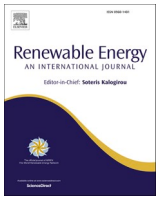
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Site selection modeling of hybrid renewable energy facilities using suitability index in spatial planning

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ABSTRACT

The research focuses on how hybrid renewable energy facilities can be addressed within the spatial planning system by adopting an approach that minimizes the problems related to the sustainability of energy. The study aims to develop a spatial model based on parameters for the site selection processes of hybrid renewable energy facilities relying on wind, solar, and biomass energy sources within the spatial planning system in Turkey. The integration of fuzzy logic approach and Geographic Information Systems (GIS) tools has been proposed to establish a spatially applicable methodological framework. The methodology focuses on the neighborhood scale in terms of planning level and covers the Karatay district, where the hybrid renewable energy potential is high. The research findings indicate that the GAMMA operator used in the methodology provides the most optimal areas with a value of $\gamma = 0.90$ and generates site selections for hybrid renewable energy facilities based on the source with the highest suitability index in single-source utilization. Additionally, the operator determines the best alternative in terms of resources in different hybrid scenarios. In this context conducted in Karatay district, it was found that the highest suitability index in terms of hybrid applications is associated with biomass-solar energy combinations.

1. Introduction

Energy is of great importance in societal life worldwide. Energy, which also has an impact on the economic development of countries, has gone through different stages and processes until today. Although crises related to oil and energy have reshaped policies throughout these processes, the significance of the concept of energy has continued to increase until the present day.

The significant increase in the cost of fossil fuels, fuel supply constraints, and their environmental impacts have highlighted the necessity of locally produced renewable energy. Renewable energy sources, which are particularly important in reducing energy dependence, have quickly gained prominence in national policies. According to the International Energy Agency (IEA), an independent organization with many member countries, the momentum of renewable energy sources is expected to accelerate, surpassing coal, and becoming the largest source of electricity generation by the early 2025. Within the renewable energy sources, which are projected to reach around 38% of electricity generation by 2027, it is anticipated that solar and wind energy alone could account for 20% of total production. These figures are expected to increase further due to the acceleration of policies and approaches by countries. The expansion of biomass energy is emphasized as a solution to the increasing amounts of waste that contribute to greenhouse gas emissions, with a projected demand for biomass energy reaching up to 22% by 2027 [1].

There are certain disadvantages associated with renewable energy sources. One of these is the intermittent nature of production and the high fluctuations in energy supply. These challenges have led to the emergence of the concept of hybrid renewable energy. The hybrid renewable energy system, defined as the presence of at least two sources within the same system for energy production, is an increasingly developing field. The importance of hybrid combinations in increasing electricity generation and reducing the intermittent and fluctuating nature of production is growing every day, as emphasized in many studies [2–7]. Solar and wind energy hybrid combinations are the most widely used systems worldwide [8–20]. However, considering that these two hybrid systems are fed from similar primary sources, having these two sources as hybrids is not sufficient to address the energy supply and variability issues.

When considering decision-making processes in planning-based site

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selections, the complexity and length of the process increase due to the involvement of multiple decision-makers and criteria. In a sound decision-making process, minimizing complexity, subjectivity, and approaches that can prolong the process is crucial.

The concrete language of the planning process is represented by spatial maps. With the increase in criteria and diversification of evaluations in the spatial mapping process, there is a growing need for Geographic Information Systems (GIS). However, GIS alone has limited functionalities to encompass the decision-making process. Therefore, establishing the relationship between GIS and Multi-Criteria/Aim Decision-Making Methods (MCADM) and developing modeling can reduce the complexity of the process and minimize subjectivity [21].

The variability and intermittency issues in providing supply for renewable energy sources in single-use scenarios raise the question of "What kind of spatial approach is required to ensure sustainability?" In this context, despite the widespread use of solar and wind energy and advancements in R&D, their inherent variability and intermittency pose challenges, leading to the view that hybrid combinations can minimize this problem. The predominant focus of existing studies is on binary hybrid combinations of solar and wind energy sources. However, hybrid combinations of renewable energy sources fed from similar primary sources can still face the same issue. Therefore, there is a need for renewable sources that can feed these systems and form hybrid combinations. Within this framework, the study found that many spatial site selections for renewable energy sources are in rural areas [22–25]. Considering the agricultural and livestock structure of rural areas, biomass energy stands out. Thus, in addition to the relationship between rural areas and renewable energy, within the intermittent nature of solar and wind energy sources, the approach of biomass-based hybrid combinations becomes significant. Especially when considering factors such as agricultural and livestock activities in rural areas, the existence of marginal agricultural lands in a state of disuse, and the electricity requirements for agricultural irrigation, the diverse benefits of biomass-based hybrid combinations become apparent.

The study primarily aims to answer the question of "What types of information and evaluation methods are necessary for spatial site selection of sustainable renewable energy?" In this regard, the research seeks to develop a model based on parameters for the site selection processes of hybrid power plants utilizing wind, solar, and biomass energy sources within the spatial planning system in Turkey. The objective is to determine suitability indices at the neighborhood scale for biomass-solar energy, biomass-wind energy, and biomass-solar-wind energy hybrid applications based on the site selection parameters. Fuzzy logic operators, specifically the GAMMA operator, were used for spatial modeling during the integration of the model with GIS.

2. Theoretical framework

2.1. Spatial planning and hybrid renewable energy

The inadequacy of conventional energy sources and the increasing energy demands in all sectors of human life pose challenges for countries. In the past decade, these challenges have drawn significant attention from researchers in terms of enhancing energy efficiency and feasibility. One of the topics that has received great interest is hybrid renewable energy systems. A hybrid renewable energy system can efficiently generate clean energy to meet energy demands. Therefore, hybrid systems are widely used to improve power system quality, reliability, and economics. However, the intermittent and fluctuating nature of renewable energy sources, such as wind speed and solar radiation, is seen as a significant challenge in ensuring energy supply. This challenge can be addressed through the integration of energy conversion and storage devices, such as electrolyzers, fuel cells, and hydrogen tanks, within hybrid renewable energy systems, along with appropriate site selection [2,6,7].

Hybrid facilities are defined as multi-source electricity generation facilities. Also known as integrated power generation plants, these systems encompass multiple energy sources with the same grid connection points. Hybrid technology plants can involve the dual or multiple utilization of thermal or renewable sources. Integration of renewable sources with thermal sources is possible in these cases. However, considering the negative environmental impacts of thermal power plants in recent years, the necessity of hybrid uses for renewable sources becomes apparent. The designed hybrid systems should be more economical compared to grid electricity. Hybrid power systems have been found to exhibit higher reliability and lower production costs compared to systems using a single energy source. Moreover, the integration of multiple renewable energy sources into hybrid renewable energy systems can provide technical, economic, and environmental benefits. From an environmental perspective, reducing energy consumption and diversifying the mix of energy sources will contribute to positive impacts on climate change and the reduction of greenhouse gas emissions [26].

The modeling and optimization of hybrid power systems involve the selection of energy sources, the creation of the load profile for the modeled region, and the selection of appropriate components based on local geographical conditions [27]. The integration of sources is crucial when utilizing hybrid technologies. Depending on the hybridization of sources, various outputs can be obtained, such as heating and hot water, cooling, hydrogen production, and electricity generation. In the process of energy conversion, photovoltaic panels are used for solar energy, turbines for wind energy, biomass boilers for biomass energy, and gasifiers for biogas. Through these devices, energy is converted into electricity via turbines. Systems based on solar, wind, biomass, and geothermal sources can offer advantages in terms of technical, environmental, and economic aspects through various hybrid combinations [28].

The focus of studies on hybrid renewable energy is predominantly centered on high profitability and system reliability. Therefore, there is a lack of interdisciplinary methodologies that consider various sustainability aspects necessary for effective planning of hybrid renewable energy systems. Solar and wind combinations are more prevalent in the studies. The most extensive hybrid combination was carried out by Ullah et al. [29], which included biomass, solar, wind, and hydro-electric energy quadruple. In studies involving biomass energy, it is evident that the hybrid combination is predominantly made with solar energy.

Urban and regional integrated energy planning is important for defining post-sustainable development and carbon reduction transition strategies [30]. Cities are facing increasing pressure to reduce carbon emissions through the adoption of low-carbon development strategies. The integration of renewable energy sources is among the key strategies that can accelerate the transition to a green economy and address climate change [31]. The development of renewable energy sources is seen as a significant opportunity to achieve sustainability goals and objectives. A renewable energy-based energy model involves the reorganization of the city or region through the widespread use of diversified energy sources [26].

