Araştırma Makalesi/Derleme Makalesi

CRITIC ve WASPAS Yöntemleri Kullanılarak Türkiye İçin En Uygun Yenilenebilir Enerji Kaynağının Seçimi

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ÖZET

Yenilenebilir Enerji kaynağı bakımından zengin olarak tanımlanan ülkemizin, enerji kaynağı noktasında dışa bağımlılığının en aza indirilmesi ve mevcut olan yenilenebilir enerji kaynaklarının bölgesel olarak en verimli şekilde kullanılabilmesi önem arz etmektedir.

Bu çalışmanın konusu Türkiye için en uygun yenilenebilir enerji kaynağının tespitinde çok kriterli karar yöntemlerinin kullanılması ile en uygun kaynağın tespitini yapabilmek, yenilenebilir enerji kaynaklarından güneş, rüzgar, jeotermal, hidroelektrik, biyokütle ve dalga olmak üzere altı enerji türü için karşılaştırma amaçlı uygunluk kriterlerini tespit edebilmek ve bu kriterlere ilişkin verileri doğru bir şekilde toparlayarak, çok kriterli karar verme yöntemlerinden CRITIC, WASPAS metotlarını bu veriler üzerinde uygulayarak örnek bir model oluşturmak ve uygulama sonucunda oluşan sonuçları analiz ederek, gelecekteki enerji yatırımları için bir değerlendirme kolaylığı sağlamaktır.

Hesaplamalarımızın sonunda dalga enerjisi en yüksek WASPAS puanına sahip enerji kaynağı olarak belirlenmiştir (0,413). Rüzgâr enerjisi (0,327) ve jeotermal enerji (0,313) sırasıyla ikinci ve üçüncü sıralarda yer almaktadır. Hidroenerji (0,286), güneş enerjisi (0,286) ve biyokütle enerjisi (0,257) ise daha düşük WASPAS puanlarına sahip enerji kaynaklarıdır. Fakat, oluşan sıralama başka faktörlere göre de değişebilir.

Başka kaynakları da hesaba katılırsa sonuçlar farklı çıkabilir. Her ülkenin, her bölgenin farklı enerji ihtiyaçları ve kaynakları vardır. Bu yüzden, karar vericiler, bu faktörleri de dikkate alarak, kendi koşullarına göre en uygun yenilenebilir enerji kaynaklarını seçmek için birden fazla kriteri dikkate almalıdır.

Anahtar Kelimeler: CRITIC, Çok Kriterli Karar Verme, WASPAS, Yenilenebilir Enerji Seçimi

The Selection of Appropriate Renewable Energy Source For Turkey by Using CRITIC and WASPAS Methods

ABSTRACT

In our country, which is defined as rich in renewable energy resources, these are important; to be able to use the existing renewable energy sources in the most efficient way and minimize foreign dependency at the point of energy source.

The topic of this case is to be able to select the most appropriate renewable energy source for Türkiye by using multi-criteria decision methods, to be able to determine the eligibility criteria to compare six sorts of renewable energy sources which are solar, wind, geothermal, hydroelectric, biomass, wave and by collecting the correct data related to these criteria, to create a study case by applying CRITIC, WASPAS methods on these data and immediately afterward to analyze the results of application to be able to provide an ease of evaluation for energy investments which will be in the future.

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At the end of our calculations, wave energy was determined as the energy source with the highest WASPAS score (0.413). Wind energy (0.327) and geothermal energy (0.313) ranked second and third, respectively. Hydro Energy (0.286), solar energy (0.286), and biomass energy (0.257) are energy sources with lower WASPAS scores. However, the ranking of results may vary according to other factors.

If other sources are taken into account, the results may be different. Because Every country and every region has different energy needs and resources. Therefore, decision-makers should consider multiple criteria to select the most suitable renewable energy sources according to their conditions, considering these factors.

Keywords: CRITIC, Multi-Criteria Decision Making, Renewable Energy Selection, WASPAS

1. INTRODUCTION

Energy is defined briefly as the driving force or the ability to do work. Every production activity requires energy usage in its unique measures.

The rapid population growth and developing industries in the world increase energy demand, which is an essential input. However, there may be some inadequacies in meeting this demand with the existing limited and depletable resources. At this point, studies are continuing on new and sustainable resources. According to the estimates of the International Energy Agency (IEA), by 2040, the world's population is expected to be 1.7 billion higher than today, and with urbanization and increases in per capita income, energy demand is expected to increase by 25% compared to today. However, the electricity demand, which constitutes 20% of the total energy consumption today, will be much higher compared to the demand for fossil fuels. The EIA predicts that by 2040, electricity demand will be almost double today's levels. While the increase in demand for electricity in developed countries remains at low levels, developing economies, especially China, show high demand. The number of people without access to electricity in the world fell below one billion for the first time in 2017. It is expected that this number will drop below 700 million by 2040. Renewable, limited, and non-renewable energy sources such as coal, oil, natural gas, and nuclear energy can cause threats to human health and the environment and can lead to negative consequences in a country's development. To minimize and/or eliminate these negative impacts, countries have begun to tend towards using renewable energy sources. At this point, the important issue has been the identification and use of the right source in the right place.

Renewable energy sources are more sustainable environmentally and are effective in reducing carbon footprint compared to non-renewable energy sources. In addition, energy security worldwide, protection against fluctuations in energy prices, and environmental protection issues have become positive options for countries in terms of economic development. Moreover, renewable energy sources play an effective role in combating climate change by reducing greenhouse gas emissions resulting from the burning of fossil fuels. When renewable energy sources are evaluated from an economic perspective, they can also revitalize local economies, add value to regional renewable energy projects and local businesses, and create employment opportunities. Furthermore, renewable energy sources generally have safer and cleaner working conditions, making them important in terms of employee health and safety. However, these types of sources can also have their difficulties. For example, while some sources can be used regionally without requiring a large amount of space, others may require larger areas for use. Additionally, the cost of renewable energy sources can vary depending on technological developments. When renewable energy sources are evaluated from an economic perspective, they can also revitalize local economies, add value to regional renewable energy projects and local businesses, and create employment opportunities. Furthermore, renewable energy sources generally have safer and cleaner working conditions, making them important in terms of employee health and safety. However, these types of sources can also have their difficulties. For example, while some sources can be used regionally without requiring a large amount of space, others may require larger areas for use. Additionally, the cost of renewable energy sources can vary depending on technological developments. The widespread use of renewable energy sources can also bring about some technological and economic challenges. Currently, there is no clear solution for the storage of the energy generated, and renewable energy sources require a storage system to provide constant power. This can increase the cost of energy due to the underdeveloped storage systems. In addition, some types of renewable energy sources can lead to high investment costs to adapt to existing infrastructure. As the cost of these sources decreases and their technologies improve, their use will become more widespread. In this regard, governments can provide incentive packages for renewable energy and various facilitative legal regulations to enable the large-scale use of these sources.

In European countries, investments in renewable energy sources are given great importance and their use is quite widespread. For these countries, these investments are important in terms of supporting economic development for their societies, contributing to environmental protection, and being important in terms of energy security.

Therefore, the European Union has set a series of targets to support renewable energy sources in its energy policies and to reduce the use of fossil fuels.

With the doubling of electricity demand in developing countries, the production of clean, cheap, and accessible electricity from renewable sources has become an important issue in development programs and policies [37]. The use of renewable sources for electricity production is at the forefront of these policies. Although investments in renewable energy areas such as wind and solar energy are increasing rapidly, the costs of these technologies are also decreasing rapidly. As a result of these investments, the share of renewable energy in the global energy mix is also increasing rapidly. According to a report published by Global Data Energy in July 2018, the installed capacity of renewable energy accounts for 18.2% of the total global energy mix, and this ratio is estimated to be 22.5% for 2020 [2]. The EIA has also predicted that the share of renewable sources in 2022 will be 30% [2]. However, in addition to the positive aspects of renewable energy, there are also some negative aspects or risks. For example, there are some obstacles to increasing investments in wind and solar energy, the foremost of which is the risk that both energy sources may cause fluctuations in energy production due to their natural characteristics. There is still no complete solution to the storage problem in electricity production. In this case, electricity production is done as demand requires and is obliged to respond instantly to demand. The cessation of electricity production in periods where sufficient wind and sunlight are not obtained is a risk that the system cannot bear. For this reason, research continues on the use of renewable and continuous sources in electricity production.

Various methods and techniques are used to obtain energy for economic purposes, and these sources are called energy sources and are classified in various ways:

A - Energy Sources According to Sustainability (Permanence, Exhaustibility) Status: This type of classification is made according to the renewable status of the energy source.
1- Renewable (Alternative) Energy Sources: Solar, Wind, Hydroelectric, Geothermal, Biomass, Hydrogen, Wave, and Tidal energies are renewable energy sources.
2- Non-renewable (Fossil, Conventional, Traditional) Energy Sources: They are also called primary sources, and conventional sources, and these energy sources cannot be renewed, meaning they are used once or are depleted. Coal, oil shale, oil, natural gas, uranium, and thorium are among the sources in this group.

