ISO1/sum_of_criteria_weights;
final_criteria_weights(1,18)=ISO2/sum_of_criteria_weights;
final_criteria_weights(1,19)=ISO3/sum_of_criteria_weights;
final_criteria_weights(1,20)=ISO4/sum_of_criteria_weights;
final_criteria_weights(1,21)=ISO5/sum_of_criteria_weights;
```

Datatable

```
table(IEC1,IEC2,IEC3,IEC4,IEC5,IEC6,IEC7,IEC8,IEC9,IEN1,IEN2,IEN3,IEN4,IEN5,IEN6,IEN7,ISO1,ISO2,ISO3,ISO4,ISO5)
```

```
xlswrite('GRA.xlsx',final_criteria_weights,1,'A6:U6')
```

# CV

## Koray ALTINTAŞ

### Education

#### **Marmara University – (2014 - )**

PhD Engineering Management (GPA: 4.00 / 4.00)

Istanbul/Turkey

#### **Brunel University – (2012 - 2013)**

MSc Sustainable Energy Technologies and Management (Merit Degree)

London/United Kingdom

#### **Bahcesehir University – (2008 - 2012)**

BSc Electrical and Electronics Engineering (GPA: 3.12 / 4.00)

Istanbul/Turkey

#### **Österreichisches St. Georgs-Kolleg – (2003 - 2008)**

Istanbul/Turkey

### Internship Experiences

#### **2011 – Summer**

##### **Turkish Airlines Technic**

Repairing and testing of avionic components

Istanbul/Turkey

#### **2010 – Summer**

##### **Merit Electronics**

Responsible for the correspondences among the foreign enterprises

Ankara/Turkey

#### **2010 – Summer**

##### **Bilkent University National Magnetic Resonance Research Center**

Helping the technical staff, who were responsible for developing an MR simulator

Ankara/Turkey

### Employment History

#### **2017 – Present**

##### **Merit Elektronik // Sales Engineer**

Ankara-Istanbul /Turkey

- Provide leadership and management to the business and responsible for the day-to-day business operations.
- Responsible for keeping excellent relationships with key business contacts.
- Identify new market opportunities and provide business strategy.
- Responsible for achieving all performance related targets.
- Responsible for providing technical support and guidance to customers.

#### **2014 – 2017**

##### **ENT Medical Center // Engineer**

Istanbul/Turkey

- Provide direct, instructional support and guidance for integrating technology within the enterprise.
- Research, evaluate, identify, and recommend new technologies to serve patients as well as to medical doctors.
- Identify best practices for technology integration, trends and applications related to technology use in the clinic.

### **Recognition/Extra Curricular Activities**

Dance course in Österreichisches St. Georgs-Kolleg High School  
Bakirkoy Music Foundation – Piano Education  
Bakirkoy Artists Association – Theatre Education

2004  
2001-2003  
2000-2003

### **Foreign Language**

<b>Turkish</b>	(Native Language)
<b>English</b>	(Fluent)
<b>German</b>	(Intermediate)

### **TOEFL iBT Test (05 January 2019)**

Reading Score : 24  
Listening Score : 28  
Speaking Score : 21  
Writing Score : 22  
Total Score : 95

### **Computer Skills**

Good knowledge of MS Excel, Word and PowerPoint  
Experienced in using Matlab, RETScreen and Dialux evo