The use of renewable energy projects in urban planning primarily relies on the spatial analysis of regional and local energy potentials. The relationship between urban planning and renewable energy is characterized by two fundamental dimensions: site selection and urban strategies. Site selection involves the simultaneous consideration of planning processes and the selection of renewable energy sources. It entails the careful analysis of regional characteristics, resource possibilities, and the identification of suitable locations for renewable energy projects that ensure the sustainability of natural values without compromising the historical natural fabric of the urban system. In this context, it is essential to extend governance and practices related to energy planning from the central stage to the lowest level of the planning system [32].

2.2. Site selection indicators

The determination of suitable areas for the placement of renewable energy facilities relies on various criteria encompassing environmental, economic, socio-political, climatological, and spatial indicators. These criteria may vary based on the existing literature, the objectives and goals of the study, the characteristics of the examined region, and the accessibility of geographically referenced databases [33].

The selection of a suitable location for a solar energy power plant (SEP) is a process that involves multiple assessment criteria, considering economic, environmental, and social impacts. In the literature, potential and suitability assessments for SEP often consider indicators such as solar radiation value, duration of sunny hours, number of rainy days, land use, protected areas, geological and geomorphological conditions, slope, aspect, elevation, settlement areas, roads, and transmission lines. To enhance the reliability and optimize the performance efficiency of large-scale SEPs, these criteria should be integrated into the site evaluation process [27].

Accurate definition of spatial criteria is necessary for determining suitable locations for SEPs. The primary indicator for identifying suitable areas for SEPs is the presence of high levels of solar radiation [34]. Although there are similarities in the methods used in site selection studies for solar energy in the literature, there are differences in the selection criteria. The most commonly used criteria in these studies are factors that affect the feasibility and cost of power plants, such as slope and solar radiation as a meteorological parameter related to climatic conditions [35–39]. Economic indicators such as distance to transformers and transmission lines, distance from settlement areas, aspect, and land use are also frequently considered [40–42]. Generally, in studies where economic criteria are emphasized, environmental-focused criteria such as distance to protected areas, community welfare and participation, and preservation of flora and fauna balance are less commonly used.

The identification and selection of suitable areas for establishing wind energy power plants (WEPs) depend on various factors such as environmental, technical, geographical, and theoretical criteria. In order to ensure that the environment and the local population are not adversely affected, criteria must be defined when determining compatible areas for harnessing wind energy. Multiple methods such as Multiple Criteria Decision Making (MCDM) and GIS are commonly used for WEP site selection. While the criteria for WEP site selection may vary across studies, factors such as slope, distance from settlement areas, wind speed, distance from transmission lines, and distance from protected areas have been the most used indicators. The primary indicator for potential area identification and site selection for WEPs is wind speed. Investing in areas with low wind speeds would not be a rational approach [43–49]. The criterion of slope is generally considered an important economic factor in the site selection process [50–54]. The criterion of distance from transmission lines, another economic indicator, has been used in many studies and is important in terms of WEPs being close to existing transmission lines and not requiring additional lines [55,56]. The parameter of distance from settlement areas is a criterion that needs to be considered due to turbine safety, noise, and visual impact [57–60].

Biomass energy utilization is a renewable energy source that has gained special attention in recent years due to the depletion of traditional fossil fuels. With concerns about global warming, there is a significant global interest in the increased use of renewable energy sources, including carbon-neutral biomass fuels.

The quantity and availability of feedstock sources used in biomass potential are important variables. In the concept evaluated as theoretical and economic potential, it is necessary to determine the sustainable potential considering social and environmental aspects. In the theoretical potential, the amount of biomass is determined based on cultivated areas, while in the economic potential, evaluations are made based on factors such as infrastructure and capacity. The environmental and political demand for more efficient use of renewable energy and biomass increases the need to use different types of biomass. Biomass potential analyses are conducted in agricultural waste, animal waste, and urban waste areas with the aim of finding more sustainable feedstock for renewable energy production [61–63].

Agricultural and animal waste, which are the main sources of biomass energy production, vary depending on the location. Therefore, considering the fact that supply and demand can be dispersed, the site selection of biomass energy systems becomes more important. Choosing a location close to the production facilities is crucial for biomass energy production. When agricultural resources are considered as feedstock for biomass production, it is important to consider the sustainability of the entire agricultural production chain [21].

In recent years, sustainable development, environment and ecology, CO_2 emissions, and energy crops concepts have been more widely addressed in biomass energy studies. The number of studies focusing on site selection for biomass energy systems is relatively smaller compared to solar and wind energies. Key concepts in site selection studies include GIS, fuzzy AHP, forest-based biomass, multi-criteria decision-making methods, and biogas. It can be observed that the focus of the studies has shifted towards economic expectations. The criteria considered in these studies include biomass potential involving urban waste quantity, agricultural production intensity, and animal production intensity [64–67], altitude, slope, distance to fault lines, landslide risk, distance from residential areas, distance from power transmission lines and transformer stations, social acceptance and impact, land use, soil structure, distance to raw materials, cost of raw materials, distance to protected areas (environmental conservation areas, national parks, heritage sites, areas protected for natural and ecological values, military areas, areas of biological importance, animal conservation areas, forest areas, absolute agricultural areas, wildlife areas), distance to water bodies (permanent water bodies, rivers, lakes, seas, etc.), distance to roads, minimum land requirement, visual impact, and odor [68–70].

3. Methodology

3.1. Study area

Within the scope of the study, Karatay district in Konya province, which is located in the TR52 region according to the Statistical Regions Classification (NUTS 2), has been selected. Karatay district has been chosen due to its high solar, wind, and biomass hybrid renewable energy potential. It is one of the leading districts in the region in terms of key criteria for determining biomass energy potential, such as agricultural and animal waste quantity, solar radiation value for solar energy systems, and average wind speed for wind energy systems. Particularly, the district has the highest biomass energy potential within the region, and it ranks high in the evaluation parameters for wind and solar energy systems, which demonstrates its hybrid renewable energy potential [71]. Karatay is one of the central districts of Konya province, along with Meram and Selçuklu. Karatay district was officially established on March 27, 1989. Prior to Law No. 6360, the district had 4 municipalities, 25 villages, and 38 hamlets, which were transformed into 80 neighborhoods with the enactment of the law. Out of these neighborhoods, 48 are classified as urban, while 32 are rural. The district is bordered by Aksaray province and Karapınar district to the east, Çumra and Meram districts to the south, and Selçuklu and Altınekin districts to the northwest (Fig. 1).

3.2. Definition of the site selection model

In the process of planning, maps are an important reference and a platform for reflecting physical decisions in the relationship between settlements and physical space. In this process, there are various and numerous data layers that facilitate the creation of maps. Integrating, combining, and preparing data for dynamic querying is crucial in

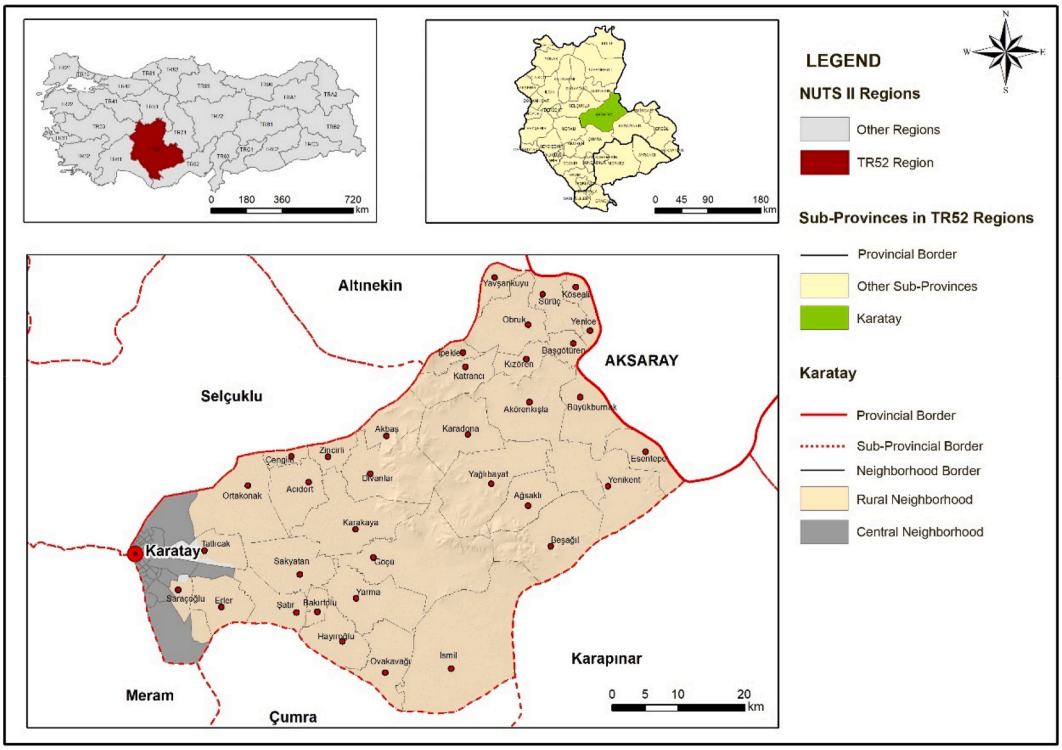


Fig. 1. Location map of Karatay district.

processes that involve economic, social, and physical parameters related to space. Comprehensive analyses, establishing relationships between data, and ensuring the smooth progress of processes require the use of programs. Programs are necessary not only for analysis and evaluation stages but also for planning. Computer-based software, known as GIS, plays a significant role in urban planning as it provides essential information, tools, and evaluation capabilities in preparation and decision-making processes. GIS can bring together different types of data and perform spatial representation through maps. Spatial querying, mapping, spatial analysis, and modeling, from the analysis stage to the planning process, can be spatially expressed through GIS [72,73].