B- Energy Sources According to Their Convertibility: This classification is made according to the direct/indirect use of energy sources as an energy source.
1- Primary Energy Sources: These are sources that directly provide energy without changing their main characteristics when used. Coal, nuclear, biomass, hydraulic, and wave energy are examples of energy sources that fall into this category.
2- Secondary Energy Sources: These are sources that are used after being converted to a different energy source. Electricity, gasoline, diesel, secondary coal, coke, and LPG energy are examples of energy sources that fall into this category.

C- Energy Sources Based on Their Underground-Aboveground Origin: This classification is made based on whether the energy source is formed aboveground/underground.
1- Underground Energy Sources: These are energy sources such as coal, oil, natural gas, geothermal, oil shale, and nuclear (radioactive) sources.
2- Aboveground Energy Sources: Sources such as solar, wind, and biomass fall into this category.
D- Energy Sources Based on Their Physical State: This classification is made based on the physical state of the energy source under normal conditions.
1- Solid Energy Sources: Sources such as coal, wood, biomass waste, and uranium fall into this category.
2- Liquid Energy Sources: Sources such as oil, LPG, diesel, and biodiesel fall into this category.
3- Gas Energy Sources: Sources such as natural gas, methane gas, and biogas fall into this category.

The cost of energy production from non-renewable sources, also known as fossil fuels, may be lower than that of renewable energy sources, but they all have a finite supply and cause negative impacts on the environment, human health, and climate change in the medium and long term. The low-cost energy production with fossil fuels causes an increase in carbon dioxide emissions, leading to higher air pollution levels and negatively affecting human health, as well as accelerating global warming due to the greenhouse effect, causing the melting of glaciers and rising sea levels, which threaten habitable land masses. Other toxic gases emitted from fossil fuels include sulfur dioxide, carbon monoxide, and nitrogen monoxide, which can lead to respiratory problems in humans over the medium and long term as the concentration of these gases increases in the air. These negative impacts on the environment and human health also lead to economic losses for countries. Moving or establishing factories and energy production facilities away from residential areas to continue using cheap energy in the industry also does not provide a definitive solution. Pollutants released into the air due to the wind effect or other sources of pollution still pose a threat to human and animal food sources and agricultural land.

There is a linear connection between electricity consumption and economic activity in Turkey. This is due to sudden changes in electricity consumption that reflect the fluctuations in the Turkish economy and growth rate. The trend of less energy consumption for growth, which is observed in developed countries, has not been seen yet in Turkey. According to data from the Turkish Electricity Transmission Corporation, there was an increase in electricity consumption and production in 2021 due to factors such as an increase in electricity demand and industrial production. Between 2010 and 2020, primary energy supply increased by approximately 34%, while gross electricity demand increased by 45%. In 2020, 290.8 billion kilowatt-hours of electricity were consumed in Turkey, and this figure increased by approximately 12% to around 329 billion kilowatt-hours in 2021. Production was recorded as 291.5 billion kilowatt-hours in 2020.

In Turkey, the largest share of the primary energy supply belongs to fossil fuels. As of 2020, the share of coal in the primary energy supply was 27.6%, oil was 28.6%, and natural gas was 27%. The remaining 16.8% share consists of renewable energy sources such as hydroelectric, wind, solar, geothermal, biomass, and waste-to-energy. Fossil fuels account for 83.3% and imported sources account for 70.2% of primary energy supply. Additionally, Turkey exported 4.1 billion kilowatt-hours of electricity in 2021, which is a 68% increase from 2020 when the number was 2.4 billion kilowatt-hours. The electricity import also increased by 23% in 2021 compared to 2020, rising from 1.8 billion kilowatt hours to 2.3 billion kilowatt hours. On the other hand, Turkey's installed capacity for electricity reached 99,819 megawatts by the end of 2021.

In addition, the need for more investment, especially in the use of alternative energy sources, is increasing day by day to compensate for the shortfall of hydroelectric power plants, which are unable to function adequately due to climate change, regional drought risks, and water scarcity, limiting living spaces and having the potential to alter ecosystems. The electricity import also increased by 23% in 2021 compared to 2020, rising from 1.8 billion kilowatt hours to 2.3 billion kilowatt hours. On the other hand, Turkey's installed capacity for electricity reached 99,819 megawatts by the end of 2021. In addition, the need for more investment, especially in the use of alternative energy sources, is increasing day by day to compensate for the shortfall of hydroelectric power plants, which are unable to function adequately due to climate change, regional drought risks, and water scarcity, limiting living spaces and having the potential to alter ecosystems.

Renewable energy sources in our country can also be defined as energy sources at can renew themselves in nature's cycle and preserve their existence. The most important feature of these sources is that they do not emit toxic gases or create a harmful factor for the environment and therefore the health of living things. Economically, it helps to reduce energy imports and keep the capital that is needed to exit the country inside and also create job opportunities through investments made within the country. In this regard, when choosing a renewable energy source that is necessary for the development of the country, economic, technical, environmental, and social factors must be taken into account. For example, renewable energy sources can also contribute to socio-economic development in rural and underdeveloped areas such as mountainous regions by creating job and infrastructure opportunities. [26]

Various mathematical methods have been developed to accurately analyze criteria with different measurement units and make the right choice based on different options. Multiple Criteria Decision-Making methods encompass various types of mathematical methods.

This study discusses renewable energy sources that could be evaluated for investment in our country, including Wind, Hydroelectric, Solar, Biomass, Geothermal, and Wave Energy. In the comparison of these sources, 26 criteria were taken into consideration, including investment cost, employment, efficiency, accident and breakdown risks, the potential of the resources, technological maturity, environmental impacts, water consumption, and government incentives.

As a result of the analysis, Wave Energy was determined to be the most accurate option numerically. The Aegean Sea was identified as the most suitable sea for energy production by utilizing the movement of sea waves. If Wave Energy, which has only recently begun to be mentioned in Turkey, had not been included as a renewable energy model in this study, and the water consumption criterion had not been taken into account during the operation of the system, hydroelectric power would have emerged as the most accurate option mathematically. Although hydroelectric power is considered a renewable energy source, the main factor in the operation of these facilities is water. Considering the limited availability of water resources, the reduction or elimination of the flow rates of rivers that feed agricultural areas during the installation of facilities may result in drought in river basins and affect agricultural production. Therefore, investments must be made for the future, and flexibility should also be considered in the decision-making process due to the presence of unmeasurable factors despite mathematical calculations.

In this study, an objective weighting model called the CRITIC Method is used to calculate criterion weighting (prioritization), and then separate one-stage analyses are conducted using the WASPAS Model, and the results obtained are evaluated. Thus, an example study is aimed to be obtained regarding the comparison of independent and numerous criteria and the conduct of efficiency analysis. This study discusses renewable energy sources that were evaluated for investment in our country, including Wind, Hydroelectric, Solar, Biomass, Geothermal, and Wave Energy. In the comparison of these sources, 26 criteria were taken into consideration, including investment cost, employment, efficiency, accident and breakdown risks, potential of the resources, technological maturity, environmental impacts, water consumption, and government incentives.

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2. THE IMPORTANCE OF RENEWABLE ENERGY INVESTMENTS FOR TURKEY

Turkey faces a large part of its energy needs from fossil fuels. However, due to reasons such as depletion of fossil fuels, environmental impacts, and energy security issues, there is a growing trend towards renewable energy sources. Turkey is a rapidly growing economy and this leads to an increase in energy demand. This, in turn, creates an increase in energy demand. Turkey, which imports 90% of its energy needs, faces possible energy supply security problems. In addition, the use of fossil fuels causes air pollution and greenhouse gas emissions. Renewable energy sources are more environmentally friendly and sustainable than fossil fuels. Turkey's potential for renewable energy sources is quite high. Renewable energy production can be achieved by using different sources such as solar, wind, hydraulic, biomass, and geothermal energy. Renewable energy investments are important for Turkey due to several reasons. First, as a country heavily dependent on fossil fuels to meet its energy demand, Turkey faces energy security risks and environmental challenges associated with the use of such fuels. Second, Turkey's economy is growing rapidly, and its energy demand is expected to increase accordingly. Investing in renewable energy sources can help meet this growing energy demand sustainably. Third, Turkey has a high potential for renewable energy sources such as solar, wind, hydro, biomass, and geothermal energy, which can be harnessed to generate clean and renewable energy. Solar energy potential is particularly high in the Marmara, Aegean, and Mediterranean regions of Turkey. Wind energy potential is generally high in the Central Anatolia and Marmara regions. Turkey also has a high potential for hydroelectric power, and both large and small hydroelectric power plants can be built in the country given its rich and efficient river resources. Biomass energy sources include the management of waste, agricultural residues, forest residues, and animal waste. Geothermal energy sources are particularly widespread in the Western Anatolia, Marmara, and Black Sea regions of Turkey.

3. LITERATURE REVİEW

3.1. Decision-Making Methods

A scientific decision-making process that can be reduced to two basic stages: identifying criteria and selecting an appropriate method, also requires rational action for rationality and efficiency.

Many methods, including classical or fuzzy logic-based, are used by researchers to solve problems known as multi-criteria decision-making (MCDM) in the literature.

Before the application of all decision-making methods, the basic steps are as follows:
• Defining the problem
• Listing all possible options
• Listing all possible situations
• Creating a decision table for technical data triggering the profit and/or cost of each option

• Selecting a decision method
• Implementing the method and determining the preference based on the results obtained after the implementation.

