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# Location selection methodology for data center with renewable energy integration

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ABSTRACT

With the development of technology, dependence on the Internet has increased the demand for data centers. However, selecting optimal locations for data centers remains a critical challenge due to the need for energy efficiency and environmental sustainability. This study addresses this research gap by proposing a novel decision-making framework that integrates renewable energy considerations into the data center site selection process. The main objective is to identify the most suitable locations for data centers by evaluating multiple criteria. Expert-based evaluations are collected and processed using the Picture-Fuzzy SWARA (PiF-SWARA) method to determine the relative importance of criteria, providing a robust weighting mechanism. The Picture-Fuzzy VIKOR (PiF-VIKOR) method is then applied to rank six potential data center locations in Türkiye. This study is the first to combine PiF-SWARA and PiF-VIKOR in the context of renewable energy-integrated data center siting, offering a novel and comprehensive decision-making approach. Findings indicate that locations with high solar and wind energy potential, coupled with strong infrastructure accessibility, offer the most viable solutions. As the first study to integrate the PiF-SWARA and PiF-VIKOR methods for data center site selection, this research contributes to developing sustainable infrastructure and offers a replicable framework for future studies.

## 1. Introduction

Data centers are critical in hosting vital applications, ensuring continuous uptime, and safeguarding sensitive data. They are essential to the operations of businesses across all sectors [1]. Organizations and governments globally depend on data centers to securely handle their essential operational processes and resources within a centralized digital framework [2]. As digitalization accelerates globally, the demand for data center services rises correspondingly [3]. Notably, the rapid expansion of the Information Technology (IT) sector and increased Internet usage drive the proliferation of data centers [4]. Consequently, data centers form the backbone of the global IT infrastructure [5] and are pivotal in advancing the collaborative networked society [6].

The surge in digital information collection, storage, processing, and transfer has significantly increased data center energy consumption [7]. Data centers account for approximately 2 % of global electricity demand, totaling around 400 TW-hours (TWh) [8]. Leading institutions like Google, Facebook, and Microsoft employ effective energy efficiency strategies, such as utilizing cold outside air for cooling [9]. Implementing energy efficiency measures often necessitates using renewable energy sources [4]. However, data security and operational reliability, influenced by the facility's location, are also paramount [5]. Additionally, data centers powered predominantly by fossil fuels contribute to environmental crises [2]. Thus, selecting a data center location requires careful consideration of environmental, economic, and social criteria.

Renewable energy sources are increasingly valued for their low costs and minimal greenhouse gas emissions [10]. The choice of location significantly impacts a data center's energy demand, especially with the use of free cooling technologies and renewable energy potential [4]. Utilizing renewable energy to reduce carbon footprints has become a major trend, driven by technological advancements and decreasing costs.

While data centers are indispensable elements of today's digital infrastructure, storing and processing massive amounts of data, they are

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also notable for their high energy consumption. This poses a significant problem in terms of environmental sustainability by increasing carbon emissions. This is where integrating renewable energy sources into data centers offers a critical solution to reduce environmental impacts and lower long-term energy costs. Data centers based on clean energy sources such as solar, wind, hydroelectric, and geothermal reduce the carbon footprint and increase the energy supply's security, enabling businesses to provide uninterrupted service. This sustainable approach demonstrates that data centers not only meet the needs of today but also take responsibility for leaving a livable world for future generations.

The primary challenge addressed in this study is the optimal selection of data center locations in Türkiye, emphasizing the integration of renewable energy sources. Data centers, crucial for modern digital infrastructure, require careful consideration of various factors to minimize environmental impact and enhance operational efficiency. This study tackles the complex problem of identifying the most suitable locations by evaluating multiple criteria, including environmental concerns, accessibility, economic factors, and renewable energy potential. The goal is to identify sites that meet operational requirements and align with sustainability objectives, thereby reducing carbon footprints and supporting Turkiye's renewable energy goals. This decision process involves many challenges. For example, data centers should be located in a safe area because they contain important and large data for a country. Both environmental and infrastructure factors should be considered in terms of safety. The possible negative environmental effects of these centers, which require significant energy, should also be considered. In addition, the operational needs of data centers require accessibility criteria. Since data centers are big electricity, water, and land consumers, the centers need to be located in appropriate locations to meet these requirements [11]. The data center location selection decision-making process requires the evaluation of all these main factors and sub-factors from a comprehensive perspective.

This study first establishes the weights for criteria related to renewable energy integration in selecting data center locations and subsequently ranks the alternative sites. In addition, data center location selection problems are complex problems that involve imprecise information. Therefore, suitable location selection can be done by considering fuzzy MCDM techniques [2].

For the first time in the literature, we consider the optimal location for data centers with renewable energy integration. To achieve this, we first identify five main criteria and thirty-four sub-criteria. We then apply the PiF-SWARA method to calculate the weights of these criteria. Following this, we select six alternative locations from various country regions and rank them using the PiF-VIKOR method. This paper uniquely integrates the PiF-SWARA and PiF-VIKOR methods, distinguishing them from existing literature.

In this study, the PiF-SWARA and PiF-VIKOR methods were selected to address the complexities and uncertainties inherent in data center site selection, especially when integrating renewable energy factors. The choice of these methods is justified by their distinct advantages over traditional MCDM approaches. Traditional fuzzy sets often fall short of capturing the full spectrum of uncertainty and hesitation present in expert evaluations [12,13]. Picture fuzzy sets extend the conventional fuzzy set theory by incorporating degrees of positive membership, neutral membership, negative membership, and refusal, allowing for a more comprehensive representation of expert opinions, leading to more reliable decision outcomes [14]. The PiF-SWARA method facilitates a structured determination of criteria weights by considering the relative importance of each criterion as assessed by experts. Operating within the picture fuzzy environment, PiF-SWARA effectively captures the hesitation and neutrality in expert judgments, resulting in a more robust and realistic weighting process [15–17]. PiF-VIKOR ranks alternatives and identifies compromise solutions in complex decision scenarios. It focuses on selecting alternatives that are closest to the ideal solution, balancing the best and worst criteria performances. The incorporation of picture fuzzy sets enables PiF-VIKOR to process the nuanced information provided by experts, ensuring that the final rankings reflect the inherent uncertainties and hesitations in the decision-making process [18,19]. By integrating PiF-SWARA and PiF-VIKOR, this study leverages their combined strengths to develop a decision-making framework that is both theoretically sound and practically applicable. This approach comprehensively evaluates potential data center locations, considering the multifaceted criteria associated with renewable energy integration and infrastructure suitability.

This study addresses the literature gap on the data center site selection process with a strategic sustainability perspective and renewable energy integration. To this end, it focuses on three main research questions.

- How is renewable energy integration ensured in the data center site selection process?
- How are sustainability principles activated in the data center site selection process?
- How can the decision-making process for data center site selection be improved using a fuzzy-based framework and how can the criteria perspective be expanded?

In light of these research questions and the gap in the literature, the main motivations of the study can be summarized as follows: A comprehensive set of criteria is defined to select the most appropriate data center location from a renewable energy integration and sustainability perspective, and an innovative hybrid MCDM methodology combining flexible criteria weighting and fuzzy logic under changing conditions is proposed with expert opinions and literature review.

This study contributes to the literature by providing a robust MCDM tool for data center location selection with sustainable renewable energy integration through the proposed innovative approach. Furthermore, this study addresses the inherent uncertainties in the decision-making process and is unique in its ability to evaluate the data center location selection process in Turkiye in light of comprehensive criteria. Therefore, this study offers new and significant contributions in terms of both the proposed novel hybrid methodology and its application.

The main contributions of this study are.

- The most suitable data center locations were determined using a novel MCDM approach with renewable energy integration.
- A widespread number of criteria within the sustainability framework were defined, including environmental, accessibility, economic, social, and renewable energy. We have detailed these criteria with 34 sub-criteria.
- Different from the literature, SWARA and VIKOR methods within the picture fuzzy environment were integrated, providing a pioneering framework for decision-making in the sustainable framework for companies or policymakers for data centers. For the first time, we proposed the PiF-SWARA method to weigh the criteria. We applied the PiF-VIKOR method by using determined criteria weights to rank alternative locations for a data center in Türkiye.