The process of site selection primarily focuses on land use and decisions in the physical space, involving the Environmental Planning and Master Development Plan. Spatial datasets were used in the selected district determined through potential area selection. Accordingly, a modeling approach was created by assigning numerical indicators to parameters. This modeling approach adopts a decision-making approach that minimizes environmental damage and follows the fuzzy logic theory based on quantitative and qualitative indicators.

The increasing complexity and the number of decision-makers make it difficult to identify alternatives that maximize all decision criteria. Energy-related evaluations may include components that involve both quantitative and qualitative factors. Moreover, in terms of scope, it encompasses technical, economic, and geographical areas with boundaries that cannot be clearly defined, along with stakeholders, each with their own demands and needs. Considering this broad and complex structure, fuzzy logic-based methods can be highly beneficial in the evaluation stage [74].

The article determines spatial suitability indices using the ArcGIS software, one of the GIS application tools, in line with the fuzzy logic approach to perform the site selection of hybrid renewable energy facilities. The study involves a four-stage process. The first stage in defining the model involves determining indicators for each of the solar, wind, and biomass energy plants and creating maps for these indicators in ArcGIS software. One of the primary objectives of the study is to consider cumulative impact, and therefore, the indicator sets were designed to focus on this evaluation. For site selection of BEP-SEP hybrid systems, parameters such as agricultural (plant) waste quantity, animal waste quantity, distance to raw materials, minimum area requirement, solar radiation value, sunshine duration, number of rainy days, aspect, land use, distance to protected areas, geologically hazardous areas, distance to settlements, distance to roads, distance to water surfaces, distance to energy transmission lines, slope, consistency with legal regulations, and impact on local residents should be considered. For BEP-WEP hybrid systems, parameters such as agricultural (plant) waste quantity, animal waste quantity, distance to raw materials, minimum area requirement, average wind speed, wind power density, number of windy days, distance to bird migration routes, distance to sensitive areas, altitude, land use, distance to protected areas, geologically hazardous areas, distance to settlements, distance to roads, distance to water surfaces, distance to energy transmission lines, slope, consistency with legal regulations, and impact on local residents should be taken into account. In the case of BEP-SEP-WEP triple hybrid combinations, all parameters should be evaluated.

The second stage involves conducting fuzzy membership operations for each criterion in the ArcGIS software. Operations are carried out using the fuzzy membership layer located in the ArcGIS spatial analysis section. In order to perform fuzzy membership operations in a ArcGIS, it is necessary to initially convert base maps defined in line, vector, and polygon formats into raster data. During the conversion to raster data, relevant parameters are selected, and euclidean distance analysis or raster conversion methods are applied to convert the parameters into raster data format. In the initial stage, fuzzy membership degrees of the parameters in raster data format are determined. Fuzzy memberships of parameters related to BEP, SEP, and WEP systems are defined by selecting suitable types from linear, small, large, MS small, MS large, and Gaussian membership types available in ArcGIS ArcMap 10.8 interface (Table 1).

After determining the function type, reclassified maps showing fuzzy membership values ranging from zero to one have been generated. The third stage in the application of fuzzy logic involves overlaying maps using different operators. In ArcGIS, by selecting the 'fuzzy overlay'

Table 1
Fuzzy membership functions for parameters [75].

Function Type	Definition	Formula
Linear	Linearly increasing or decreasing evaluations are utilized	$\mu(x) = 0 : x < \min$ $\mu(x) = 1 : x \geq \max$ $\mu(x) = \frac{(x - min)}{(max - \min)}$
Increasing Sigmoid (Large)	It signifies the membership degree's sigmoidal transition according to the increase in value.	$\mu(x) = \frac{1}{1 + \frac{x^{-f_1}}{f_2}}$ f_1: spread value f_2: midpoint
Decreasing Sigmoid (Small)	It signifies the sigmoidal decrease in the membership degree according to the increase in value.	$\mu(x) = \frac{1}{1 + \frac{x^{f_1}}{f_2}}$ f_1: spread value f_2: midpoint
MS Large	It signifies the sigmoidal increase defined by the mean and standard deviation.	$\mu(x) = \frac{bs}{x - am + bs}$ $x \geq am; \mu(x) = 0$ m: mean s: standard deviation a: multiplier of the mean b: multiplier of the standard deviation
MS Small	It expresses the sigmoidal decrease defined by the mean and standard deviation.	$\mu(x) = \frac{bs}{x - am + bs}$ $x \geq am; \mu(x) = 1$ m: mean s: standard deviation a: multiplier of the mean b: multiplier of the standard deviation
Gaussian	It is used in evaluations where the membership degree is highest at an intermediate value.	$\mu(x) = e^{-f_1} \times (x\text{-}f_2)^2$ f_1: spread value f_2: midpoint

from the 'spatial analysis' tools, overlay operations are first performed for each renewable energy source. To complete this step, one of the fuzzy overlay operators needs to be selected. Through the chosen operator, the fuzzy overlay operation is performed, and the appropriate areas are mapped in ArcGIS's ArcMap 10.8 interface. The fuzzy overlay tool allows for probabilistic analysis of an object belonging to multiple clusters in a multicriteria overlay analysis. Fuzzy overlay determines both the membership of the object in different clusters and analyzes the relationships between multiple cluster memberships. The overlay type lists the existing methods to combine data-driven fuzzy set theory analysis. Each method enables the exploration of the membership of each cell for various input criteria. Available operators for fuzzy overlay include fuzzy AND, OR, PRODUCT, SUM, and GAMMA. These approaches provide different aspects of membership for each cell regarding multiple input criteria [76]. In this stage, fuzzy overlay analysis is performed for each source of WEP, SEP, and BEP by assigning different values to the GAMMA operator ($\gamma = 0.25$, $\gamma = 0.50$, $\gamma = 0.75$, $\gamma = 0.90$). The rationale for selecting the GAMMA operator lies in its ability to produce more results in the suitability index with different values and to present the results of other operators based on the assigned values [77]. For energy sources, the index values for each source are ranked between [0–1] according to the formulas of the operators. Equation (1) is used for evaluation based on the GAMMA operator. The variables in Equation (1) represent.

$$\mu_\gamma = \left(\prod_{i=1}^{n} \mu_i\right)^{1-\gamma} \left(1 - \prod_{i=1}^{n} (1 - \mu_i)\right)^{\gamma} \quad (1)$$

μ_γ: The suitability index value at the respective gamma value according to the fuzzy logic approach,
μ_i: The membership value of the *i*-th map layer
n: The number of maps associated with the parameters,
γ: The gamma value, denoted by γ, represents values ranging between [0,1].

The final stage involves the hybrid fuzzy overlay analysis, which includes determining suitable areas for hybrid utilization. In the second stage, fuzzy overlay analyses were conducted for wind, solar, and biomass energy sources, and the results were combined based on the hybrid type. By diversifying the energy source combinations (BEP-SEP, BEP-WEP, BEP-SEP-WEP), hybrid areas were identified using the GAMMA operator ($\gamma = 0.90$) (Fig. 2). The fuzzy overlay analysis resulted in index values ranging between [0,1], where a maximum value close to or equal to 1 indicates high spatial suitability and suitability for site selection.