3.2. The Originality of The Study

This study focuses on renewable energy sources in terms of their renewable nature. When considering the literature and published articles on this topic, it is seen that many studies have been conducted on renewable energy sources. In recent studies, it is observed that mainly a single type of renewable energy source is emphasized, and in comparative studies, usually five types of renewable energy sources are focused on.

One of the aims of this study is to provide a broader perspective by comparing six different renewable energy sources together. Although comparing six types of energy sources is the most distinctive feature of this study, the objective-based weighting method used in the calculations is also different from the subjective-based method generally preferred in articles. The criteria used in the calculations are more comprehensive than those in previous studies, which also adds to the uniqueness of the study. In CRITIC-weighted applications, the criteria are listed horizontally and the alternatives are listed vertically in the calculations. However, in this study, the options are listed horizontally, and the criteria are listed vertically, resulting in a different calculation method compared to other studies. Overall, this study stands out from others in terms of its approach, objectives, and methodology, and provides new insights into the comparison of different types of renewable energy sources.

4. METHODOLOGY

4.1. CRITIC

In the first stage of the application process of Multi-Criteria Decision Methods, which is Criterion Weighting, an objective method called CRITIC has been preferred in the study. When subjective methods are preferred in the criterion weighting process, the experiences and interpretation styles of decision-makers who prioritize criterion weights are important, but the possibility of changes in priority rankings from person to person still exists. At this point, using mathematical methods based on data will lead to a more reliable result in terms of determining priorities. In this context, the application of the objective method CRITIC has been carried out. In the CRITIC method, the weight of each criterion is determined by taking into account the correlations between the criteria as well as the standard deviation of each criterion (Wang and Luo, 2010). The following steps are applied in the CRITIC method (Çakır and Perçin, 2013; Diakoulaki et al., 1995; Işık, 2019; Kiracı and Bakır, 2018; Şenol and Ulutaş, 2018; Akbulut, 2019):

4.1.1. The Stages of CRITIC

Step 1: *Creating the Decision Matrix*

First, the type of criteria is determined. The decision matrix is then created with n-piece alternatives and m-piece criteria, as shown in Formula 4.1.

$$\mathbf{X} = \begin{vmatrix} x_{11} & x_{12} & x_{1m} \\ x_{21} & x_{22} & x_{2m} \\ & & \vdots \\ x_{n1} & x_{n2} & x_{nm} \end{vmatrix} \qquad \textbf{(4.1)}$$

Step 2: *Normalization of the Decision Matrix*

The values in the decision matrix are normalized using Equations (4.2) for benefit (maximization) criteria and Equation (4.3) for cost (minimization) criteria.

$$r_{ij} = \frac{x_{ij} - x_j^{min}}{x_j^{max} - x^{min}{}_j} \qquad \textbf{(4.2)}$$

$$r_{ij} = \frac{x_j^{max} - x_{ij}}{x_j^{max} - x_j^{min}} \qquad \textbf{(4.3)}$$

Where x_j^{min} , represents the minimum value of the j-th criterion and x_j^{max}, represents the maximum value of the j-th criterion.

Step 3: *Creating the Correlation Coefficient Matrix*

Equation (4.4) is used to calculate the correlations between pairs of criteria and measure the degree of relationship between criteria

$$\rho_{jk} = \frac{\sum_{i=1}^{n}(r_{ij} - \bar{r}_j)(r_{ik} - \bar{r}_k)}{\sqrt{\sum_{i=1}^{n}(r_{ij} - \bar{r}_j)^2 \sum_{i=1}^{n}(r_{ik} - \bar{r}_k)^2}}, j,k = 1,2,...,m \quad \textbf{(4.4)}$$

Step 4: *Calculation of* C_J Value

C_j represents the total amount of data for each criterion and is calculated by using equation (4.5). The σj value, which is the standard deviation of the criteria equation (4.6) and equation (4.5), is calculated.

$$C_j = \sigma_j \sum_{k=1}^{m}(1 - t_{jk}), \mathrm{j} = 1,2,...,m \quad \textbf{(4.5)}$$

The correlation coefficient between criterion pairs is expressed by t_{jk}.

$$\sigma_j = \sqrt{\sum_{i=1}^{m}(r_{ij} - \bar{r}_j)^2 / m} \quad \textbf{(4.6)}$$

Step 5: *Calculation of Criterion Weights* W_j

Criterion weights are calculated by using Equation (4.7).

$$W_j = \frac{C_j}{\sum_{k=1}^{m} C_k}, j,k = 1,2,...,m \quad \textbf{(4.7)}$$

4.2. WASPAS

WASPAS (Weighted Aggregated Sum Product Assessment) is an effective Multi-Criteria Decision Making (MCDM) method that combines the Weighted Sum Model (WSM) and the Weighted Product Model (WPM) into a single approach by integrating a coefficient into the weighted sum and weighted product models. In practice, it is based on the combination of WSM and WPM. In a study conducted by Zavadskas, Turskis, Antucheviciene, and Zakarevicius (2012), WASPAS was proposed as a combined method that consists of WSM and WPM. Furthermore, it was found that while the weighted sum achieves the highest prediction accuracy, WASPAS improves ranking accuracy.

4.2.1. The Stages of WASPAS

Before moving on to the steps of the WASPAS method, the problem at hand is presented with *m* options *Ai* (i = 1, 2, …, m) and *n criteria Cj* (j = 1,2,…,n). There are 4 steps of the WASPAS method in total.

Step 1: *Creating the Decision Matrix*

A decision matrix X is prepared that shows the performances of different options under different criteria. The weight ratio of each criterion in the total - related to priorities - can be individually determined in the range of $0 \leq x \leq 1$ [0,1]. Alternatively, one of the ANP or AHP methods can be applied in this step to determine the percentage intervals of the criteria according to their priorities.

$$X = [x_{ij}]_{mxn} = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ x_{m1} & x_{m2} & \cdots & x_{mn} \end{bmatrix} \quad (i = 1,2\ldots,m \ \text{ve} \ j = 1,2,\ldots,n) \tag{4.8}$$

The performance of the *i*.-th option under the *j*.-th criterion in the decision matrix *X* is represented by *xij*.

Step 2: *Normalization of the Decision Matrix*

To compare performance measurements, eliminate data repetitions, and increase data consistency, it is necessary to make them dimensionless. Therefore, all elements in the decision matrix with different measurement units are made dimensionless by applying Equation (4.8) for Maximization (Benefit Criteria) and Equation (4.9) for Minimization (Cost Criteria). Thus, the normalization process on the criteria is completed.

$$x^*_{ij} = \frac{x_{ij}}{\max_i(x_{ij})} \qquad i = 1, 2,\ldots,m \ \text{ve} \ j = 1, 2,\ldots,n \tag{4.9}$$

$$x^*_{ij} = \frac{\min_i x_{ij}}{x_{ij}} \qquad i = 1, 2,\ldots,m \ \text{ve} \ j = 1, 2,\ldots,n \tag{4.10}$$

In these equations, the normalized performance value of the *i*-th alternative under the *j*-th criterion is denoted by X*ij.

Step 3: *Calculation of Relative Importance of Alternatives*

In this step, the total relative importance of the *i*-th alternative is calculated separately according to WSM and WPM. According to WSM, the total relative importance of an alternative is determined as the weighted sum of criterion values, while according to WPM, the total relative importance of an alternative is calculated as the product of criterion weights and the power of criterion performance value. The total relative importance of an alternative according to WSM is calculated as shown in equation (4.11), and the total relative importance of an alternative according to WPM is calculated as shown in equation (4.12).

$$Q_i^{(1)} = \sum_{j=1}^{n} r_{ij} w_j \tag{4.11}$$

$$Q_i^{(2)} = \prod_{j=1}^{n} r_{ij}^{w_j} \tag{4.12}$$

Step 4: *Finding the Common Generalized Criterion Value*

The total relative importance of alternatives calculated according to the WSM and WPM methods in Step 3 can be generalized by using Equation (4.13)

$$Q_i = \lambda Q_i^{(1)} + (1-\lambda) Q_i^{(2)} \tag{4.13}$$

Here, *Qi* represents the total relative importance of the *i*-th alternative according to the WASPAS method. λ is a parameter used in the WASPAS method and takes values between 0 and 1. When λ is taken as 0 and 1, the WASPAS method turns into the WPM and WSM methods, respectively.

The choice of λ value depends on the decision maker. Zavadskas et al. (2012) suggest calculating the optimal λ value. In our study, this value was taken as 0.6 due to its high accuracy.

Finally, the ranking of alternatives based on their total relative importance is performed in the WASPAS method by considering the Qi values. The alternative with the highest Qi value is selected as the best option.

5. APPLICATION

5.1. Data and Criteria Based Sample

As a Renewable Energy Source, after considering 6 types of sources which are Wind, Solar, Hydropower, Biomass, Geothermal, and Wave Energy, and determining criteria under 4 main headings: Technical, Sociological, Environmental, and Economic for their preference statuses, sub-criteria were also created and grouped under these main criteria. Following this, data for each item was determined. The preference weighting of the criteria was calculated with the CRITIC Method, and after normalizing the calculations with the WASPAS method, the preference analyses of these 6 options were completed separately. An evaluation was made based on the results obtained.