Despite the increasing interest in data center optimization studies, research on these important centers' location selection is limited. Moreover, advanced fuzzy logic models should evaluate this decision process from a broad criteria perspective. In addition, the renewable energy factor, which has become a very important issue with the increasing energy consumption worldwide, should be considered. When all these are evaluated, this study fills these important gaps in the literature. Thus, this study addresses the relationship between sustainability and operational efficiency from the perspective of renewable energy integration in the data center location selection process in a detailed and comprehensive manner. Overall, it provides guidance on how to apply the fuzzy-based framework with an expanded set of criteria in light of the research questions and contributes significantly to the site selection literature. Moreover, this study addresses the inherent uncertainties in the decision-making process in light of comprehensive criteria and is unique in its ability to assess Türkiye's data center location selection process. Hence, this study proposes novel and vital contributions regarding the proposed hybrid methodology and its application.

Section 2 discusses the PiF-SWARA and PiF-VIKOR methods proposed to determine the criteria weights and ranking of the alternatives. Section 3 presents the pilot study for Turkiye. Section 4 discusses the results, and finally, concluding remarks and potential future research are provided in Section 5.

### 1.1. Literature review

The increasing demand for energy in the world increases the importance of both data centers and renewable energy sources. This section summarizes renewable energy integrated studies under the MCDM framework, especially data center-focused optimization studies and site selection studies for data centers, which are the main subject of this study and are relatively limited in the literature.

The demand for environmentally friendly renewable energy sources and sustainable approaches increases the studies in this field. For example, Dehshiri and Amiri evaluated the risks of Internet of Things (IoT) integration in renewable energy systems using MCDM approaches [20]. They also used MCDM techniques to evaluate hydrogen production strategies under the sustainability perspective with renewable energy integration [21]. Another study evaluates blockchain technology strategies for reducing renewable energy development risks. The study emphasizes the need for a decentralized energy system based on blockchain technology to reduce the cost and price of renewable energy production [22]. In another study focusing on wind energy, which is also a renewable energy source, MCDM approaches were used to evaluate the development of hydrogen projects from wind energy. These studies show both the importance of renewable energy-integrated activities and the effectiveness of MCDM approaches in evaluation and decision-making processes [23].

Recent studies have explored various approaches to data center site selection, particularly focusing on energy efficiency, environmental impact, and cost optimization. For instance, Al-Ayyoub et al. and Depoorter et al. emphasized the importance of cooling strategies and energy source selection in reducing operational energy demands [4,9]. Wang and Lv investigated the role of digital infrastructure expansion in determining data center location preferences [3]. More recently, Erdem and Özdemir proposed a sustainability-based risk evaluation model for data centers using a multi-criteria approach [2]. In parallel, there has been increasing interest in applying fuzzy and hybrid decision-making tools in location problems, as summarized in Table 1. For example, Taibi et al. applied fuzzy-AHP for prioritizing industrial infrastructure sites [24], while Khalaj et al. introduced a fuzzy-TOPSIS model to integrate environmental factors into site selection [10]. Unlike studies directed with MCDM techniques, Wang et al. [25] developed a bi-objective optimization model that minimizes data center expansion costs and carbon emission power usage.

Particularly, the latest studies focus on sustainable data center design and efficiency and emphasize the importance of these centers [26–29]. For instance, Zhang et al. focused on the use of excess capacity of energy storage systems for emergency situations in data centers. For this purpose, they developed two optimization models for the optimal distribution of energy storage capacity and the design optimization of storage systems [26]. Similarly, Wu and He developed a multimodal data fusion algorithm that analyzes energy consumption patterns by integrating environmental sensor data, system logs, and visual information to optimize energy management in data centers [27]. Stoll et al. presented a simulation model that evaluated these factors under different scenarios to meet energy needs and reduce carbon emissions in data centers [28]. Liu et al. developed a multi-objective optimization model considering the energy consumption and energy demand of data centers [29]. However, these studies either focus on general infrastructure or apply crisp or intuitionistic fuzzy environments without fully capturing the hesitation component inherent in expert evaluations. Recent studies are especially focused on energy optimization and model development. Despite the growing attention, limited studies have combined advanced fuzzy logic models with renewable energy criteria for data center siting. This research addresses this gap by using picture fuzzy logic to reflect uncertainty better and by integrating PiF-SWARA (Picture Fuzzy Step-wise Weight Assessment Ratio Analysis) and PiF-VIKOR (Picture Fuzzy VlseKriterijumska Optimizacija I Kompromisno Resenje)—two advanced and complementary methods not yet applied together in this context.

Data centers are very important centers for governments and, therefore, for societies. With the increasing dependency on the internet, the demand for data centers has also increased. Therefore, as mentioned before, these centers must be located in suitable sites. Many criteria, such as environmental, economic, energy, social, etc., need to be considered. When we look at the literature, there are few data center site selection studies. In addition, this study will significantly contribute to the literature by integrating an essential element, such as renewable energy, into the data center location selection.

**Table 1**
Site selection studies for data centers.

| References | Solution method | Application area |
|---|---|---|
| [1] | TOPSIS, MABAC | Egypt |
| [25] | Bi-objective model | China |
| [30] | Best–Worst method (BWM) | Iran |
| [11] | Case study selection, strategy analysis | Sweden |
| [31] | Fuzzy analytic hierarchy | China |
| [32] | PROMETHEE, multi-choice goal programming | China |
| [33] | Dynamic mathematical model | Germany |
| [34] | AHP, EDAS | Asian Countries |
| *This study* | *PiF-SWARA, PiF-VIKOR* | *Turkiye* |

## 2. Proposed methodology

In this section, we ensured a two-level criteria hierarchy to select the optimal location with renewable energy integration for the data center, considering experts' views and literature review. The first step defined detailed main criteria and sub-criteria, and criteria weights were calculated with the PiF-SWARA method. Then, by the criteria weights, we applied the PiF-VIKOR method to rank the alternative locations. Operating Picture Fuzzy Sets offers a more detailed representation of membership, non-membership, and indefiniteness values, thus increasing the accuracy and reliability of the decision-making process.

The selection of the PiF-SWARA and PiF-VIKOR methods for this study was driven by their unique capabilities in addressing the complexities and uncertainties inherent in the data center location selection process. PiF-SWARA was chosen for its ability to systematically determine the weights of criteria using fuzzy numbers, providing a more nuanced representation of expert opinions and reducing the potential for inconsistency [17,35]. The efficacy of integrating fuzzy SWARA in location selection has been evidenced in studies focusing on logistics centers, where it improved the accuracy of criteria weighting under uncertain conditions [36]. PiF-VIKOR, on the other hand, was selected for its robust framework in achieving a compromise solution that balances conflicting criteria, making it particularly suitable for ranking potential data center locations [37,38]. Applications of picture fuzzy VIKOR in facility location problems have demonstrated its robustness in providing discriminative rankings amidst uncertainty [39]. These methods were preferred over traditional approaches due to their enhanced ability to handle imprecise data and provide a more transparent and systematic decision-making process [40,41]. Fig. 1 illustrates the flowchart of the proposed methodology.