4. Findings

The identification of fuzzy membership operations involves the first step in the implementation of the fuzzy logic. In the study, the parameters determined exhibit both common and varying ranges for BEP, WEP, and SEP. Distance to protected areas (national parks, nature reserves, natural heritage sites, archaeological sites, wildlife conservation areas, etc.), areas with geological constraints (fault lines, landslide-prone areas), slope, land use, distance to settlements, distance to water surfaces, distance to roads, distance to transmission lines, consistency with legal regulations, and local population indicators are common assessment parameters for all three renewable energy sources. Solar radiation value, sunshine hours, aspect parameters are specific to SEP, average wind speed, wind power density, distance to bird migration routes, distance to airports are specific to WEP, and proximity to raw materials, agricultural potential, animal production potential parameters are considered only for BEP. The table below (Table 2) presents the determination of membership degrees and conditions for the parameters used in the study. The minimum, maximum, average, and spread indicators are used in defining the value range based on the function type. For linearly increasing, decreasing, or directly linear function types, the minimum and maximum indicators are used. For function types such as sigmoidal decrease, increase and Gaussian evaluations are made based on the average and spread indicators.

In this stage of the study, maps representing the current situation were transformed according to membership degrees. In these transformation processes, the values representing the potential in terms of plant waste quantity, animal waste quantity, solar radiation value, average wind speed, and wind power density indicate the highest value within the study area. Therefore, the expression of the maximum value for these indicators may vary depending on the differentiation of the study areas.

In Karatay district, the areas with the highest membership degree in terms of solar radiation value are located within the boundaries of İsmil, Göçü, and Yarma neighborhoods, while in terms of sunshine duration, neighborhoods such as İsmil, Ovakavağı, Hayrolu, Bakırtolu, and Yarma located in the southern part have higher potential.

Regarding average wind speed, wind speeds ranging between 5 and 6 m/s are more concentrated in larger areas of the district, and in terms of the indicator, the areas with the highest values are observed along the boundaries of Beşağıl, Göçü, Yağlıbayat, Obruk, Sakyatan, and Göçü neighborhoods. Wind power density values in the district range from 78 to 846 W/m^2. According to the membership function, the places with the maximum degree of suitability are located along the boundaries of İpekler, Katrancı, Akbaş, Karadona, Divanlar, Yağlıbayat, Göçü, and Beşağıl neighborhoods.

In Karatay district, the neighborhoods with the highest agricultural production areas are İsmil, Akörenkışla, and Beşağıl, followed by Yarma, Karakaya, Yağlıbayat, Obruk, Sakyatan, and Göçü neighborhoods. As a result of the fuzzy membership operation, the highest suitability values are observed in İsmil and Akörenkışla neighborhoods, while Karakaya,

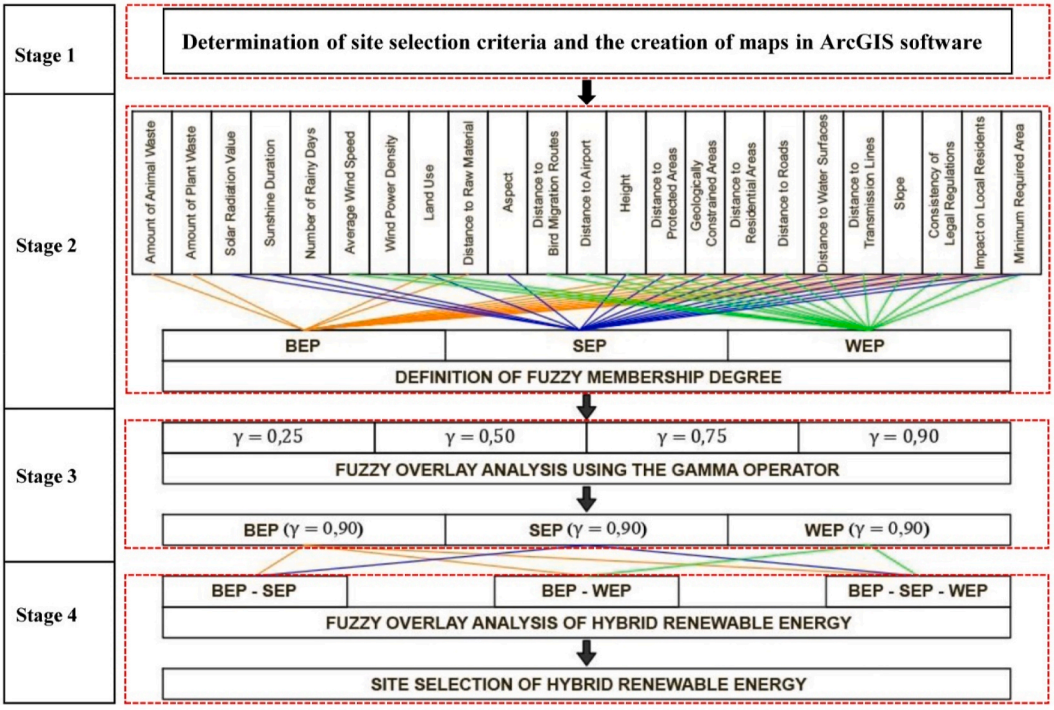


Fig. 2. Site selection model.

Yarma, Şatır, Beşağıl, and Obruk neighborhoods also have high membership values. Based on the membership degrees related to animal waste quantity, İsmil, Hayıroğlu, Göçü, and Karakaya neighborhoods have high values.

The fuzzy overlay constitutes the second stage of the study. In this context, the spatial suitability of different GAMMA values was examined by presenting standard deviation values, aiming to determine the most optimal value. Additionally, the selection of the GAMMA operator is justified by its ability to provide more diversity in suitability levels and enable comparative representation of spatial suitability. The study presented standard deviation and suitability index values of the method based on different GAMMA values of $\gamma = 0.25$, $\gamma = 0.50$, $\gamma = 0.75$, and $\gamma = 0.90$. This allowed for comparisons to be made among the suitability index values. As the GAMMA value increases, the suitability index also increases, reaching an optimal level at the 0.90 level. Consequently, it was concluded that it would be more accurate to make the final site selections based on the $\gamma = 0.90$, which covers a larger area and exhibits higher suitability index values. An essential indicator in terms of the results of overlay analyses is that the index value should be 1 or close to 1. When comparing index values for different sources within the same area, it is more appropriate to select the source with the value closest to 1. Furthermore, an index value below 0.50 is considered low in terms of spatial suitability. For the evaluations related to BEP, the suitability index reaches a maximum level of 0.99 for $\gamma = 0.25$ and $\gamma = 0.50$, while it reaches the maximum level of 1.00 for $\gamma = 0.75$ and $\gamma = 0.90$. Standard deviation and suitability index values vary depending on the increase in the GAMMA value. When the value is 0.90, the standard deviation reaches its lowest value. Among different GAMMA values, İsmil neighborhood has the highest suitability index. When the GAMMA value is 0.90, Karakaya, Göçü, Ovakavağı, and Hayıroğlu neighborhoods also exhibit areas with good suitability index values (Fig. 3).

In the evaluations for SEP, the suitability index reaches a maximum of 0.56 for $\gamma = 0.25$, 0.67 for $\gamma = 0.50$, 0.82 for $\gamma = 0.75$, and up to 0.92 for $\gamma = 0.90$. As the GAMMA value increases, the standard deviation decreases, and the suitability index increases. Starting from lower GAMMA values, the areas with the highest suitability index are located within the boundaries of İsmil, Ovakavağı, and Şatır neighborhoods, while at the maximum GAMMA value, Karakaya and Sakyatan neighborhoods also have suitable areas (Fig. 4).

In the evaluations for WEP, the suitability index reaches a maximum of 0.19 for $\gamma = 0.25$, 0.33 for $\gamma = 0.50$, 0.57 for $\gamma = 0.75$, and up to 0.87 for $\gamma = 0.90$. As the GAMMA value increases, the standard deviation decreases, and the suitability index increases. When the GAMMA value is 0.90, the standard deviation reaches its lowest value. Starting from lower GAMMA values, the areas with the highest index value are located within the boundaries of Ortakonak and Başgötüren neighborhoods. However, the results indicate that the suitability index for RES is lower compared to BEP and SEP. In cases where a single or dual investment is considered, an approach based on BEP and SEP can be more beneficial (Fig. 5).

When considering that the study focuses on hybrid sources involving biomass, the suitability of location selections for BEP-SEP, BEP-WEP, and BEP-SEP-WEP in terms of source diversity was determined based on $\gamma = 0.90$. Generally, in single location selections, it has been observed that the suitability area index and the amount of suitable area are higher based on $\gamma = 0.90$. In BEP-SEP hybrid location selections, the suitability index ranges from 0.00 to 0.99. In location selections based on BEP-SEP, Karakaya, Göçü, İsmil, Ovakavağı, Şatır, and Hayıroğlu neighborhoods have higher spatial suitability index values (Fig. 6). In BEP-WEP-based hybrid location selections, the suitability index ranges from 0.00 to 0.95. In the BEP-WEP source diversity, there are areas with a high degree of suitability index within the boundaries of İsmil, Göçü, Karakaya, Sakyatan, Hayıroğlu, Başgötüren, Yenice, Obruk, and Sürüç neighborhoods (Fig. 7). In BEP-SEP-WEP-based hybrid location selections, the suitability index ranges from 0.00 to 0.94. In BEP-SEP-WEP hybrid location selections, there are areas with suitability within the boundaries of İsmil, Göçü, Karakaya, Hayıroğlu, Satır, Başgötüren, Yenice, Obruk, and Sürüç neighborhoods (Fig. 8). Results indicate that the high suitability indexes of hybrid utilization suggest the possibility of location selections by ensuring source diversity. Overall, the overlay analysis results indicate the possibility of suitable areas in Karakaya, İsmil, and Ovakavağı neighborhoods in hybrid situations.