5.1.1. Identification of Criteria in Renewable Energy Selection

This is an example study aiming to determine the most suitable renewable energy source for installation by identifying the preferred study criteria for potential renewable energy sources in our country. These criteria are among the 26 most commonly encountered criteria in the literature search. Table 5.1 shows the criteria and the sources from which the data for each criterion were obtained for the comparison process.

Table 5.1: General criteria identified for the study and sources of data acquisition

No	Criteria	Description	References | Authors
K01	Energy Efficiency	It is the ratio of the output energy of the power plant to the input energy.	Özcan and others 2017
K02	Economic Potential (GW/year)	The amount of energy that can be economically produced under specific conditions.	Görez and Alkan 2005; Edenhofer O., Pichs-Madruga R., Sokona Y., Seyboth K., Kadner S., Zwickel T., Eickemeier P., Hansen G., Schlomer S., Von Stechow C. ve Matschoss P., 2012. (Wave en.)
K03	Operating Life (years)	The economic lifetime of the investment is an important criterion that determines profitability due to the high costs of power plant installation and operation.	Zheng and Wang 2020
K04	Global Installed Capacity (%)	Power generation capacity of the power plant	REN21,2015

K05	Capacity Factor (%)	It is the ratio of the amount of power generated by an energy plant during a certain period (year) to the amount of power that could be generated by operating at full capacity for every hour of that period.	NETL,2013
K06	Low Risk of Breakdowns and Accidents	It determines the probability of failure and accident risks of the facility.	Ligus and Peternek 2010
K07	Investment Cost ($/kW)	The amount of capital spent during the installation and operation phases.	Raza, Janajreh and Ghenai, 2014; Yücenur, Çaylak, Gönül and Postalcıoğlu,2020; Alizadeh, Soltanisehat, Lund and Zamanisabzi, 2020; Özcan, Ünlüsoy and Evren, 2017
K08	Fixed Operation and Maintenance Cost ($/MW-yr)	The rental, depreciation, insurance, and property tax are fixed operating costs. The cost per unit varies according to the production volume of the product.	NETL, 2013 Study; Thorpe, T W. 1999. (Wave En.)
K09	Electricity Production Cost ($/kW-hr)		EİA, 2016 Study; Delucchi M. A. and Mark Z. J., 2011 (Wave En.)
K10	LCOE Elektricity Production Cost ($/MWh)	Levelled Cost of Energy (LCOE); is a measure of the average net present cost of electricity generation over the lifetime of a power plant. It is used to plan investments and to compare different electricity generation methods consistently.	US Energy Information Administration, 2015;
K11	Amortization Period (year)	The payback period for investment	Keny, Lawve Pearce, 2010
K12	Specific Water Consumption (m^3/kWh)	This is the amount of water consumption value per unit of electricity produced.	Şahin, 2016; Sitorus and Parada, 2020
K13	Land Requirement (km^2/MW)	The total area usage and the amount of energy per unit area.	Beccali, Cellura and Mistretta, 2003; Rani Mishra, Pardasani, Mardani, Liao and Streimikiene, 2019;

			Kayakutlu and Ercan 2015
K14	Turnkey Delivery Time (year)		Wang and others,2020
K15	Government Incentives ($/kW)	The financial support provided by the government during the investment and operation phases.	Nigim and Munier, 2004; Ren and Sovacool, 2015; Özcan and others.2017
K16	Nitrogen Oxide Emissions (g/MWh)		NETL, 2013; Brooke,2003 IEA 2009 [55] (Wave)
K17	Carbon Dioxide Emissions (g-CO2/kWh)		IPCC, 2014; Brooke,2003 IEA 2009 [55] Wave)
K18	Carbon Monoxide Emissions (g/MWh)		NETL, 2013
K19	Sulfur Dioxide Emissions (g/MWh)		NETL, 2013 IEA 2009 [55] (Wave)
K20	Particulate Emissions (g/MWh)		NETL, 2013
K21	Non-Methane Emissions (g/MWh)		NETL, 2013
K22	External Cost	It is the cost that a company incurs to protect its profit margins from the negative effects of another company.	Stein, 2013
K23	Installation, Operation, and Maintenance Employment (person/MW)	It is the total number of staff required throughout the existence of the power plant, at every stage of its operation.	Kaya, and Kahraman 2010; Amer and Daim, 2011; Kabak and Dağdeviren, 2014; Şengül, Eren Shiraz, Gezder ve 2015; Lee and Chang, 2018; Solangi and others. 2019; Wang, Xu and Solangi, 2020
K24	Social Acceptability	It indicates the level of social acceptability of power plants	Tsoutsos, Drandaki, Frantzeskaki, Losifidis, and Kiosses,2009; Kahraman, Kaya, and Cebi, 2009; Demirtas, 2013; Özcan and others. 2017; Lee and Chang, 2018; Rani and others. 2019
K25	Technological Maturity	The prevalence of technology in regional, national, and international contexts	Demirtaş, 2013; Ren and Sovacool, 2015;

			Özkale, Çelik, Türkmen, and Cakmaz, 2017; Nigim and Munier, 2004; Zheng and Wang 2020
K26	Noise Factor (dB)		Solangi and others .2019; Zheng and Wang 2020 For wind En. [50][51][52], For Hydraulic [53] For Biomass [54]

5.1.1.1 Technical Criteria

Technical criteria refer to the technical specifications of each renewable energy investment, based on numerical data. This group of criteria includes sub-headings such as the economic life of the operation, efficiency, potential, and installed power capacity. Table 5.2 shows the technical criteria and their corresponding numerical data.

Table 5.2: Technical Criteria

No	Sub Criteria | Sources of Energy	Solar	Wind	HydroP.	Biomass	GeoT	Wave
K01	Energy Efficiency	21	26	**90**	40	16	15
K02	Economic Potential (GW/year)	91	98	140	0,4	4	**3.650**
K03	Operating Life (years)	25	25	**30**	20	25	**30**
K04	Global Installed Capacity (%)	2,9	**6,1**	17,5	1,5	0,2	2,41
K05	Capacity Factor (%)	27,4	30	37,1	85	**90**	30
K06	Low Risk of Breakdowns and Accidents	16,6	17	11	10	**9**	15

The other technical criteria that can be used in a subjective approach that does not have a numerical measure are defined as Reliability, Low Risk of Malfunction and Accidents, and Modularity in Production and Installation.

5.1.1.2 Economic Criteria

The technical specifications of the relevant investment may appear much better compared to other options, but its monetary factors (return) may not be sufficient. At this point, data on sub-headings should also be included in selection models as a separate criterion heading. In this group, the cost of electricity per unit amount and the return on investment related to it is important. Table 5.3 shows the sub-headings of the Economic Criteria and the data determined for each option.

Table 5.3. Economic Criteria

No	SubCriteria | Sources of Energy	Solar	Wind	HydrP.	Biomas	GeoT	Wave
K07	Investment Cost ($/kW)	3873	**2213**	2936	4114	4362	2500
K08	Fixed Operation and Maintenance Cost ($/MW-yr)	56780	24050	**4120**	86600	164640	46608
K09	Electricity Production Cost ($/kW-hr)	0,125	0,07	0,08	0,1	**0,05**	**0,05**
K10	LCOE Electricity Production Cost ($/MWh)	125,3	73,6	83,5	100,5	**47,8**	90
K11	Amortization Period (years)	1,85	**0,9**	11,8	1,92	5,7	8
K12	Specific Water Consumption (m3/kWh)	**0**	**0**	3,97	**0**	**0**	**0**
K13	Land Requirement (km2/MW)	11	**10**	**10**	25	38	20
K14	Turnkey Delivery Time (years)	**0,5**	1	1,08	2	1	1
K15	Government Incentives ($/kW)	**22,5**	11	9,6	18,9	13,2	10

5.1.1.3 Criteria Relation to Ecological Impacts

Environmental impacts should also be considered alongside technical and economic criteria for the investment to be made. Environmental factors directly affect human health, so the subheadings and data belonging to this group are as important as the other main group criteria.

Table 5.4. Ecological Criteria

No	SubCriteria | Sources of Energy	Solar	Wind	HydrP	Biomas	GeoT	Wave
K16	Nitrogen Oxide Emissions (g/MWh)	94,40	26,8	17,30	959	12,50	**0,10**
K17	Carbon Dioxide Emissions (g-CO2/kWh)	41	**11**	24	230	38	24,60
K18	Carbon Monoxide Emissions (g/MWh)	607	38,10	12,20	1490	25,10	**0**
K19	Sulfur Dioxide Emissions (g/MWh)	59,20	29,90	11,20	439	3,11	**0,24**
K20	Particulate Emissions (g/MWh)	0,0352	0,0168	0,0053	0,325	0,0013	**0**
K21	Non-Methane Emissions (g/MWh)	37,60	7,24	0,597	40,50	0,442	**0**

5.1.1.4 Socioeconomic Criteria

This is the main criteria group that covers the social and economic impacts of the relevant investments. Acceptability of the investment by the public in the region where the investment is planned, as well as the benefits of the investment for the public in both the region and a wider circle, can be defined under this criteria group title.