Also, to enhance the clarity and reproducibility of the proposed

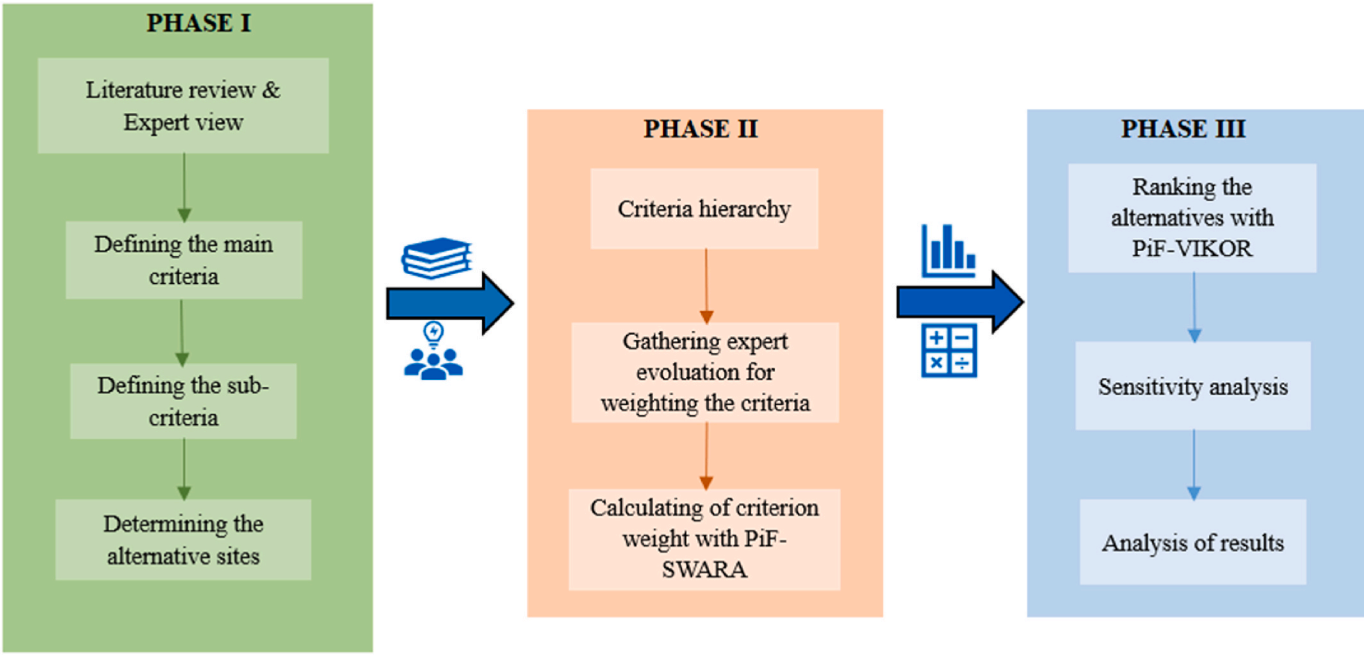


**Fig. 1.** Flowchart of the proposed methodology.

approach, a structured step-by-step pseudo-code of the proposed methodology is given in Algorithm 1. This pseudo-code outlines the sequential steps required first to derive the criteria weights using the PiF-SWARA method and then to rank the alternative sites using the PiF-VIKOR method, ensuring that both uncertainty and imprecision are handled through the use of picture fuzzy numbers.

**Algorithm: PiF-SWARA-PiF-VIKOR for Data Center Location Selection**

**Input:**
SWARA: Expert linguistic evaluations for criteria (using Table 2)
VIKOR: Expert linguistic evaluations for alternatives (using Table 3)
τ: Threshold value for VIKOR (0 < τ < 1)
n: Number of criteria
m: Number of alternatives
**Output:**
w[j] for j = 1,2, …,n (Final criteria weights)
Ranking of alternatives based on Q[i] for i = 1,2, …,m
**Begin**
**//Phase 1: PiF-SWARA for Criteria Weighting**
1. For each criterion j = 1 to n:
Gather expert evaluations using linguistic terms and convert them into Picture Fuzzy Numbers (PiFNs).
2. For each criterion j:
Aggregate expert evaluations using the PFWGO operator to form an aggregated evaluation A[j].
3. For each criterion j:
Convert A[j] to a crisp score S[j].
4. Rank the criteria in descending order based on S[j].
5. For j = 1 to n do:
If j = 1 then
k[1] = 1
q[1] = 1
Else
d[j] = S[j-1] - S[j]
k[j] = d[j] + 1
q[j] = q[j-1]/k[j]
EndIf
EndFor
6. Compute total_q = Sum(q[j]) for j = 1 to n.
For each j:
w[j] = q[j]/total_q
**//Phase 2: PiF-VIKOR for Alternative Ranking**
7. For each alternative i = 1 to m and each criterion j = 1 to n:
Gather expert evaluations using linguistic terms and convert them into PiFNs.
Aggregate these evaluations using PFWGO to obtain X[i][j].

(*continued on next column*)

(*continued*)

**Algorithm: PiF-SWARA-PiF-VIKOR for Data Center Location Selection**

8. For each criterion j:
If criterion j is BENEFIT then
$A^*$ [j] = max{ X[i][j] for all i }
$A^-$ [j] = min{ X[i][j] for all i }
Else if criterion j is COST then
$A^*$ [j] = min{ X[i][j] for all i }
$A^-$ [j] = max{ X[i][j] for all i }
EndIf
9. For each alternative i:
Compute S[i] = Sum (for j = 1 to n) { w[j] * (d(X[i][j], $A^*$ [j])/d($A^-$ [j], $A^*$ [j])) }
Compute R[i] = max (for j = 1 to n) { w[j] * (d(X[i][j], $A^*$ [j])/d($A^-$ [j], $A^*$ [j])) }
10. Determine:
$S^*$ = min{ S[i] for all i }
$S^-$ = max{ S[i] for all i }
$R^*$ = min{ R[i] for all i }
$R^-$ = max{ R[i] for all i }
11. For each alternative i:
Compute Q[i] = τ * ((S[i] - $S^*$)/($S^-$ - $S^*$)) + (1 - τ) * ((R[i] - $R^*$)/($R^-$ - $R^*$))
12. Rank all alternatives in ascending order of Q[i]. The alternative with the lowest Q[i] is considered the best.
End.

### 2.1. Preliminaries of picture fuzzy sets

PiFSs, developed by Cuong and Kreinovich [14], is a generalization of intuitionistic fuzzy sets (IFSs) consisting of four terms: positive, negative, rejection, and abstention degrees. PiFSs have more freedom to deal with real-life situations [42]. PiFSs improve upon traditional fuzzy sets (FSs) and IFSs by incorporating a wider range of response possibilities, thus better handling uncertainty and imprecision [14]. PiFSs include operators that extend the concepts of FSs and IFSs, making them particularly useful for managing ambiguous and uncertain information [43]. Picture fuzzy numbers minimize information loss in practical decision-making processes with fuzzy and uncertain data. PiFSs provide a more precise and comprehensive method for expressing evaluation information than FSs and IFSs, especially when decision-makers need to evaluate the four types of responses mentioned previously [44]. Thus, PiFSs extend the capabilities of FSs, IFSs, and hesitant fuzzy sets by covering a wider range of responses and providing a more detailed and accurate approach to complex decision-making processes [45]. The basic definitions of PiFS are explained in the following [14,46,47].

**Definition 1.** PiFs of the universe of discourse $U$ are defined as $\widetilde{A}_p = \left\{\langle u, \left(\mu_{\tilde{A}_p}(u), I_{\tilde{A}_p}(u), v_{\tilde{A}_p}(u)\right) \middle| u \in U\right\}$. $\mu_{\tilde{A}_p}(u), v_{\tilde{A}_p}(u)$ and $I_{\tilde{A}_p}(u)$ are membership, non-membership, and indeterminacy degrees of $u$ to $\widetilde{A}_p$, respectively. They take the values between 0 and 1; their sum cannot exceed 1. The refusal degree of the element is calculated.

$$\pi_{\tilde{A}_p} = 1 - \left(\mu_{\tilde{A}_p}(u) + v_{\tilde{A}_p}(u) + I_{\tilde{A}_p}(u)\right) \tag{1}$$

**Definition 2.** Let $\widetilde{A}_p = (\mu_{\tilde{A}_p}, I_{\tilde{A}_p}, v_{\tilde{A}_p})$ and $\widetilde{B}_p = (\mu_{\tilde{B}_p}, I_{\tilde{B}_p}, v_{\tilde{B}_p})$ are two picture fuzzy numbers. Basic operations between them [48,49]:

$$\widetilde{A}_p \oplus \widetilde{B}_p = \left\{\mu_{\tilde{A}_p} + \mu_{\tilde{B}_p} - \mu_{\tilde{A}_p}\mu_{\tilde{B}_p}, I_{\tilde{A}_p}I_{\tilde{B}_p}, v_{\tilde{A}_p}v_{\tilde{B}_p}\right\} \tag{2}$$

$$\widetilde{A}_p \otimes \widetilde{B}_p = \left\{\mu_{\tilde{A}_p}\mu_{\tilde{B}_p}, I_{\tilde{A}_p}I_{\tilde{B}_p}, v_{\tilde{A}_p} + v_{\tilde{B}_p} - v_{\tilde{A}_p}v_{\tilde{B}_p}\right\} \tag{3}$$

$$\widetilde{A}_p^{\lambda} = \left\{\mu_{\tilde{A}_p}^{\lambda}, I_{\tilde{A}_p}^{\lambda}, \left(1 - \left(1 - v_{\tilde{A}_p}\right)^{\lambda}\right)\right\} \tag{4}$$

$$\lambda \cdot \widetilde{A}_p = \left\{\left(1 - \left(1 - \mu_{\tilde{A}_p}\right)^{\lambda}\right), I_{\tilde{A}_p}^{\lambda}, v_{\tilde{A}_p}^{\lambda}\right\} \tag{5}$$