Table 2
Definition of membership functions for the area in the scope of the study.

Parameter		Fuzzy Membership Indicators				Fuzzy Membership Function Type
		maximum	minimum	Midpoint	Spread value	
Amount of plant waste (ton/year)		170000	0	-	-	Linear (increasing)
Amount of animal waste (ton/year)		50000	0	-	-	Linear (increasing)
Distance to raw material (meter)		-	-	3000	5	Decreasing Sigmoid (Small)
Solar radiation value (kWh/m^2-year)		1836	1600			Linear (increasing)
Sunshine duration (hours-year)		2743	2500			Linear (increasing)
Aspect (degree)		-	-	180	0,1	Gaussian
Average wind speed (m/s)		8,7	4	-	-	Linear (increasing)
Wind power density (W/m^2)		846	200	-	-	Linear (increasing)
Distance to bird migration routes (meter)		1000	500	-	-	Linear (increasing)
Distance to airports (meter)		2500	2000	-	-	Linear (increasing)
Elevation (meter)		0	2000	-	-	Linear (decreasing)
Land Use	Distance to agricultural areas (meter)	1000	500	-	-	Linear (increasing)
	Distance to forest areas (meter)					
	Distance to pasture areas (meter)					
	Distance to industrial areas (meter)					
	Distance to military areas (meter)					
Distance to protected areas (meter)		1000	500	-	-	Linear (increasing)
Geologically hazardous areas	Fault line distance (meter)	1000	500	-	-	Linear (increasing)
	Landslide risk areas distance (meter)	1000	500	-	-	
Distance to residential areas (meter)*		2000	1000	-	-	Linear (increasing)
Distance to roads (kilometer)**		0,5	10	-	-	Linear (decreasing)
Distance to water surfaces (meter)		1000	500	-	-	Linear (increasing)
Distance to energy transmission lines (kilometer)		0	10	-	-	Linear (decreasing)
Slope (%)		20	30	-	-	Linear (decreasing)
Minimum area requirement (hectare)		2	1	-	-	Linear (increasing)
Consistency with legal regulations		High	Medium	-	-	Linear (increasing)
İmpact on local residents	Awareness	High	Medium	-	-	Linear (increasing)
	Contribution					
	Validation					
	Employment					
	Economic development					
	These parameters are valid only for biomass energy plants and hybrid combinations (BEP).					
	These parameters are valid only for solar energy plants and hybrid combinations (SEP).					
	These parameters are valid only for wind energy plants and hybrid combinations (WEP).					
	Parameters common to Solar and Wind Energy Plants.					
	Parameters common to Solar, Wind, and Biomass Energy Plants					

*For SEP, with variations, a minimum value of 500 meters and a maximum value of 1000 meters have been considered.
** The criteria listed in the table are indicators for SEP and WEP. For BEP, in the linear decreasing membership, a maximum distance of 0.5 kilometers and a minimum distance of 1 kilometer have been used for evaluation.

5. Results and discussion

5.1. Spatial planning and hybrid renewable energy approach

There are some disadvantages associated with renewable energy sources. These include the intermittency of production and significant fluctuations in energy supply [78,79], an increase in environmental damage due to processes that prioritize potential in site selections [23], a high level of subjectivity in assessment methods for site selections, with a greater emphasis on the technical and economic aspects [80]. These drawbacks have led to various efforts in search of solutions. Particularly, hybrid renewable energy approaches addressing the fundamental issue of supply have come to the forefront, while there are various approaches focusing on spatial issues through potential determination and site selection.

Since site selection processes are oriented towards space, the issue of planning and implementation methods also comes into consideration. Planning approaches, which have undergone various stages up to the present day, have progressed towards spatial planning that integrates instrumental and communicative rationality. Especially, evaluation methods based on multiple criteria have been viewed as a significant tool within planning. In today's spatial planning system, instrumental rationality and communicative rationality represent an important approach [81]. It is necessary to integrate approaches that bring together these two concepts into the planning system. Evaluating GIS together, in terms of feasibility, is important for ensuring both communicative rationality through multi-criteria evaluation methods and instrumental rationality. While GIS and MCDA methods have been used in many studies, the application of spatial modeling approach in spatial planning processes will enhance the objectivity dimension in terms of establishing the relationship with conceptual planning. This is because approaching site selections through a single parameter, a

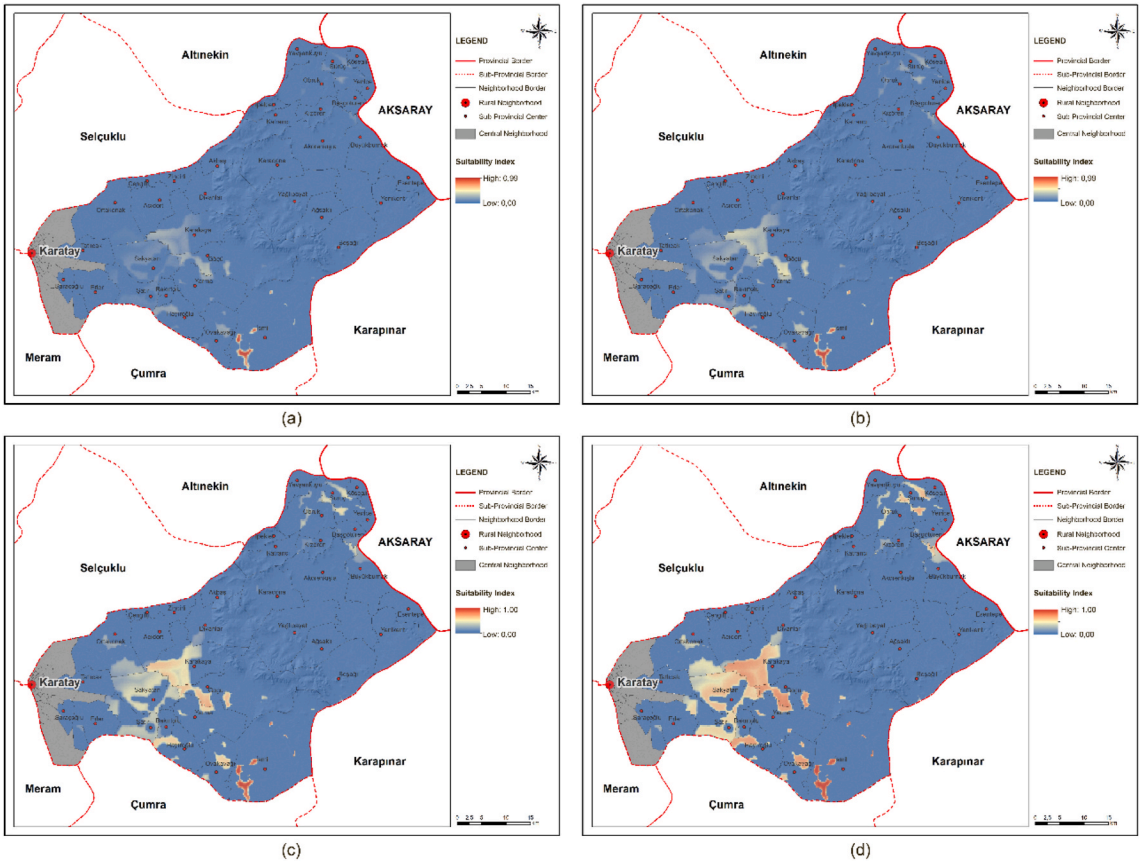


Fig. 3. Suitability index for BEP (a) $\gamma = 0.25$, (b) $\gamma = 0.50$, (c) $\gamma = 0.75$, (d) $\gamma = 0.90$.

profit-related evaluator, or approaches where subjectivity is prominent can lead to an increase in environmental degradation. The fuzzy logic-GIS combination ensures that the degree of subjectivity is minimized in establishing the relationship between the cumulative effect of evaluation parameters and the language of planning, which is conveyed through maps.