Table 5.5. Socioeconomic Criteria

No	SubCriteria | Sources of Energy	Solar	Wind	Hydr	Bioma	GeoT	Wave
K22	External Costs	0,60	**0,19**	0,54	2,01	0,20	0,8
K23	Installation, Operation, and Maintenance Employment (person/MW)	0,53	0,40	0,33	1	**2,13**	0,30
K24	Social Acceptability	0,1137	**0,1340**	0,0479	0,1270	0,1312	0,05
K25	Technological Maturity	2	3	**5**	**5**	4	3
K26	Noise Factor (dB)	0	47	72,3	79,9	82	70

Table 5.6. Maximization (Benefit) and Minimization (Cost) Oriented Criteria

Primary Criteria Categories	Sub Criteria	Max / Min
Technique	Energy Efficiency	Max
	Economic Potential (GW/year)	Max
	Operating Service Life (year)	Max
	Global Installed Capacity (%)	Max
	Capacity Factor (%)	Max
	Probability of Failure and Accident Risk	Min
Economic	Investment Cost ($/kW)	Min
	Fixed Op. and Maintenance Cost ($/MW-year)	Min
	Electricity Generation Cost ($/Kw-h)	Min
	LCOE Electricity Generation Cost ($/MWh)	Min
	Amortization Period (year)	Min
	Specific Water Consumption (kg/MW)	Min
	Land Use Requirement (km2/MW)	Min
	Turnkey Delivery Time (year)	Min
	Government Incentives ($/MW)	Max
Ecological	Nitrogen Oxide Emissions (g/MWh)	Min
	Carbon Dioxide Emissions (g-CO2/GWh)	Min
	Carbon Monoxide Emissions (g/MWh)	Min
	Sulfur Dioxide Emissions (g/MWh)	Min
	Particulate Emissions (g/MWs)	Min
	Non-Methane Emissions (g/MWs)	Min
Social	External Cost	Min
	Employment during Installation, Operation, and	Max
	Social Acceptability	Max
	Technological Maturity	Max
	Noise Factor	Min

5.2. Stages of CRITIC Methods

In the first stage of applying the CRITIC method, after determining the types of criteria, a decision matrix consisting of 6 options and 26 criteria were formed, as shown in Table 5.7, taking into account the data in Tables 5.2, 5.3, 5.4, and 5.5, to obtain an objective prioritization as in equation (4.1).

Table 5.7. Decision matrix including measurable data for renewable energy source types

Decision Matrix							
No	**Criteria | Options**	**Solar**	**Wind**	**HydroE**	**Biomass**	**Geoth.**	**Wave**
K01	Energy Efficiency	21	26	**90**	40	16	15
K02	Ekonomic Potential (GW/yıl)	91	98	**140**	0,4	4	3,65
K03	Operating Life (year)	25	25	**30**	20	25	**30**
K04	Global Installed Capacity (%)	2,90	6,10	**17,50**	1,50	0,20	2,41
K05	Capacity Factor (%)	27,40	30,00	37,10	85,00	**90,00**	30,00
K15	Government Incentives ($/kW)	**22,5**	11	10	18,9	13,2	10
K23	Installation, Operation, and Maintenance Employment (person/MW)	0,53	0,40	0,33	1,00	**2,13**	0,30
K24	Social Acceptability	0,1137	**0,1340**	0,0479	0,1270	0,1312	0,0500
K25	Technological Maturity	2	3	**5**	**5**	4	3
K06	Low Risk of Breakdowns and Accidents	16,6	17	11	10	**9**	15
K07	Investment Cost ($/kW)	3.873	**2.213**	2.936	4.114	4.362	2.500
K08	Fixed Operation and Maintenance Cost ($/MW-yr)	56.780	24.050	**4.120**	86.600	164.640	46.608
K09	Electricity Production Cost ($/Kw-saat)	0,125	0,070	0,080	0,100	**0,050**	**0,050**
K10	LCOE Electricity Production Cost ($/MWs)	125,30	73,60	83,50	100,50	**47,80**	90,00
K11	Amortization Period (year)	1,85	**0,9**	12	1,92	5,7	8
K12	Specific Water Consumption (m3/kWh)	**0**	**0**	3,9700	**0**	**0**	**0**
K13	Land Requirement (km2/MW)	11	**10**	**10**	25	38	20
K14	Tumkey Delivery Time (year)	**0,50**	1	1,08	2	1	1
K16	Nitrogen Oxide Emissions (g/MWs)	94,40	26,80	17,30	959,00	12,50	**0,10**
K17	Carbon Dioxide Emissions (g-CO2/kWh)	41	**11**	24	230	38	24,60
K18	Carbon Monoxide Emissions (g/MWs)	607	38,10	12,20	1.490	25,10	**0,00**
K19	Sulfur Dioxide Emissions (g/MWs)	59,20	29,90	11,20	439	3,11	**0,24**
K20	Particulate Emissions (g/MWs)	0,0352	0,0168	0,0053	0,3250	0,0013	**0,00**
K21	Non-Methane Emissions (g/MWs)	37,600	7,240	0,597	40,500	0,442	**0,00**
K22	External Cost	0,6	0,19	1	2,01	0,2	0,8
K26	Noise Factor (dB)	0	47	72	79,9	82	70

The numerical data in the Decision Matrix are standardized by using the benefit or cost directionality (Equations 4.2 and 4.3). Table 5.8 shows the structure of the standardized decision matrix.

Table 5.8. The Normalization Table obtained by standardization

Normalization Matrix							
No	**Criteria | Options**	**Solar**	**Wind**	**HydroP.**	**Biomass**	**Geother.**	**Wave**
K01	Energy Efficiency	0,920	0,853	0,000	0,667	0,987	1,000
K02	Economic Potential (GW/year)	0,351	0,301	0,000	1,000	0,974	0,977
K03	Operating Service Life (year)	0,500	0,500	0,000	1,000	0,500	0,000
K04	Global Installed Capacity (%)	0,844	0,659	0,000	0,925	1,000	0,872
K05	Capacity Factor (%)	1,000	0,958	0,845	0,080	0,000	0,958
K15	Government Incentives ($/MW)	0,000	0,891	1,000	0,279	0,721	0,969
K23	Employment during Installation, Operation, and Maintenance (person/MW)	0,874	0,945	0,984	0,617	0,000	1,000
K24	Social Acceptability	0,236	0,000	1,000	0,081	0,033	0,976
K25	Technological Maturity	1,000	0,667	0,000	0,000	0,333	0,667
K06	Probability of Failure and Accident Risk	0,950	1,000	0,250	0,125	0,000	0,750
K07	Investment Cost ($/kW)	0,772	0,000	0,336	0,885	1,000	0,134
K08	Fixed Op. and Maintenance Cost ($/MW-year)	0,328	0,124	0,000	0,514	1,000	0,265
K09	Electricity Generation Cost ($/Kw-h)	1,000	0,267	0,400	0,667	0,000	0,000
K10	LCOE Electricity Generation Cost ($/MWh)	1,000	0,333	0,461	0,680	0,000	0,545
K11	Amortization Period (year)	0,087	0,000	1,000	0,094	0,440	0,651
K12	Specific Water Consumption (kg/MW)	0,000	0,000	1,000	0,000	0,000	0,000
K13	Land Use Requirement (km2/MW)	0,036	0,000	0,000	0,536	1,000	0,357
K14	Turnkey Delivery Time (year)	0,000	0,333	0,387	1,000	0,333	0,333
K16	Nitrogen Oxide Emissions (g/MWh)	0,098	0,028	0,018	1,000	0,013	0,000
K17	Carbon Dioxide Emissions (g-CO2/GWh)	0,137	0,000	0,059	1,000	0,123	0,062
K18	Carbon Monoxide Emissions (g/MWh)	0,407	0,026	0,008	1,000	0,017	0,000
K19	Sulfur Dioxide Emissions (g/MWh)	0,134	0,068	0,025	1,000	0,007	0,000
K20	Particulate Emissions (g/MWs)	0,108	0,052	0,016	1,000	0,004	0,000
K21	Non-Methane Emissions (g/MWs)	0,928	0,179	0,015	1,000	0,011	0,000
K22	External Cost	0,225	0,000	0,192	1,000	0,005	0,335
K26	Noise Factor (dB)	0,000	0,573	0,882	0,974	1,000	0,854

The correlation table obtained from correlation analysis between criterion pairs is shown in Table 5.9 using Equation (4.4) to calculate the correlations and measure the degree of relationship between the criteria.

In the next step, the total amount of data in each criterion, denoted as C_j, is calculated using equation (4.5). The standard deviation of the criteria, σj, is calculated using equation (4.6) and equation (4.5) where the total number of data is calculated. The results of these calculations are shown in Table 5.10. Finally, the weights of the criteria are determined by using equation (4.7), and the priorities within the list of 26 criteria are established. And finally, priorities have been determined within the list of 26 criteria, which were identified by calculating the weights of the criteria using equation (4.7).