**Definition 3.** Picture Fuzzy Weighted Geometric Operator (PFWGO) for multiple picture fuzzy numbers $w = (w_1, w_2, \ldots, w_n)$; $0 \le w_j \le 1$; $\sum_{j=1}^{n} w_j = 1$.

$$\text{PFWG}_w\left(\widetilde{A}_1, \ldots, \widetilde{A}_n\right) = \left\{\prod_{j=1}^{n} \mu_{\tilde{A}_j}^{w_j}, \prod_{j=1}^{n} I_{\tilde{A}_j}^{w_j}, 1 - \prod_{j=1}^{n} \left(1 - v_{\tilde{A}_j}\right)^{w_j}\right\} \tag{6}$$

**Definition 4.** Let $\widetilde{A}_p = \left(\mu_{\tilde{A}_p}, I_{\tilde{A}_p}, v_{\tilde{A}_p}\right)$ is a picture fuzzy number. The score function for a $\widetilde{A}_p$.

$$\text{Score}\left(\widetilde{A}_p\right) = \left(2\mu_{\tilde{A}_p} - v_{\tilde{A}_p} - \frac{I_{\tilde{A}_p}}{2}\right) \tag{7}$$

**Definition 5.** Let $\widetilde{A}_p = \left(\mu_{\tilde{A}_p}, I_{\tilde{A}_p}, v_{\tilde{A}_p}\right)$ and $\widetilde{B}_p = \left(\mu_{\tilde{B}_p}, I_{\tilde{B}_p}, v_{\tilde{B}_p}\right)$ are two picture fuzzy numbers. The distance between $\widetilde{A}_p$ and $\widetilde{B}_p$ [50].

$$d(\widetilde{A}_p, \widetilde{B}_p) = \frac{1}{4}\left(\left|\mu_{\tilde{A}_p} - \mu_{\tilde{B}_p}\right| + \left|I_{\tilde{A}_p} - I_{\tilde{B}_p}\right| + \left|v_{\tilde{A}_p} - v_{\tilde{B}_p}\right| + \left|\pi_{\tilde{A}_p} - \pi_{\tilde{B}_p}\right|\right) + \frac{1}{2}max\left(\left|\mu_{\tilde{A}_p} - \mu_{\tilde{B}_p}\right|, \left|I_{\tilde{A}_p} - I_{\tilde{B}_p}\right|, \left|v_{\tilde{A}_p} - v_{\tilde{B}_p}\right|, \left|\pi_{\tilde{A}_p} - \pi_{\tilde{B}_p}\right|\right) \tag{8}$$

### 2.2. Picture fuzzy SWARA

SWARA, which developed as a decision-maker-oriented subjective decision-making method [51], is one of the MCDM methods used to determine and rank the criteria weights. The method uses expert opinions while determining the criteria weights, and the roles of decision-makers are an important factor in this method's criteria [52]. In this phase, we apply the PiF-SWARA method to determine the importance weights of main criteria and sub-criteria at each hierarchical level. To determine the criteria weights for selecting data center locations, we employ the PiF-SWARA method, which involves the following steps:

**Step 1:** Expert evaluations for each criterion are gathered via linguistic terms outlined in Table 2.

**Step 2:** PFWGO is utilized to aggregate expert evaluations.

**Table 2**
Linguistic terms for PiF-SWARA.

| Linguistic Terms | PiFNs $(\mu, I, v)$ |
|---|---|
| VLI-Very Low Importance | (0.1, 0.01, 0.85) |
| LI-Low Importance | (0.25, 0.05, 0.6) |
| MI-Medium Importance | (0.5, 0.1, 0.4) |
| HI-High Importance | (0.75, 0.05, 0.1) |
| VHI-Very High Importance | (0.9, 0.01, 0.05) |

**Step 3:** Picture fuzzy aggregated evaluation matrix is converted to crisp score values.

**Step 4:** Criteria are ranked in descending order.

**Step 5:** The comparative significance of each criterion is determined by calculating the difference in score values between the current criterion ($j$) and the preceding one ($j-1$).

**Step 6:** Comparative coefficients are calculated.

$$k_j = \begin{cases} 1, j = 1 \\ s_j + 1, j > 1 \end{cases} \tag{9}$$

**Step 7:** Recalculated weights are estimated.

$$q_j = \begin{cases} 1, j = 1 \\ \dfrac{q_{(j-1)}}{k_j}, j > 1 \end{cases} \tag{10}$$

**Step 8:** The final criteria weights are determined.

$$w_j = \frac{q_j}{\sum_{j=1}^{n} q_j} \tag{11}$$

where $n$ is the criteria number.

### 2.3. Picture fuzzy VIKOR

The VIKOR method is an MCDM method developed by Opricović (1998) for solving discrete multi-criteria decision-making problems and determining a compromise solution for decision-makers. Most studies use distance measurements in using the VIKOR approach. However, in some cases, using distance measurements is unreliable, and there are some PiF sets where the distance between them is the same but not equal [19]. The PiF-VIKOR method extends the traditional VIKOR framework to address decisions characterized by uncertainty, imprecision, and non-commensurability. It incorporates picture fuzzy numbers to form the decision matrix and applies picture arithmetic operators throughout the evaluation process. PiF-VIKOR calculates separation measures between fuzzy positive and negative values by utilizing picture fuzzy distance operators. This approach enables decision-makers to identify the optimal alternative based on more accurate and detailed information [53]. The PIF-VIKOR methodology used in this study involves the following steps:

**Step 1:** The alternative evaluation matrix is formed via linguistic terms given in Table 3. $\widetilde{Y}_{ij}^{k}$ is the expert $k$'s evaluation value of alternative $i$ for criterion $j$.

**Step 2:** PFWGO is utilized to aggregate expert evaluations. $\widetilde{X}_{ij}$ is the

**Table 3**
Linguistic terms for PiF-VIKOR.

| Linguistic Terms | PiFNs $(\mu, I, v)$ |
|---|---|
| VL-Very Low | (0.10, 0.05, 0.80) |
| L-Low | (0.20, 0.05, 0.70) |
| ML-Moderately Low | (0.30, 0.05, 0.60) |
| F-Fair | (0.50, 0.10, 0.40) |
| MH-Moderately High | (0.60, 0.05, 0.30) |
| H-High | (0.75, 0.05, 0.15) |
| VH-Very High | (0.90, 0.05, 0.05) |

fuzzy value for aggregated evaluation of alternative $i$ according to criterion $j$.

**Step 3:** The positive $(A^*)$ and negative $(A^-)$ ideal solutions are determined based on score values derived from the aggregated decision matrix.

For benefit criteria;

$$A^* = \left\{ \widetilde{X}_{ij} \text{ where } \max_i \widetilde{x}_{ij} | i = 1, 2, \ldots, m \right\} \tag{12}$$

$$A^- = \left\{ \widetilde{X}_{ij} \text{ where } \min_i \widetilde{x}_{ij} | i = 1, 2, \ldots, m \right\} \tag{13}$$

For cost criteria;

$$A^* = \left\{ \widetilde{X}_{ij} \text{ where } \min_i \widetilde{x}_{ij} | i = 1, 2, \ldots, m \right\} \tag{14}$$

$$A^- = \left\{ \widetilde{X}_{ij} \text{ where } \max_i \widetilde{x}_{ij} | i = 1, 2, \ldots, m \right\} \tag{15}$$

$A^*$ $A^-$ and are shown as $x_j^+ = \left(\mu_j^*, v_j^*\right)$, $x_j^* = \left(\mu_j^-, v_j^-\right)$, respectively.