Turkey is one of the leading countries in terms of renewable energy potential and renewable energy source diversity [1]. This research primarily focuses on hybrid source diversity based on biomass energy. Various reasons are important in adopting source diversity. The prominence of solar and wind energy sources in renewable energy sources, both in terms of being more environmentally friendly and being preferred in terms of research and development structure and application dimensions, highlights their significance. However, in recent years, the intermittent and variable nature of solar and wind-based renewable energy sources has raised concerns about the sustainability of energy production. As a solution to this issue, solar-wind hybrid renewable structures [8,9,11,12,15] have been proposed. However, relying solely on these two sources with similar climatological conditions may not provide a permanent solution to the intermittent and variable nature of energy production. In addressing this issue, a hybrid approach incorporating biomass energy sources can provide a more balanced and stable system, minimizing the intermittent nature of energy production.

Studies conducted within the scope of hybrid renewable energy, such as biomass-solar energy, biomass-wind energy, and biomass-solar-wind energy, primarily focus on the technical and economic characteristics of the system. In general, the results indicate that hybrid combinations based on biomass support the system technically and economically [9, 82–87]. These findings suggest an increasing need for spatially focused site selection studies for hybrid combinations in the context of hybrid renewable energy.

The majority of site selections for renewable energy sources are observed in rural areas. Considering the high agricultural and livestock activities in rural areas (at least the presence of favorable conditions), the potential of biomass as a source becomes apparent. In this context, biomass energy provides an important advantage as a renewable energy source that can balance the intermittent supply, be stored, and offer flexibility [23–25]. Additionally, considering the potential of biomass in rural areas and the possibility of integrating marginal agricultural lands into the system for energy crops, biomass-based hybrid site selections can be a significant alternative. Incentives and technological advancements related to biomass resources can further enhance the level of productivity. Particularly, utilizing marginal lands for energy crops and employing advanced agricultural techniques can enable countries to increase their hybrid power potential [88]. Marginal agricultural lands are typically defined as areas that are difficult to cultivate and have low economic value. However, when development for energy crops is supported in such areas, a significant potential can be created.

Spatial planning reveals the hierarchy between various scales, ranging from the national level to the neighborhood level. This hierarchical structure in the planning system in Turkey extends from Strategic Spatial Planning, Environmental Master Plan, Master Development Plan, to Implementation Development Plan [89]. Considering the hierarchy and guiding principle between scales will contribute to planned development from a spatial perspective. One of the significant deficiencies in energy-related planning and approaches is the lack of systematic approaches that consider the energy-environment relationship and progress the process from the highest planning scale to the lowest planning scale. Existing studies in the literature tend to focus on rural areas as a general concept rather than delving into detailed aspects such as neighborhoods/villages. This deficiency necessitates the development of an approach and methodology that encompasses all criteria, including environmental and social aspects, in the energy planning process.

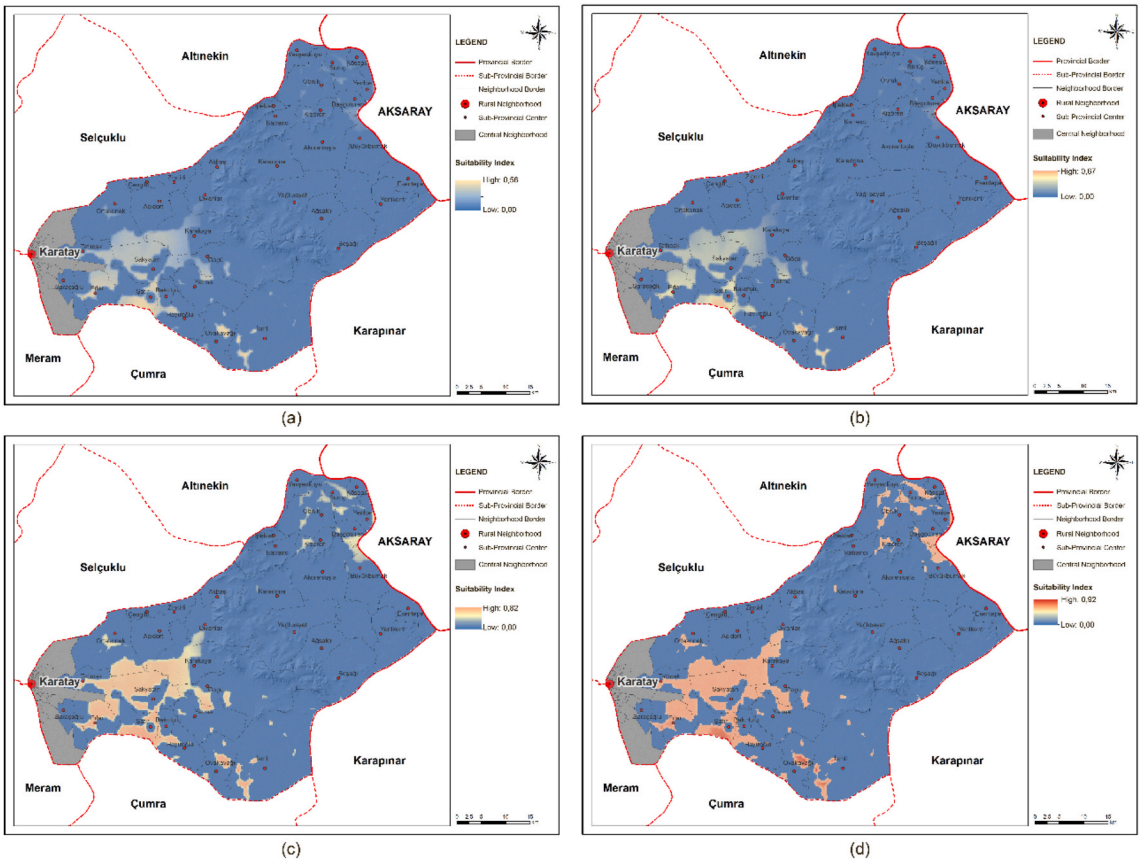


Fig. 4. Suitability index for SEP (a) $\gamma = 0.25$, (b) $\gamma = 0.50$, (c) $\gamma = 0.75$, (d) $\gamma = 0.90$.

5.2. Site selection and evaluation methods

Studies on renewable energy site selection primarily focus on multi-criteria decision-making and Geographic Information Systems (GIS). Specifically, the process advances through weighting and overlaying maps, particularly utilizing the Analytic Hierarchy Process (AHP) method [90]. Various software tools such as HOMER, MATLAB, HYBRID2, and HOGA are used to support the design of hybrid systems. These types of software tools primarily assist in technical and economic analyses [91]. In spatial site selection studies, the ArcGIS software, one of the application tools of GIS, is frequently employed. Through ArcGIS, fuzzy models applied to weighted linear combination [92], ordered weighted averaging, weighted sum [93], and Multiple Criteria Decision Analysis (MCDA) methods are used for overlay analyses [94]. However, assigning relative importance weights to criteria increases subjectivity in site selection. When criteria set accounting for cumulative impact in a site selection process is established, assigning each criterion the same level of significance will lead to more objective and sustainable decision-making.

Establishing the fuzzy logic-GIS relationship in site selections for renewable energy facilities is a crucial tool in spatial decision-making processes. Additionally, the development of site selection models for hybrid renewable energy facilities through operators based on fuzzy logic will enhance objectivity in spatial decision-making [42]. In spatial planning in Turkey, the emphasis is mostly on the site selection evaluation known as the classical logic approach. In this approach, the suitability of the site selection indicator is expressed with the digits 0 or 1, and a definite definition is made within strict and clear boundaries based on whether it is suitable or not. However, the differing significances assigned to variables in indicator sets, along with the presence of multiple evaluators and stakeholders, make it challenging to express boundaries sharply. In other words, in such cases, a result dominated by the prevailing view, far from consensus, emerges. With this study, it is indicated that, unlike the classical logic approach in planning, there is a necessity for an approach, referred to as fuzzy logic, that can consider all aspects in the decision-making process, and an applied study has been conducted. In terms of demonstrating diversity and integrating all processes into the system, the implementation tools for the fuzzy logic method should also be taken into consideration in integrating it into the planning system in Turkey. The ArcGIS software, one of the application tools of GIS, is widely used in institutions and organizations in the planning system in Turkey. Additionally, the recent process of defining fuzzy logic operators in ArcGIS software has become feasible.