Table 5.9. Relationship Correlation Table

Correlation Matrix																										
No	K01	K02	K03	K04	K05	K15	K23	K24	K25	K06	K07	K08	K09	K10	K11	K12	K13	K14	K16	K17	K18	K19	K20	K21	K22	K26
K01	1	0,63219	0,28187	0,91235	-0,095	-0,2817	-0,3236	-0,4854	0,67194	0,34831	0,14196	1	-0,17331	-0,03864	-0,59762	-0,9481	0,40888	-0,2369	-0,0793	-0,0593	0,0055	-0,0744	-0,0748	0,12169	-0,1172	-0,2488
K02	0,63219	1	0,3795	0,82343	-0,6368	-0,1358	-0,5547	-0,2402	-0,0837	-0,36924	0,41769	1	-0,35428	-0,20356	-0,20391	-0,6736	0,81877	0,44516	0,41621	0,48072	0,3313	0,38896	0,40376	0,10531	0,44059	0,46017
K03	0,28187	0,3795	1	0,55382	-0,6143	-0,6754	-0,4318	-0,8481	-0,1463	-0,21898	0,59247	0	0,44436	0,14072	-0,79625	-0,5423	0,33296	0,55129	0,7864	0,77464	0,81375	0,79945	0,79275	0,74729	0,54958	-0,0329
K04	0,91235	0,82343	0,55382	1	-0,4255	-0,4673	-0,5095	-0,5841	0,38524	0,03295	0,44615	1	-0,04977	0,0068	-0,63363	-0,9514	0,618	0,09648	0,28658	0,32444	0,34609	0,28363	0,28555	0,3508	0,22366	-0,0653
K05	-0,095	-0,6368	-0,6143	-0,4255	1	0,18521	0,8694	0,48247	0,60316	0,85363	-0,75963	-1	0,1664	0,4475	0,11816	0,21405	-0,8709	-0,6306	-0,56	-0,6265	-0,4392	-0,5327	-0,544	-0,1554	-0,3886	-0,6178
K15	-0,2817	-0,1358	-0,6754	-0,4673	0,18521	1	0,15471	0,50991	-0,283	-0,08327	-0,66952	0	-0,83975	-0,67568	0,63302	0,42433	-0,0297	-0,014	-0,5058	-0,5129	-0,7421	-0,5258	-0,5097	-0,9287	-0,4347	0,58233
K23	-0,3236	-0,5547	-0,4318	-0,5095	0,8694	0,15471	1	0,54971	0,26413	0,68512	-0,76054	-1	0,27979	0,58885	0,12422	0,31226	-0,9085	-0,1774	-0,1367	-0,2177	-0,0876	-0,1124	-0,1208	0,0447	0,06044	-0,3945
K24	-0,4854	-0,2402	-0,8481	-0,5841	0,48247	0,50991	0,54971	1	-0,1432	0,0233	-0,463	-1	-0,23164	0,14301	0,85872	0,63567	-0,334	-0,1568	-0,3475	-0,3319	-0,3983	-0,367	-0,3579	-0,4545	-0,0315	0,18504
K25	0,67194	-0,0837	-0,1463	0,38524	0,60316	-0,283	0,26413	-0,1432	1	0,84484	-0,23019	0	0,1779	0,35938	-0,43043	-0,5394	-0,3104	-0,7662	-0,4906	-0,5141	-0,2678	-0,4629	-0,4765	0,10736	-0,443	-0,8043
K06	0,34831	-0,3692	-0,219	0,03295	0,85363	-0,0833	0,68512	0,0233	0,84484	1	-0,62193	-1	0,23687	0,46678	-0,38331	-0,2924	-0,7062	-0,5821	-0,3921	-0,4682	-0,2341	-0,3543	-0,3693	0,09192	-0,3227	-0,7625
K07	0,14196	0,41769	0,59247	0,44615	-0,7596	-0,6695	-0,7605	-0,463	-0,2302	-0,62193	1	1	0,3413	0,0408	-0,2065	-0,2157	0,6499	0,21692	0,45206	0,52866	0,54264	0,43788	0,43683	0,50597	0,33124	0,05055
K08	0,52693	0,72332	0,46558	0,71285	-0,827	-0,2794	-0,9583	-0,5436	-0,099	-0,5707	0,78107	1	-0,23587	-0,43563	-0,223	-0,514	0,94007	0,15456	0,18813	0,27425	0,17561	0,16436	0,17257	0,06953	0,04308	0,30414
K09	-0,1733	-0,3543	0,44436	-0,0498	0,1664	-0,8397	0,27979	-0,2316	0,1779	0,23687	0,3413	0	1	0,83982	-0,43346	0,01389	-0,4568	-0,028	0,42375	0,38918	0,65454	0,45436	0,43373	0,87693	0,39308	-0,6831
K10	-0,0386	-0,2036	0,14072	0,0068	0,4475	-0,6757	0,58885	0,14301	0,35938	0,46678	0,0408	0	0,83982	1	-0,26791	-0,0618	-0,5607	-0,091	0,3209	0,28678	0,54112	0,346	0,3302	0,75204	0,46983	-0,6717
K11	-0,5976	-0,2039	-0,7962	-0,6336	0,11816	0,63302	0,12422	0,85872	-0,4304	-0,38331	-0,2065	0	-0,43346	-0,26791	1	0,77361	-0,0053	-0,093	-0,4002	-0,3525	-0,5139	-0,4328	-0,4189	-0,6546	-0,1919	0,46289
K12	-0,9481	-0,6736	-0,5423	-0,9514	0,21405	0,42433	0,31226	0,63567	-0,5394	-0,29239	-0,21567	-1	0,01389	-0,06181	0,77361	1	-0,3947	-0,0167	-0,2159	-0,2202	-0,2853	-0,2255	-0,2234	-0,3502	-0,1333	0,21572
K13	0,40888	0,81877	0,33296	0,618	-0,8709	-0,0297	-0,9085	-0,334	-0,3104	-0,70624	0,6499	1	-0,45676	-0,56073	-0,00534	-0,3947	1	0,33908	0,22763	0,31891	0,12244	0,19238	0,20806	-0,1112	0,1406	0,59192
K14	-0,2369	0,44516	0,55129	0,09648	-0,6306	-0,014	-0,1774	-0,1568	-0,7662	-0,58215	0,21692	0	-0,028	-0,09104	-0,09304	-0,0167	0,33908	1	0,86424	0,86155	0,66422	0,84849	0,85957	0,28329	0,80821	0,67545
K16	-0,0793	0,41621	0,7864	0,28658	-0,56	-0,5058	-0,1367	-0,3475	-0,4906	-0,39207	0,45206	0	0,42375	0,3209	-0,40016	-0,2159	0,22763	0,86424	1	0,99323	0,9498	0,99879	0,99959	0,72448	0,93476	0,25527
K17	-0,0593	0,48072	0,77464	0,32444	-0,6265	-0,5129	-0,2177	-0,3319	-0,5141	-0,46823	0,52866	0	0,38918	0,28678	-0,35251	-0,2202	0,31891	0,86155	0,99323	1	0,94261	0,98736	0,9897	0,70415	0,93623	0,29892
K18	0,0055	0,3313	0,81375	0,34609	-0,4392	-0,7421	-0,0876	-0,3983	-0,2678	-0,23415	0,54264	0	0,65454	0,54112	-0,51387	-0,2853	0,12244	0,66422	0,9498	0,94261	1	0,9572	0,95158	0,90005	0,89297	-0,0359
K19	-0,0744	0,38896	0,79945	0,28363	-0,5327	-0,5258	-0,1124	-0,367	-0,4629	-0,35426	0,43788	0	0,45436	0,346	-0,4328	-0,2255	0,19238	0,84849	0,99879	0,98736	0,9572	1	0,99968	0,7473	0,92783	0,21552
K20	-0,0748	0,40376	0,79275	0,28555	-0,544	-0,5097	-0,1208	-0,3579	-0,4765	-0,36926	0,43683	0	0,43373	0,3302	-0,41886	-0,2234	0,20806	0,85957	0,99959	0,9897	0,95158	0,99968	1	0,73236	0,9312	0,23851
K21	0,12169	0,10531	0,74729	0,3508	-0,1554	-0,9287	0,0447	-0,4545	0,10736	0,09192	0,50597	0	0,87693	0,75204	-0,65457	-0,3502	-0,1112	0,28329	0,72448	0,70415	0,90005	0,7473	0,73236	1	0,66552	-0,464
K22	-0,1172	0,44059	0,54958	0,22366	-0,3886	-0,4347	0,06044	-0,0315	-0,443	-0,3227	0,33124	0	0,39308	0,46983	-0,19185	-0,1333	0,1406	0,80821	0,93476	0,93623	0,89297	0,92783	0,9312	0,66552	1	0,25582
K26	-0,2488	0,46017	-0,0329	-0,0653	-0,6178	0,58233	-0,3945	0,18504	-0,8043	-0,76254	0,05055	0	-0,68315	-0,67168	0,46289	0,21572	0,59192	0,67545	0,25527	0,29892	-0,0359	0,21552	0,23851	-0,464	0,25582	1

Table 5.10. Table of (1-pjk)