**Step 4:** $S_i$ and $R_i$ are calculated based on the distance function. $S_i$ is the average gap, and $R_i$ is the maximal gap for improvement priority [54].

$$S_i = \sum_{j=1}^{n} w_j \frac{d(x_{ij}, x_j^+)}{d(x_j^-, x_j^+)} \tag{16}$$

$$R_i = max\left\{ w_j \frac{d(x_{ij}, x_j^+)}{d(x_j^-, x_j^+)} \right\} \tag{17}$$

**Step 5:** $Q_i$ is calculated for each alternative to combine the average and maximal gaps [55].

$$Q_i = \tau \frac{S_i - S^*}{S^- - S^*} + (1 - \tau) \frac{R_i - R^*}{R^- - R^*} \tag{18}$$

where

$$R^- = \max_i R_i \tag{19}$$

$$R^* = \min_i R_i \tag{20}$$

$$S^- = \max_i S_i \tag{21}$$

$$S^* = \min_i S_i \tag{22}$$

$\tau$ is the threshold value for the strategy of maximum group effectiveness.

**Step 6:** The alternatives are ordered in ascending for $S_i$, $R_i$ and $Q_i$. First ranked in $Q_i$ is selected as the best alternative $(Alt')$.

## 3. Application

The case study focuses on identifying the optimal site for a data center in Turkiye that integrates renewable energy sources. Turkiye is endowed with a diverse range of renewable energy potentials, including solar, biomass, hydroelectric, wind, and geothermal, which offer sustainable alternatives to meet the growing energy demands of data centers. Leveraging these renewable resources can significantly reduce the environmental impact of data centers by lowering carbon emissions and energy costs.

The evaluation process considers a comprehensive set of criteria encompassing environmental, social, economic, and renewable energy-related factors. The criteria and sub-criteria were identified through a rigorous process that combined expert evaluations and a thorough literature review. Specifically, five main criteria and 34 sub-criteria are established from a sustainability perspective, with a particular focus on renewable energy integration. The weighting process for these criteria and sub-criteria uses the PiF-SWARA method, which systematically incorporates expert opinions through picture fuzzy numbers to account for uncertainties and subjectivity. Experts are asked to evaluate the relative importance of each criterion and sub-criterion. Seven experts with substantial experience in data center operations and renewable energy were engaged to assess the importance of each criterion. These experts provided their evaluations using linguistic terms, which were then converted into picture fuzzy numbers to capture the degrees of membership, non-membership, and hesitation. The PiF-SWARA method facilitated the aggregation of these evaluations, resulting in precise weightings for each criterion that reflect both the experts' insights and the inherent uncertainties in their judgments. The criteria, definitions, their sources, and the detailed weighting process are presented in Table 4.

### 3.1. *Expert team*

This study focuses on determining the optimal location for a renewable energy-integrated data center in Turkey. Seven experts—E1, E2, E3, E4, E5, E6, and E7—who possess extensive knowledge in relevant fields are assembled. These experts participated in identifying criteria, determining their importance levels, and evaluating potential locations. Information about experts is given in Table 5.

### 3.2. *Calculation of criteria weights with PiF-SWARA method*

As previously mentioned, seven experts are consulted to determine the criteria weights at each renewable energy-integrated data center level. The experts are asked to evaluate the criteria using a survey to support the goal of meeting the data center's energy needs through sustainable sources, thereby reducing its carbon footprint. Based on the linguistic terms provided in Table 2, expert evaluations for the main criteria are shown in Table 6.

Initially, the evaluations are converted into picture fuzzy numbers. Following this, the expert opinions are aggregated, assuming equal weight for each expert. The aggregation process is carried out using the PFWGO method. The resulting picture fuzzy numbers are then utilized to determine the criteria weights, as illustrated in Fig. 2.

The weight distribution of the main criteria highlights the significance of environmental and renewable energy factors in selecting the optimal location for a data center. With the highest weight at 26.71 %, environmental considerations such as carbon emissions, water availability, and seismic activity are prioritized, reflecting the importance of minimizing ecological impact. Close behind, renewable energy integration holds a 25 % weight, emphasizing the need to harness sustainable energy sources like solar and wind to power the data center. This balanced approach aligns to develop a sustainable, cost-effective, and community-supported data center. The same experts are consulted again to evaluate the sub-criteria of the five main criteria. The experts' evaluations of the sub-criteria are presented in Table 7.

The expert opinions are once again aggregated, and the local weights are then determined using the PiF-SWARA methodology for each main criterion. The final weights of the sub-criteria are obtained by multiplying their respective local weights with the weights of the corresponding main criteria, as presented in Table 8.

The most important sub-criteria for selecting a data center location emphasizes safety, sustainability, and renewable energy integration. Among the sub-criteria, seismic intensity (C13) holds the highest weight at 0.0588, making it the most critical factor in selecting the location for a data center. This emphasizes the importance of ensuring that the chosen site is in a region with low seismic activity to minimize the risk of operational disruptions and potential damage to infrastructure. The availability of water resources is also crucial, as it directly impacts the efficiency and sustainability of cooling systems, which are critical

**Table 4**
Definitions of sub-criteria.

| Sub-criteria | Definitions | References |
|---|---|---|
| Availability of water resources ($C_{11}$) | The accessibility and sufficiency of water resources required for cooling and other operational needs of the data center. | [6] |
| Conflicts with reserves and natural parks ($C_{12}$) | The data center's location could interfere with protected natural areas, wildlife reserves, or national parks. | [6] |
| Seismic intensity ($C_{13}$) | The likelihood and potential severity of earthquakes in the area affects the structural safety of the data center. | [6] |
| Climate ($C_{14}$) | The overall weather patterns, including temperature, humidity, and precipitation. | [1] |
| Carbon emissions ($C_{15}$) | The amount of carbon dioxide and other greenhouse gases produced by the data center's operations. | [4] |
| Proximity to telecommunications networks ($C_{21}$) | The distance from the data center to the existing telecommunications infrastructure. | [6] |
| Proximity to electrical power ($C_{22}$) | The closeness of the data center to power sources or substations. | [6] |
| Proximity to main road access ($C_{23}$) | The ease of access to major roadways. | [6] |
| Proximity to railway ($C_{24}$) | The distance to railway stations provides an alternative transportation route for heavy equipment or goods. | [6] |
| Proximity to airports ($C_{25}$) | The closeness to airports facilitates the quick transportation of critical components or personnel. | [6] |
| Transport & logistics operations ($C_{26}$) | The overall efficiency and availability of transport and logistics services are essential for smooth operation and maintenance. | [5] |
| Proximity to renewable energy sources ($C_{27}$) | Proximity to renewable energy sources, such as solar, wind, etc., is an advantage in terms of energy use alternatives. | [5] |
| Distance to city center ($C_{28}$) | The distance from the data center to communities. | [1] |
| Land cost ($C_{31}$) | The expense associated with purchasing land for the data center. | Expert view |
| Investment cost ($C_{32}$) | The total capital required to develop and establish the data center, including construction and equipment. | [5] |
| Network communications connection cost ($C_{33}$) | The expense involved connecting the data center to communication networks, such as fiber optics. | [5] |
| Cost of renewable energy infrastructure ($C_{34}$) | The financial outlay required to install and maintain renewable energy systems like solar panels or wind turbines. | Expert view |
| Financial incentives for renewable energy ($C_{35}$) | Monetary benefits or subsidies provided by the government or other entities to encourage the use of renewable energy | Expert view |
| Cooling cost ($C_{36}$) | The operational expenses associated with cooling the data center to maintain optimal operating temperatures. | Expert view |
| Energy cost ($C_{37}$) | The ongoing cost of energy required to power the operations. | [1] |
| Safety ($C_{41}$) | The level of security and risk management measures are in place to protect the data center from potential threats. | [5] |
| Availability of skilled labor ($C_{42}$) | The presence and accessibility of a workforce with the necessary skills to operate and maintain the data center. | [5] |

**Table 4** (*continued*)

| Sub-criteria | Definitions | References |
|---|---|---|
| Community acceptance ($C_{43}$) | The degree of support or opposition from the local community regarding establishing the data center. | Expert view |
| Regulatory environment ($C_{45}$) | The legal and regulatory framework governs the data center's establishment and operation. | Expert view |
| Local incentives ($C_{46}$) | Local authorities offer economic benefits, such as tax breaks or grants, to attract data center investment. | Expert view |
| Development rate ($C_{47}$) | The speed and extent of infrastructure and economic development in the area where the data center is located. | [1] |
| Annual average sunshine duration ($C_{51}$) | The average number of hours of sunshine the location receives per year is relevant for solar energy potential. | Expert view |
| Annual total solar radiation ($C_{52}$) | The total amount of solar energy received per year influences the effectiveness of solar power systems. | Expert view |
| Wind energy density ($C_{53}$) | The concentration of wind power available at the site affects the feasibility of wind energy generation. | [10] |
| Geothermal energy potential ($C_{54}$) | The availability and viability of using geothermal energy resources at the location. | Expert view |
| Wave energy potential ($C_{55}$) | The potential to harness energy from waves in the region is relevant for coastal locations. | Expert view |
| Hydroelectric energy potential ($C_{56}$) | The location has the potential to generate electricity from water resources, such as rivers or dams. | Expert view |
| Biomass energy potential ($C_{57}$) | The availability and suitability of organic materials for the area's energy source. | Expert view |
| Environmental impact of renewable energy infrastructure ($C_{58}$) | The effect of installing and operating renewable energy systems on the local environment. | Expert view |

The PiF-SWARA method is employed to calculate the criteria weights to determine the significance of each criterion. The alternative locations are ranked by integrating the derived weights into the PiF-VIKOR method. This approach effectively handles uncertainty and complexity and provides a robust framework for strategically selecting data center locations.