Within the scope of the study, the fuzzy logic approach with the GAMMA operator was adopted for overlay analysis. It has been stated that the value of 0 or 1 is not suitable for the method in GAMMA assessments, and the most appropriate value for γ is 0.90 [77,95]. In this study, evaluations were conducted with γ values of 0.25, 0.50, 0.75, and 0.90, and it was determined that the γ value of 0.90 produced the most suitable result in terms of standard deviation values and spatial quantities. Therefore, a site selection study was conducted based on this value axis. By enhancing the rotation operations favoring a greater emphasis on renewable energy sources due to their dominant characteristics, the GAMMA operator produced a result in site selection that prioritizes hybrid uses based on biomass. This result proves that the GAMMA operator demonstrates prioritization by considering the highest suitability index as the main source and increasing the values of individual source types in resource diversity. Thus, when the method is used for both individual and hybrid uses, it contributes to determining which one should be selected based on the suitability index value. Within this scope, it was observed that the suitability index values increase when the SEP and WEP suitability index form a hybrid combination with, which has the highest suitability index in the area. In the evaluations of the Karatay district, while the highest suitability index for BEP was

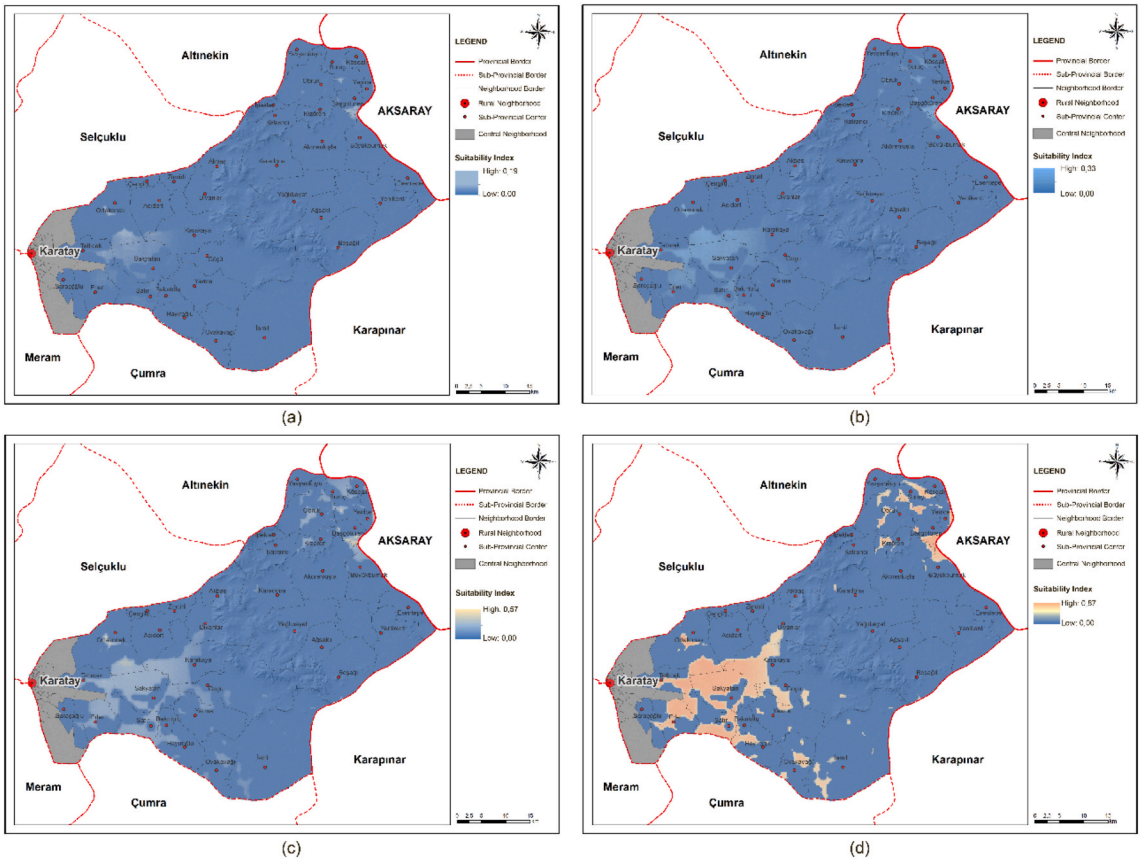


Fig. 5. Suitability index for WEP (a) $\gamma = 0.25$, (b) $\gamma = 0.50$, (c) $\gamma = 0.75$, (d) $\gamma = 0.90$.

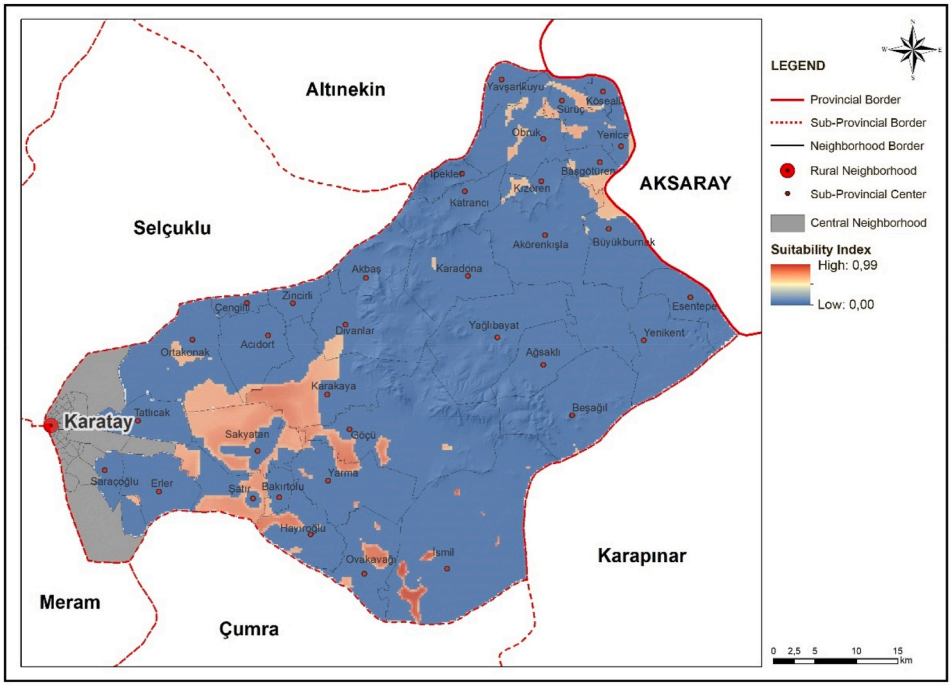


Fig. 6. Suitability index for BEP-SEP hybrid utilization based on $\gamma = 0.90$.

observed in individual uses, the values of SEP and WEP also increased in hybrid use. Therefore, the rational decision of hybrid use is supported by the GAMMA operator. Prominent locations in the Karatay district, especially within the Ismil neighborhood, exhibit a high degree of suitability index for SEP and BEP. The fact that the area with the highest suitability index for BEP in individual use also demonstrates a high suitability index in the BEP-SEP hybrid use indicates that the most suitable hybrid use in this area could be BES-SEP. Hybrid systems of

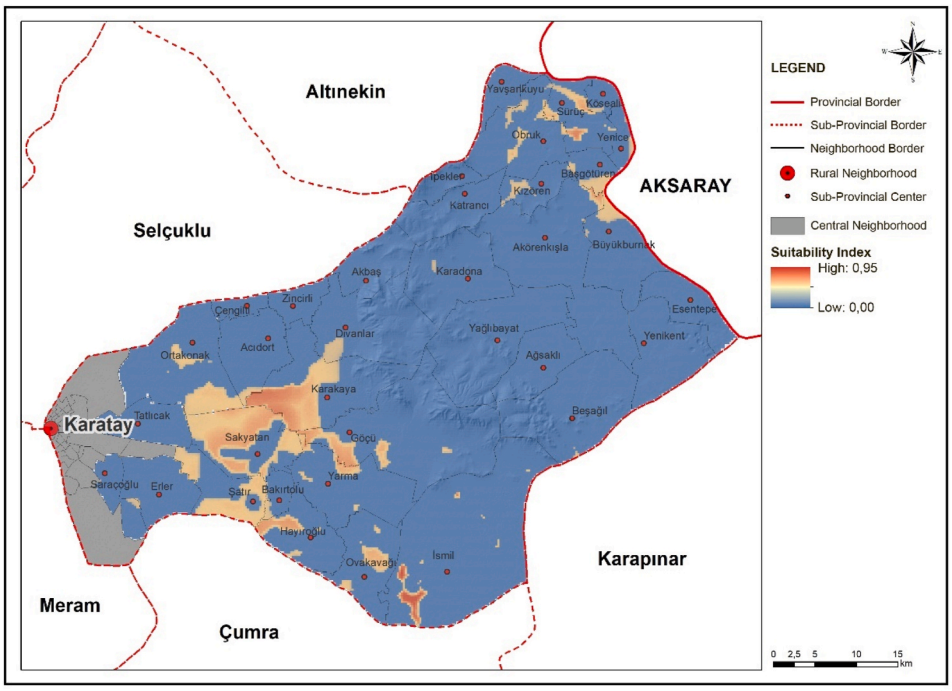


Fig. 7. Suitability index for BEP-WEP hybrid utilization based on $\gamma = 0.90$.