(1-pjk) Matrix																										
No	K01	K02	K03	K04	K05	K15	K23	K24	K25	K06	K07	K08	K09	K10	K11	K12	K13	K14	K16	K17	K18	K19	K20	K21	K22	K26
K01	0	0,36781	0,71813	0,08765	1,09498	1,28174	1,32356	1,48536	0,32806	0,65169	0,85804	0,47307	1,17331	1,03864	1,59762	1,94811	0,59112	1,2369	1,07929	1,05929	0,9945	1,07436	1,07484	0,87831	1,11721	1,24881
K02	0,36781	0	0,6205	0,17657	1,63681	1,13576	1,55474	1,24022	1,08371	1,36924	0,58231	0,27668	1,35428	1,20356	1,20391	1,67365	0,18123	0,55484	0,58379	0,51928	0,6687	0,61104	0,59624	0,89469	0,55941	0,53983
K03	0,71813	0,6205	0	0,44618	1,61425	1,67537	1,4318	1,84813	1,14625	1,21898	0,40753	0,53442	0,55564	0,85928	1,79625	1,54233	0,66704	0,44871	0,2136	0,22536	0,18625	0,20055	0,20725	0,25271	0,45042	1,03286
K04	0,08765	0,17657	0,44618	0	1,42551	1,4673	1,50953	1,5841	0,61476	0,96705	0,55385	0,28715	1,04977	0,9932	1,63363	1,95136	0,382	0,90352	0,71342	0,67556	0,65391	0,71637	0,71445	0,6492	0,77634	1,06532
K05	1,09498	1,63681	1,61425	1,42551	0	0,81479	0,1306	0,51753	0,39684	0,14637	1,75963	1,82702	0,8336	0,5525	0,88184	0,78595	1,87088	1,63061	1,56002	1,62648	1,43923	1,53269	1,54405	1,15544	1,38856	1,61785
K15	1,28174	1,13576	1,67537	1,4673	0,81479	0	0,84529	0,49009	1,28298	1,08327	1,66952	1,27941	1,83975	1,67568	0,36698	0,57567	1,02967	1,01399	1,50584	1,51293	1,74215	1,52576	1,50972	1,92871	1,4347	0,41767
K23	1,32356	1,55474	1,4318	1,50953	0,1306	0,84529	0	0,45029	0,73587	0,31488	1,76054	1,9583	0,72021	0,41115	0,87578	0,68774	1,90851	1,17744	1,13673	1,21772	1,08755	1,1124	1,12083	0,9553	0,93956	1,39448
K24	1,48536	1,24022	1,84813	1,5841	0,51753	0,49009	0,45029	0	1,14317	0,9767	1,463	1,54363	1,23164	0,85699	0,14128	0,36433	1,33396	1,15683	1,34752	1,33193	1,39826	1,36701	1,35787	1,45446	1,03147	0,81496
K25	0,32806	1,08371	1,14625	0,61476	0,39684	1,28298	0,73587	1,14317	0	0,15516	1,23019	1,09901	0,8221	0,64062	1,43043	1,53936	1,31044	1,76623	1,49056	1,51409	1,26783	1,46291	1,47649	0,89264	1,44295	1,8043
K06	0,65169	1,36924	1,21898	0,96705	0,14637	1,08327	0,31488	0,9767	0,15516	0	1,62193	1,5707	0,76313	0,53322	1,38331	1,29239	1,70624	1,58215	1,39207	1,46823	1,23415	1,35426	1,36926	0,90808	1,3227	1,76254
K07	0,85804	0,58231	0,40753	0,55385	1,75963	1,66952	1,76054	1,463	1,23019	1,62193	0	0,21893	0,6587	0,9592	1,2065	1,21567	0,3501	0,78308	0,54794	0,47134	0,45736	0,56212	0,56317	0,49403	0,66876	0,94945
K08	0,47307	0,27668	0,53442	0,28715	1,82702	1,27941	1,9583	1,54363	1,09901	1,5707	0,21893	0	1,23587	1,43563	1,223	1,51404	0,05993	0,84544	0,81187	0,72575	0,82439	0,83564	0,82743	0,93067	0,95692	0,69586
K09	1,17331	1,35428	0,55564	1,04977	0,8336	1,83975	0,72021	1,23164	0,8221	0,76313	0,6587	1,23587	0	0,16018	1,43346	0,98611	1,45676	1,028	0,57625	0,61082	0,34546	0,54564	0,56627	0,12307	0,60692	1,68315
K10	1,03864	1,20356	0,85928	0,9932	0,5525	1,67568	0,41115	0,85699	0,64062	0,53322	0,9592	1,43563	0,16018	0	1,26791	1,06181	1,56073	1,09104	0,6791	0,71322	0,45888	0,654	0,6698	0,24796	0,53017	1,67168
K11	1,59762	1,20391	1,79625	1,63363	0,88184	0,36698	0,87578	0,14128	1,43043	1,38331	1,2065	1,223	1,43346	1,26791	0	0,22639	1,00534	1,09304	1,40016	1,35251	1,51387	1,4328	1,41886	1,65457	1,19185	0,53711
K12	1,94811	1,67365	1,54233	1,95136	0,78595	0,57567	0,68774	0,36433	1,53936	1,29239	1,21567	1,51404	0,98611	1,06181	0,22639	0	1,39468	1,01666	1,21587	1,22019	1,28533	1,2255	1,22342	1,35019	1,13334	0,78428
K13	0,59112	0,18123	0,66704	0,382	1,87088	1,02967	1,90851	1,33396	1,31044	1,70624	0,3501	0,05993	1,45676	1,56073	1,00534	1,39468	0	0,66092	0,77237	0,68109	0,87756	0,80762	0,79194	1,11122	0,8594	0,40808
K14	1,2369	0,55484	0,44871	0,90352	1,63061	1,01399	1,17744	1,15683	1,76623	1,58215	0,78308	0,84544	1,028	1,09104	1,09304	1,01666	0,66092	0	0,13576	0,13845	0,33578	0,15151	0,14043	0,71671	0,19179	0,32455
K16	1,07929	0,58379	0,2136	0,71342	1,56002	1,50584	1,13673	1,34752	1,49056	1,39207	0,54794	0,81187	0,57625	0,6791	1,40016	1,21587	0,77237	0,13576	0	0,00677	0,0502	0,00121	0,00041	0,27552	0,06524	0,74473
K17	1,05929	0,51928	0,22536	0,67556	1,62648	1,51293	1,21772	1,33193	1,51409	1,46823	0,47134	0,72575	0,61082	0,71322	1,35251	1,22019	0,68109	0,13845	0,00677	0	0,05739	0,01264	0,0103	0,29585	0,06377	0,70108
K18	0,9945	0,6687	0,18625	0,65391	1,43923	1,74215	1,08755	1,39826	1,26783	1,23415	0,45736	0,82439	0,34546	0,45888	1,51387	1,28533	0,87756	0,33578	0,0502	0,05739	0	0,0428	0,04842	0,09995	0,10703	1,03595
K19	1,07436	0,61104	0,20055	0,71637	1,53269	1,52576	1,1124	1,36701	1,46291	1,35426	0,56212	0,83564	0,54564	0,654	1,4328	1,2255	0,80762	0,15151	0,00121	0,01264	0,0428	0	0,00032	0,2527	0,07217	0,78448
K20	1,07484	0,59624	0,20725	0,71445	1,54405	1,50972	1,12083	1,35787	1,47649	1,36926	0,56317	0,82743	0,56627	0,6698	1,41886	1,22342	0,79194	0,14043	0,00041	0,0103	0,04842	0,00032	0	0,26764	0,0688	0,76149
K21	0,87831	0,89469	0,25271	0,6492	1,15544	1,92871	0,9553	1,45446	0,89264	0,90808	0,49403	0,93067	0,12307	0,24796	1,65457	1,35019	1,11122	0,71671	0,27552	0,29585	0,09995	0,2527	0,26764	0	0,33448	1,46405
K22	1,11721	0,55941	0,45042	0,77634	1,38856	1,4347	0,93956	1,03147	1,44295	1,3227	0,66876	0,95692	0,60692	0,53017	1,19185	1,13334	0,8594	0,19179	0,06524	0,06377	0,10703	0,07217	0,0688	0,33448	0	0,74418
K26	1,24881	0,53983	1,03286	1,06532	1,61785	0,41767	1,39448	0,81496	1,8043	1,76254	0,94945	0,69586	1,68315	1,67168	0,53711	0,78428	0,40808	0,32455	0,74473	0,70108	1,03595	0,78448	0,76149	1,46405	0,74418	0

Table 5.11. Table showing Importance Weights of Criteria

Criteria No	Standard deviation σj	cj	The correlation wj	Weights of Criteria %
K01	0,38121832	9,44749252	0,03993273	3,99327253
K02	0,43667728	9,25265976	0,0391092	3,91092048
K03	0,37638633	7,64055945	0,03229517	3,22951684
K04	0,36904342	8,11810415	0,03431366	3,43136575
K05	0,46857849	13,9561554	0,05898997	5,89899719
K15	0,41168557	12,8053599	0,05412578	5,41257818
K23	0,38722187	10,3623705	0,04379974	4,37997376
K24	0,47201173	13,1836236	0,05572463	5,57246294
K25	0,40368671	11,3342912	0,04790786	4,79078588
K06	0,4398153	12,3797849	0,05232696	5,23269584
K07	0,41964136	9,23751864	0,03904521	3,90452063
K08	0,35433176	8,50068797	0,03593077	3,59307654
K09	0,39195616	8,76417532	0,03704448	3,70444755
K10	0,33579679	7,36272563	0,03112082	3,11208185
K11	0,39341453	11,5146058	0,04867001	4,86700139
K12	0,40824829	11,9267044	0,05041187	5,04118749
K13	0,39897829	9,48723602	0,04010071	4,01007134
K14	0,32664399	6,57351417	0,02778497	2,77849742
K16	0,3969398	7,26647414	0,03071398	3,0713982
K17	0,38030161	6,92606551	0,02927514	2,92751405
K18	0,40315698	7,34265978	0,031036	3,1036004
K19	0,39235379	7,19519029	0,03041268	3,0412679
K20	0,39560913	6,8298602	0,0288685	2,88684993
K21	0,4766679	7,93800732	0,03355242	3,3552423
K22	0,37009753	5,82392878	0,02461662	2,46166216
K26	0,38127629	5,41546275	0,02289011	2,28901146