**Table 5**
Information about experts.

| | Experience | Education Level | Job Title | Area of Expertise |
|---|---|---|---|---|
| E1 | 20+ | PhD in Electrical-Electronics Engineering | Professor | Energy systems, renewable energy, data center design |
| E2 | 15+ | PhD in Civil Engineering | Associate Professor | Structural engineering, geotechnics, earthquake engineering |
| E3 | 20+ | PhD in Environmental Engineering | Professor | Environmental impact assessment, sustainability, waste management |
| E4 | 10+ | PhD in Computer Engineering | Assistant Professor | Network systems, data security, cybersecurity |
| E5 | 15+ | PhD in Industrial Engineering | Associate Professor | Logistics, supply chain management |
| E6 | 20+ | PhD in Urban and Regional Planning | Professor | Urban planning, land use, regional development |
| E7 | 10+ | Masters in Business Administration | Regional Manager | Local governance, investment incentives, community relations |

**Table 6**
Experts' evaluations for main criteria.

| | E1 | E2 | E3 | E4 | E5 | E6 | E7 |
|---|---|---|---|---|---|---|---|
| **Environmental** | VHI | HI | HI | HI | HI | MI | HI |
| **Accessibility** | HI | VHI | HI | LI | HI | HI | HI |
| **Economic** | MI | HI | HI | HI | HI | HI | VHI |
| **Social** | LI | HI | MI | HI | LI | MI | MI |
| **Renewable Energy** | VHI | HI | VHI | VHI | VHI | VHI | VHI |

components of data center operations. Carbon emissions are a significant concern, making it essential to select a location that supports low-carbon energy sources, thereby enhancing the environmental sustainability of the data center. Additionally, the annual average sunshine duration plays a vital role in maximizing solar energy potential, further supporting the integration of renewable energy into the data center's power supply.

### *3.3. Ranking alternatives with PiF-VIKOR method*

To tackle the complex task of selecting the optimal location for a renewable energy-integrated data center, six potential sites—Konya (A1), İzmir (A2), Trabzon (A3), Antalya (A4), Şanlıurfa (A5), and Çanakkale (A6)—are carefully chosen for evaluation. This issue is particularly significant for Türkiye, as the strategic siting of data centers powered by renewable energy can significantly enhance the country's energy independence while reducing its carbon footprint. By focusing on locations with diverse regional characteristics and renewable energy potential, this study aims to contribute to developing a more sustainable and resilient energy infrastructure in Türkiye. The geographical distribution of these alternative sites is illustrated in Fig. 3.

First, the expert team evaluates the alternative locations, as shown in Table 9, based on the predefined criteria for data centers with renewable energy integration. While evaluating the alternatives, the integration of renewable energy sources is one of the key factors in assessing the suitability of each site. The assessment considers the availability of solar, wind and other alternative energy sources to ensure a diversified energy portfolio. In addition, economic feasibility, including infrastructure costs and policy incentives, is examined to determine the viability of implementing renewable energy solutions. The environmental impact of energy infrastructure is also considered to ensure alignment with sustainability objectives. By incorporating these factors, the proposed decision framework provides a balanced assessment that captures both energy potential and economic viability. The Modified Delphi method is employed to achieve consensus among the experts to ensure a thorough and well-informed assessment. This method is particularly effective in scenarios where multiple expert opinions are required on a specific topic, allowing for the systematic collection and integration of these views [56]. The Modified Delphi method facilitates the examination and aggregation of anonymous expert opinions through written interviews, discussions, and successive feedback rounds. Through these iterative cycles of knowledge sharing and opinion exchange, the experts work towards reaching a consensus [57].

Subsequently, the decision matrix is constructed by converting the linguistic terms into picture-fuzzy numbers. The best $\widetilde{X}^*$ and worst $\widetilde{X}^-$ values for each criterion are identified based on their type. In this evaluation, all criteria are considered benefit-type, except C12 (Conflicts with reserves and natural parks), C13 (Seismic intensity), C31 (Land cost), C32 (Investment cost), C33 (Network communications connection cost), C34 (Cost of renewable energy infrastructure), C36 (Cooling cost), C37 (Energy cost), and C58 (Environmental impact of renewable energy infrastructure), which are treated as cost-type criteria. Using the consolidated evaluations and criteria weights, the $S_i$, $R_i$ and $Q_i$ values are calculated for each alternative. In this calculation, the final criteria weights are applied, and the parameter λ is set at 0.5 [37]. The $S_i$, $R_i$ and $Q_i$ values for each alternative location are presented in Table 9. The overall ranking of the alternatives is also provided in Table 10, based on the lowest $Q_i$ values.

In the application of the PiF-VIKOR method for selecting data center locations, the site with the lowest $Q_i$ value is prioritized as the most suitable for installation. According to the results, Izmir is the top location, followed by Konya, Antalya, Sanliurfa, Trabzon, and Canakkale. This ranking is crucial as it highlights the most and least favorable sites for the data center based on the criteria assessed. Izmir, Konya, and Antalya emerge as ideal locations due to their favorable characteristics, such as significant renewable energy potential, low infrastructural costs, and accessibility to essential infrastructure.

The compromise ranking of PiF-VIKOR ensures that the best-ranked locations offer an optimal combination of renewable energy potential, accessibility, and economic feasibility. The findings revealed that İzmir emerged as the most suitable site, excelling in infrastructure, connectivity [58], and access to renewable energy resources [59–61], followed closely by Konya, which demonstrated strong solar energy potential [62, 63] and land availability. Meanwhile, Trabzon and Çanakkale ranked lower due to challenges in terrain, accessibility, and energy infrastructure limitations. The PiF-VIKOR ranking highlights the trade-offs between renewable energy potential and logistical feasibility, supporting a