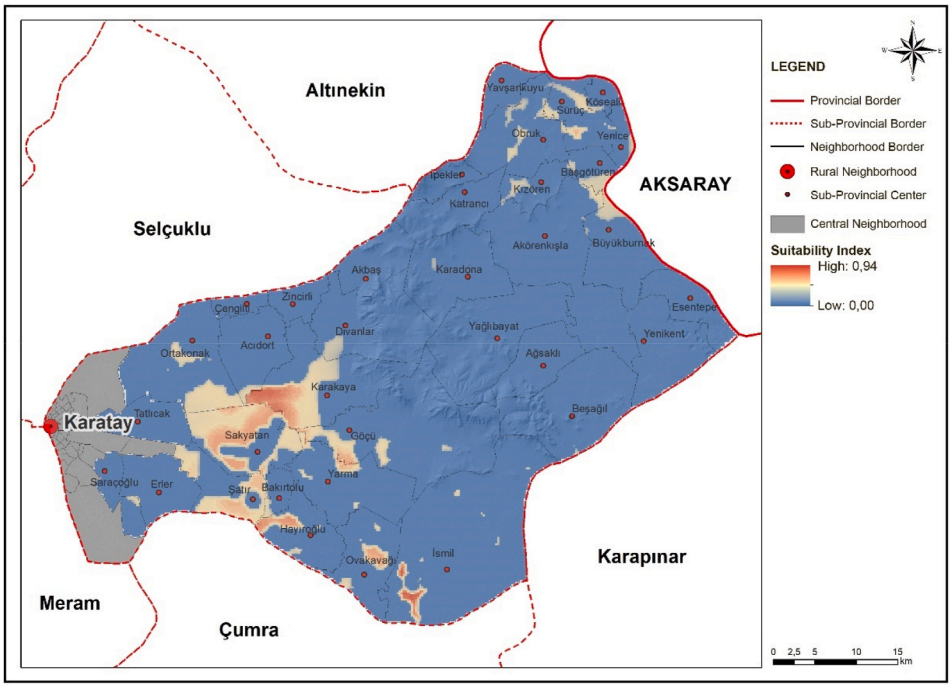


Fig. 8. Suitability index for BEP-SEP-WEP hybrid utilization based on $\gamma = 0.90$.

BEP-SEP not only provide electricity generation but also have the potential for hydrogen production, indicating their technical feasibility. Guo et al. [28], in their study analyzing the technical aspects of hybrid systems, state that the SEP-BEP combination among hybrid systems offers more advantages in terms of physical, technical, and economic aspects compared to other combinations. Based on this, it can be concluded that SEP-BEP hybrid renewable energy investments in this field will have positive effects.

When considering the current site selections for solar and biomass energy facilities within the boundaries of the Karatay district, it can be observed that a process is being carried out based on potential. The Ismil neighborhood is seen as the area with the highest suitability index for biomass potential, and the fact that the current facility is located on pasture areas indicates that the site selection of the facility was based on potential indicators. Similarly, the SEP located within the Başgötüren, Obruk, Kızören, and Karadona neighborhoods are positioned in areas where the suitability for potential is high. However, the fact that they are located within the boundaries of wetland buffer zones, internationally protected borders, and absolute agricultural areas supports the idea that the site selection process for SEP is determined based on

potential. In general, the concepts of potential and site selection must be evaluated within their own boundaries, and it is important for the process, which begins with potential determination, to progress with site selection indicators to make sustainable decisions. Because when the location selection process is carried out based solely on indicators such as the amount of plant waste and animal waste for a biomass energy system, solar radiation and sunshine duration for a solar energy system, average wind speed and wind density for a wind energy system, the cumulative effect is ignored, leading to an inevitable increase in issues where the natural environment is disrupted. In terms of the results of the existing facilities, it is necessary to adopt the understanding that potential determination and site selection process are two different concepts and form a progressive stage that feeds into each other within the process.

In the studies available in the literature, the process of determining indicators for site selection progresses by referring to previous studies. While there are studies that take into account the legislative structures of countries, a common system based on weighting criteria is considered. Two aspects are important in this regard: the process of determining criteria and the process that proceeds through weighting. The determination of criteria is shaped according to the researcher's approach. For example, when a researcher in the relevant professional discipline conducts a study based on technical and economic aspects, the criteria determined for site selection are shaped accordingly. However, when one dimension of site selection is considered while ignoring others, it can lead to discussions more focused on the sustainability of the environment rather than the sustainability of energy. Regardless of the type and nature of the indicator, all parameters have been considered equally in site selection, and accordingly, a fuzzy logic-based evaluation framework has been proposed in GIS. However, since the parameter sets are created considering the spatial planning system in Turkey, it is possible for indicator sets to vary in different countries. Within the spatial planning levels, by addressing potential determination and site selection indicators separately, a sustainable hybrid renewable energy approach can be achieved in terms of spatial planning.

6. Conclusion

The fluctuating and intermittent nature of renewable energy sources in providing energy supply has prompted an investigation of the hybrid renewable energy approach from both technical and economic perspectives. Many studies demonstrate the benefits of hybrid renewable energy sources in technical and economic aspects. However, in processes that rely solely on technical and economic indicators for the site selection of renewable energy sources, the level of environmental damage may increase. Additionally, proceeding with potential-based processes in physical space, utilizing methods with high subjectivity in site assessments, and placing greater emphasis on the economic dimension can also lead to problems. In this context, the necessity of formulating a decision strategy considering the cumulative effect in spatial site selection and adopting the hybrid renewable energy approach as a solution to the variable nature of renewable energy sources in supply has emerged. Since site selections constitute a spatial decision, the spatial planning dimension in land use is a crucial stage in terms of the sustainability of energy.

This study develops and applies a spatial model within the scope of the fuzzy logic-GIS approach using the suitability index method to demonstrate how the site selection of hybrid renewable energy facilities can be addressed in spatial planning. The proposed model is significant in its ability to incorporate multi-criteria decisions regarding land use into the planning process. It is valuable not only for visualization and data management purposes but also for evaluating selection alternatives based on spatially relevant criteria. Additionally, it proves useful for assessing and managing various spatial data by simultaneously incorporating processes into different scenarios in the decision-making process. In this context, an empirical study covering the Karatay district, which has a high potential for hybrid renewable energy, was conducted to develop a model envisioned to contribute to spatial planning consistency. The model was implemented through the GAMMA operator in ArcGIS software, utilizing GIS application tools.

The results of the study demonstrate that biomass-prioritized hybrid site selections, aimed at minimizing the intermittent nature of renewable energy sources, support solar and wind energy sources, resulting in increased diversity in site selection. The application results of the model have shown that the suitability index value for solar and wind energy increases when combined with biomass compared to their individual use. Therefore, the intermittent and fluctuating nature in energy supply can be minimized through biomass-based hybrid combinations. Particularly, by supporting marginal agricultural lands that are currently in disuse with energy crops related to biomass energy sources, the amount of energy production can be augmented. Additionally, due to the model's comprehensive consideration of all criteria, particularly prioritizing environmental conservation, the spatial sustainability of energy will also be ensured.

In the application, it was determined that the γ value of 0.90 yielded the most optimal results in terms of standard deviation and spatial diversity. Additionally, the GAMMA operator determines the highest suitability index source in fuzzy overlay analyses for individual source use, and when transitioning to hybrid source use, it evaluates the results based on the source with the highest suitability index, using weighting to reach a final decision. Therefore, considering that not every resource can have the same potential in each field, the decision based on the high suitability index in hybrid site selections also demonstrates the rationality of the model. The development of the agricultural and livestock structure of the study area indicates a high suitability index for biomass. As a result, it has been revealed that the most suitable source diversity in terms of hybrids could be the combination of BEP and SEP within the boundaries of the Ismil neighborhood in the Karatay district. In terms of the model's results, an area of approximately 584 ha with a high suitability index for BEP-SEP hybridization has been identified within the neighborhood boundaries.

In future research, potential determination and site selection processes for various hybrid renewable energies can be elucidated through establishing relationships using fuzzy logic and GIS, as applied in this study. Furthermore, in spatial site selection studies proceeding through land use, the site selection process can be delineated through the fuzzy logic-GIS relationship.

CRediT authorship contribution statement

Ahmet Sekeroglu: Conceptualization, Methodology, Software, Visualization, Writing – review & editing, Resources. **Demet Erol:** Data curation, Supervision, Writing – review & editing, Resources.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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