Table 5.12. Weighting results obtained according to the criteria of the CRITIC Method

Primary Criteria Categories	Criteria		Weighting Rate 0≤x≤1
Technique	K01	Energy Efficiency	0.0399327253
	K02	Economic Potential (GW/year)	0.0391092048
	K03	Operating Service Life (year)	0.0322951684
	K04	Global Installed Capacity (%)	0.0343136575
	K05	Capacity Factor (%)	**0.0589899719**
	K06	Probability of Failure and Accident Risk	0.0523269584
Economic	K07	Investment Cost ($/kW)	0.0390452063
	K08	Fixed Op. and Maintenance Cost ($/MW-year)	0.0359307654
	K09	Electricity Generation Cost ($/Kw-h)	0.0370444755
	K10	LCOE Electricity Generation Cost ($/MWh)	0.0311208185
	K11	Amortization Period (year)	0.0486700139
	K12	Specific Water Consumption (kg/MW)	0.0504118749
	K13	Land Use Requirement (km2/MW)	0.0401007134
	K14	Turnkey Delivery Time (year)	0.0277849742
	K15	Government Incentives ($/MW)	**0.0541257818**
Ecologic	K16	Nitrogen Oxide Emissions (g/MWh)	0.030713982
	K17	Carbon Dioxide Emissions (g-CO2/GWh)	0.0292751405
	K18	Carbon Monoxide Emissions (g/MWh)	0.031036004
	K19	Sulfur Dioxide Emissions (g/MWh)	0.030412679
	K20	Particulate Emissions (g/MWs)	0.0288684993
	K21	Non-Methane Emissions (g/MWs)	**0.033552423**
Social	K22	External Cost	0.0246166216
	K23	Employment during Installation, Operation, and Maintenance (person/MW)	0.0437997376
	K24	Social Acceptability	**0.0557246294**
	K25	Technological Maturity	0.0479078588
	K26	Noise Factor	0.0228901146

As seen in Table 5.13, the capacity factor in technical criteria, state incentives in economic criteria, non-methane emissions in ecological criteria, and social acceptability in social criteria have gained weight compared to other criteria in their respective groups.

5.3. WASPAS Method Application for Ranking Renewable Energy Options

In the second stage of the process, renewable energy sources are ranked based on their performances in the criteria by using the WASPAS method. The decision matrix prepared in the CRITIC method is normalized using equations (4.9) and (4.10) for each criterion in terms of benefit and cost directionality. With this process, the first step of this method is completed. Table 5.14 lists the normalized data.

Table 5.13. Normalized Data

Normalized Table							
No	**Criteria | Options**	**Solar**	**Wind**	**HydroE**	**Biomass**	**Geoth.**	**Wave**
K01	Energy Efficiency	0,233	0,289	1,000	0,444	0,178	0,167
K02	Ekonomic Potential (GW/yıl)	0,650	0,700	1,000	0,003	0,029	0,026
K03	Operating Life (year)	0,833	0,833	1,000	0,667	0,833	1,000
K04	Global Installed Capacity (%)	0,166	0,349	1,000	0,086	0,011	0,138
K05	Capacity Factor (%)	0,304	0,333	0,412	0,944	1,000	0,333
K15	Government Incentives ($/kW)	1,000	0,489	0,427	0,840	0,587	0,444
K23	Installation, Operation, and Maintenance Employment (person/MW)	0,249	0,188	0,155	0,469	1,000	0,141
K24	Social Acceptability	0,849	1,000	0,357	0,948	0,979	0,373
K25	Technological Maturity	0,400	0,600	1,000	1,000	0,800	0,600
K06	Low Risk of Breakdowns and Accidents	0,542	0,529	0,818	0,900	1,000	0,600
K07	Investment Cost ($/kW)	0,571	1,000	0,754	0,538	0,507	0,885
K08	Fixed Operation and Maintenance Cost ($/MW-yr)	0,073	0,171	1,000	0,048	0,025	0,088
K09	Electricity Production Cost ($/Kw-saat)	0,400	0,714	0,625	0,500	1,000	1,000
K10	LCOE Electricity Production Cost ($/MWs)	0,381	0,649	0,572	0,476	1,000	0,531
K11	Amortization Period (year)	0,486	1,000	0,076	0,469	0,158	0,113
K12	Specific Water Consumption (m3/kWh)	1,000	1,000	0,000	1,000	1,000	1,000
K13	Land Requirement (km2/MW)	0,909	1,000	1,000	0,400	0,263	0,500
K14	Tumkey Delivery Time (year)	1,000	0,500	0,463	0,250	0,500	0,500
K16	Nitrogen Oxide Emissions (g/MWs)	0,001	0,004	0,006	0,000	0,008	1,000
K17	Carbon Dioxide Emissions (g-CO2/kWh)	0,268	1,000	0,458	0,048	0,289	0,447
K18	Carbon Monoxide Emissions (g/MWs)	0,000	0,000	0,000	0,000	0,000	1,000
K19	Sulfur Dioxide Emissions (g/MWs)	0,004	0,008	0,021	0,001	0,077	1,000
K20	Particulate Emissions (g/MWs)	0,000	0,001	0,002	0,000	0,008	1,000
K21	Non-Methane Emissions (g/MWs)	0,000	0,000	0,000	0,000	0,000	1,000
K22	External Cost	0,317	1,000	0,352	0,095	0,950	0,238
K26	Noise Factor (dB)	1,000	0,000	0,000	0,000	0,000	0,000

In the third step, the process of calculating the relative importance of the options has been completed. In this process, the weight values of the criteria obtained by the CRITIC method are included in the calculation to obtain the Weighted Decision Matrix. Then, using the values in this new table, the total relative importance of each option is calculated separately according to WSM and WPM.

The total relative importance of an option according to WSM is determined by the weighted sum of criterion values using equation (4.11). According to WPM, the criterion-based performance value of an option is calculated using equation (4.12), multiplied by the criterion weight. The results obtained are shown in Table 5.15.

Table 5.14. Performance Values of Options According to Criteria Weights Based on WPM and Total Relative Importance of Options According to WSM

Values	Solar	Wind	Hydropower	Biomass	Geothermal	Wave
WPM	0.098	0.110	0.075	0.046	0.104	0.297
WSM	0.474	0.544	0.496	0.468	0.521	0.530

Furthermore, the Common Generalized Criterion Value is calculated by applying a λ value (λ=0.5 in this case) using equation (4.13) on the WPM and WSM data. Thus, the process of ranking the options based on their total relative importance (Qi) is completed. The option with the highest Qi value is interpreted as the most suitable option. As a result of this thesis study, the following ranking has been obtained for the evaluation of renewable energy sources based on criteria for sustainability in our country.

Table 5.15: Result Values Obtained by WASPAS Method

Options	Result Values (*Q*i)	Ranking
Wave	0.413	1
Wind	0.327	2
Geothermal	0.313	3
Hydropower	0.286	4
Solar	0.286	5
Biomass	0.257	6

6. RESULTS AND EVALUATIONS

In conclusion, based on the factors considered and the collected data, it is not possible to have a completely 100% clean and/or green energy source and production. The positive environmental impacts of renewable energy production are associated with their current usage and low greenhouse gas emissions. However, if the production and usage areas continue to increase, sufficient information on the long-term environmental impacts and the extent of the negative effects has not yet been obtained.

In our study, wave energy was identified as the energy source with the highest WASPAS score (0.413). Wind energy (0.327) and geothermal energy (0.313) ranked second and third, respectively. Hydropower (0.286), solar energy (0.286), and biomass energy (0.257) are energy sources with lower WASPAS scores.

These results provide a guide that can be considered when choosing and planning energy sources in the future. The numerical rankings obtained from the calculations confirm the fact that low-carbon energy sources supporting environmental sustainability should be preferred in the energy sector. In addition, the results can be considered by strategic decision-makers in the energy sector, and countries and companies wishing to transition to sustainable energy sources can select the most appropriate energy sources by taking these results into account.

However, we would like to emphasize that further research is needed to strengthen these results, i.e., to make them more reliable and comprehensive, and to consider more criteria. At this point, this study also shows that the WASPAS method can be used in the comparison process of energy sources and provide guidance in the decision-making process.

Additionally, the determined rankings may vary depending on other factors. In this study, only six different renewable energy sources were considered. When other renewable energy sources are included in the ranking process, the results may differ. The determinacy of the factors to be considered or required can vary from country to country, even from region to region. Each country, region, and local condition has different energy needs and sources. Therefore, decision-makers in the energy sector should consider multiple criteria to select the most appropriate renewable energy sources for their conditions, taking these factors into account.

This study should be considered as only a guideline in terms of criteria and evaluation calculations and decisions related to the energy sector should be supported by more comprehensive studies with wider coverage.

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There are no conflicts of interest among the authors

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The study has been conducted in accordance with research and publication ethics.

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