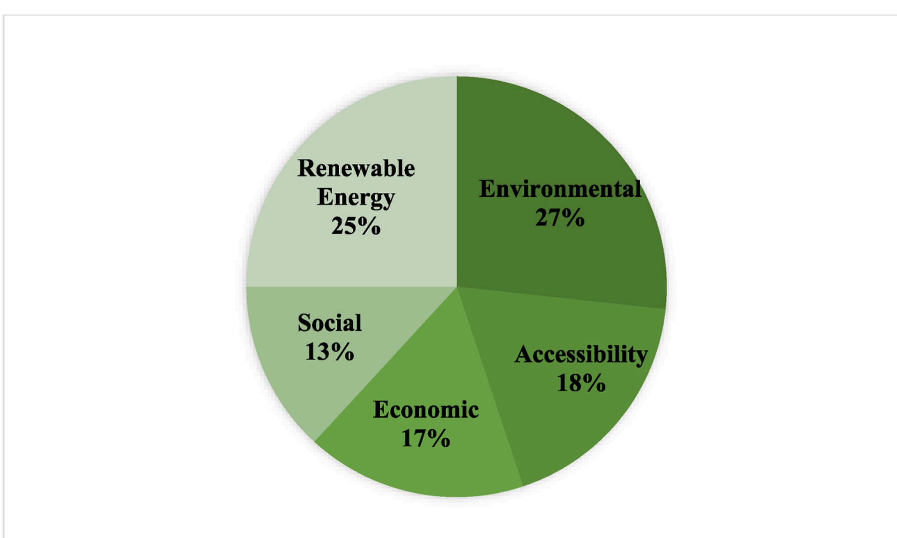


**Fig. 2.** Main criteria weights.

**Table 7**
Expert evaluations for sub-criteria.

| Sub Criteria | E1 | E2 | E3 | E4 | E5 | E6 | E7 |
|---|---|---|---|---|---|---|---|
| C11. Availability of water resources | VHI | MI | MI | LI | MI | MI | HI |
| C12. Conflicts with reserves and natural parks | MI | VHI | LI | VHI | VLI | LI | HI |
| C13. Seismic intensity | VHI | MI | MI | VHI | VHI | VHI | MI |
| C14. Climate | HI | MI | HI | MI | MI | HI | HI |
| C15. Carbon emissions | HI | HI | VHI | LI | LI | HI | VHI |
| C21. Proximity to telecommunications networks | VHI | VHI | VHI | VHI | VHI | HI | VHI |
| C22. Proximity to electrical power | HI | HI | MI | LI | VHI | HI | VHI |
| C23. Proximity to main road access | LI | MI | LI | HI | HI | MI | HI |
| C24. Proximity to railway | LI | MI | LI | MI | MI | MI | HI |
| C25. Proximity to airports | LI | MI | LI | MI | HI | MI | HI |
| C26. Transport & logistics operations | LI | HI | LI | MI | HI | MI | HI |
| C27. Proximity to renewable energy sources | HI | HI | HI | VHI | MI | VHI | HI |
| C28. Distance to city center | MI | MI | HI | HI | LI | LI | VLI |
| C31. Land cost | LI | HI | MI | HI | HI | MI | VHI |
| C32. Investment cost | LI | HI | MI | HI | HI | HI | VHI |
| C33. Network communications connection cost | HI | HI | MI | HI | VHI | MI | HI |
| C34. Cost of renewable energy infrastructure | VHI | HI | HI | VHI | HI | HI | HI |
| C35. Financial incentives for renewable energy | HI | HI | HI | VHI | HI | HI | HI |
| C36. Cooling cost | VHI | HI | VHI | LI | HI | HI | VHI |
| C37. Energy cost | VHI | VHI | VHI | MI | HI | HI | VHI |
| C41. Safety | VHI | VHI | HI | VHI | VHI | VHI | HI |
| C42. Availability of skilled labor | HI | HI | HI | MI | VHI | LI | HI |
| C43. Community acceptance | MI | MI | MI | HI | MI | LI | MI |
| C44. Regulatory environment | HI | VHI | VHI | HI | HI | MI | MI |
| C45. Local incentives | MI | HI | MI | LI | HI | LI | VLI |
| C46. Development rate | VLI | MI | HI | MI | HI | MI | LI |
| C51. Annual average sunshine duration | HI | HI | HI | VHI | MI | VHI | VHI |
| C52. Annual total solar radiation | MI | HI | HI | VHI | MI | VHI | VHI |
| C53. Wind energy density | LI | HI | HI | VHI | MI | HI | VHI |
| C54. Geothermal energy potential | LI | MI | HI | MI | VLI | MI | HI |
| C55. Wave energy potential | VLI | MI | HI | HI | LI | LI | HI |
| C56. Hydroelectric energy potential | LI | MI | HI | MI | MI | MI | HI |
| C57. Biomass energy potential | VLI | MI | HI | MI | LI | MI | VHI |
| C58. Environmental impact of renewable energy infrastructure | VHI | HI | VHI | VHI | HI | HI | VHI |

balanced decision-making approach for selecting the most sustainable data center location.

### 3.4. Sensitivity analysis

A sensitivity analysis is performed to validate the robustness and reliability of the proposed methodology for selecting data center locations under varying parameters. This analysis examines the impact of changes in the threshold value $(v)$, which is incrementally increased by 0.1, ranging from 0.1 to 0.9? By applying this approach, the analysis evaluates the framework's resilience and stability in different scenarios, ensuring that the recommended sites remain optimal under varying conditions. This process is crucial for confirming the framework's effectiveness in addressing the complex requirements of data center site selection. The rankings of alternatives for the various threshold values are illustrated in Fig. 4.

**Table 8**
Final weights of sub-criteria.

| Sub Criteria | Local Weight | Final Weight | Rank |
|---|---|---|---|
| C11. Availability of water resources | 0.2171 | 0.0580 | 2 |
| C12. Conflicts with reserves and natural parks | 0.1989 | 0.0531 | 5 |
| C13. Seismic intensity | 0.2199 | 0.0588 | 1 |
| C14. Climate | 0.1629 | 0.0435 | 8 |
| C15. Carbon emissions | 0.2012 | 0.0537 | 3 |
| C21. Proximity to telecommunications networks | 0.2657 | 0.0483 | 6 |
| C22. Proximity to electrical power | 0.1185 | 0.0215 | 20 |
| C23. Proximity to main road access | 0.0911 | 0.0166 | 29 |
| C24. Proximity to railway | 0.0745 | 0.0135 | 34 |
| C25. Proximity to airports | 0.0775 | 0.0141 | 33 |
| C26. Transport & and logistics operations | 0.0933 | 0.0170 | 28 |
| C27. Proximity to renewable energy sources | 0.1661 | 0.0302 | 12 |
| C28. Distance to city center | 0.1132 | 0.0206 | 24 |
| C31. Land cost | 0.1628 | 0.0276 | 14 |
| C32. Investment cost | 0.1006 | 0.0171 | 27 |
| C33. Network communications connection cost | 0.1176 | 0.0199 | 26 |
| C34. Cost of renewable energy infrastructure | 0.1614 | 0.0274 | 15 |
| C35. Financial incentives for renewable energy | 0.1454 | 0.0247 | 17 |
| C36. Cooling cost | 0.1452 | 0.0246 | 18 |
| C37. Energy cost | 0.1670 | 0.0283 | 13 |
| C41. Safety | 0.3055 | 0.0402 | 9 |
| C42. Availability of skilled labor | 0.1555 | 0.0205 | 25 |
| C43. Community acceptance | 0.1143 | 0.0150 | 30 |
| C44. Regulatory environment | 0.2050 | 0.0270 | 16 |
| C45. Local incentives | 0.1106 | 0.0146 | 31 |
| C46. Development rate | 0.1091 | 0.0143 | 32 |
| C51. Annual average sunshine duration | 0.2143 | 0.0536 | 4 |
| C52. Annual total solar radiation | 0.1354 | 0.0339 | 10 |
| C53. Wind energy density | 0.1271 | 0.0318 | 11 |
| C54. Geothermal energy potential | 0.0835 | 0.0209 | 22 |
| C55. Wave energy potential | 0.0939 | 0.0235 | 19 |
| C56. Hydroelectric energy potential | 0.0857 | 0.0214 | 21 |
| C57. Biomass energy potential | 0.0832 | 0.0208 | 23 |
| C58. Environmental impact of renewable energy infrastructure | 0.1769 | 0.0442 | 7 |

The sensitivity analysis results demonstrate how the rankings of alternative sites for data center locations vary with different threshold values. The sensitivity analysis reveals that İzmir consistently ranks as the top site across all threshold values, demonstrating high stability and confirming its robust suitability for data center deployment. This consistency suggests that İzmir maintains its optimal position regardless of decision-makers' risk tolerance changes due to its strong infrastructure, high renewable energy potential, and economic feasibility. This reinforces its strong infrastructure, accessibility, and renewable energy potential, making it resilient to changes in parameter settings. In contrast, the rankings of other locations shift with varying threshold values. For instance, Konya rises from third to second place as the threshold value increases, indicating improved priority under a higher emphasis on individual regret. Antalya, second in the current ranking, emerges as the third alternative when the threshold values are set to 0.4, 0.5, 0.6 and 0.7, and the fourth alternative when the threshold values are set to 0.8 and 0.9. Antalya and Trabzon experience notable ranking shifts, indicating that transportation accessibility, infrastructure, and economic feasibility are more sensitive to parameter variations.

The analysis also identified that ranking stability is influenced most by renewable energy potential, infrastructure accessibility, and economic feasibility. Locations with higher renewable energy integration and better infrastructure tend to maintain more substantial positions, while those with limited grid access or higher investment costs exhibit greater ranking fluctuations. These insights can be used to further refine decision-making strategies, ensuring that site selection remains robust under varying conditions.

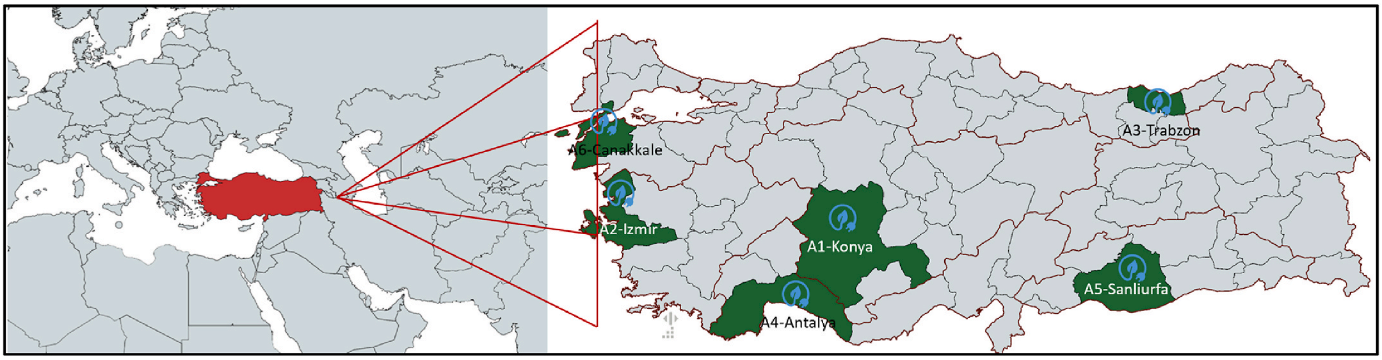


**Fig. 3.** Alternative locations.

**Table 9**
The alternative evaluation matrix.

| | Konya | Izmir | Trabzon | Antalya | Sanliurfa | Canakkale |
|---|---|---|---|---|---|---|
| C11. Availability of water resources | F | MH | H | F | L | MH |
| C12. Conflicts with reserves and natural parks | F | ML | MH | F | L | F |
| C13. Seismic intensity | L | F | F | F | H | H |
| C14. Climate | F | ML | F | ML | L | F |
| C15. Carbon emissions | L | F | ML | F | L | ML |
| C21. Proximity to telecommunications networks | MH | VH | MH | H | MH | MH |
| C22. Proximity to electrical power | MH | VH | H | MH | H | MH |
| C23. Proximity to main road access | H | VH | MH | H | MH | H |
| C24. Proximity to railway | VH | L | L | H | MH | ML |
| C25. Proximity to airports | H | VH | VH | VH | H | MH |
| C26. Transport & logistics operations | MH | VH | MH | H | MH | MH |
| C27. Proximity to renewable energy sources | VH | H | H | H | VH | H |
| C28. Distance to city center | MH | ML | ML | ML | MH | MH |
| C31. Land cost | ML | H | MH | VH | L | MH |
| C32. Investment cost | MH | H | H | VH | MH | MH |
| C33. Network communications connection cost | MH | ML | F | ML | MH | MH |
| C34. Cost of renewable energy infrastructure | ML | MH | MH | MH | ML | MH |
| C35. Financial incentives for renewable energy | MH | MH | F | MH | MH | F |
| C36. Cooling cost | MH | MH | ML | MH | H | MH |
| C37. Energy cost | MH | MH | F | MH | F | MH |
| C41. Safety | MH | F | H | F | L | H |
| C42. Availability of skilled labor | MH | VH | MH | H | ML | MH |
| C43. Community acceptance | F | MH | F | MH | MH | H |
| C44. Regulatory environment | MH | F | F | F | MH | F |
| C45. Local incentives | MH | F | ML | F | ML | MH |
| C46. Development rate | MH | VH | MH | H | MH | MH |
| C51. Annual average sunshine duration | VH | H | ML | VH | VH | H |
| C52. Annual total solar radiation | VH | H | ML | VH | VH | H |
| C53. Wind energy density | F | MH | F | ML | MH | VH |
| C54. Geothermal energy potential | VL | H | VL | ML | VL | ML |
| C55. Wave energy potential | VL | VL | MH | L | VL | L |
| C56. Hydroelectric energy potential | VL | L | MH | ML | VH | VL |
| C57. Biomass energy potential | MH | MH | MH | F | MH | F |
| C58. Environmental impact of renewable energy infrastructure | ML | F | MH | F | ML | F |

**Table 10**
$S_i$, $R_i$ and $Q_i$ values.

| | $S_i$ | $R_i$ | $Q_i$ | Ranking |
|---|---|---|---|---|
| **Konya** | 0.443 | 0.054 | 0.396 | **2** |
| **Izmir** | 0.450 | 0.035 | 0.017 | **1** |
| **Trabzon** | 0.671 | 0.054 | 0.892 | **5** |
| **Antalya** | 0.599 | 0.043 | 0.519 | **3** |
| **Sanliurfa** | 0.537 | 0.059 | 0.707 | **4** |
| **Canakkale** | 0.644 | 0.059 | 0.943 | **6** |

### *3.5. Comparative analysis*

This section provides a comparative analysis of the PiF-SWARA-VIKOR approach against four widely utilized MCDM methods within a picture-fuzzy environment: TOPSIS [64], SAW (Simple Additive Weighting) [65], WASPAS (A Weighted Aggregated Sum Product Assessment) [66], and WISP (Simple Weighted Sum-Product) [67]. These methods are selected due to their broad application in decision-making, particularly in infrastructure planning and site selection problems involving multiple evaluation criteria.

The comparison aims to assess the proposed approach's accuracy, consistency, and effectiveness relative to existing methodologies. By incorporating a picture fuzzy environment, the PiF-SWARA-PiF-VIKOR method effectively manages uncertainty and hesitancy in expert evaluations, a crucial factor in selecting optimal locations for data centers. Traditional MCDM methods typically rely on defuzzified or crisp values, which may lead to the loss of nuanced expert preferences.

To ensure an objective comparison, the rankings generated by all methods were defuzzified, and Spearman's rank correlation coefficient ($r_s$) was computed to evaluate the degree of alignment between the PiF-SWARA-PiF-VIKOR rankings and those derived from the other methods.

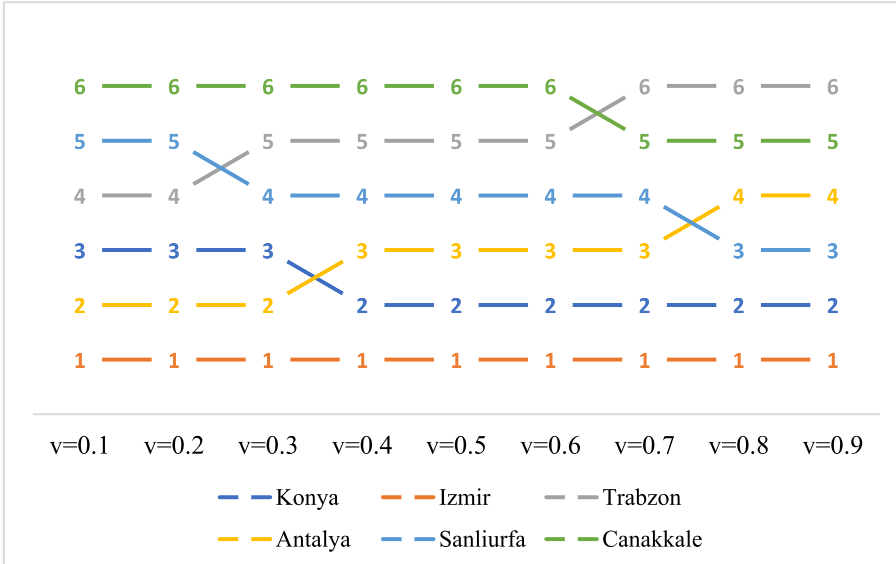


**Fig. 4.** The results of sensitivity analysis.

A high correlation suggests strong consistency between methodologies, reinforcing the validity of the proposed framework. The ranking outcomes for each method are presented in Table 11, offering a direct comparison of decision-making consistency across different techniques.

The comparative analysis of data center site rankings across different MCDM methods reveals a strong consistency between the proposed PiF-SWARA-PiF-VIKOR approach and traditional techniques, with Spearman's rank correlation coefficients ($r_s$) ranging from 0.77 to 0.88. İzmir consistently ranks as the most suitable location across all methods except TOPSIS, where it is placed second, demonstrating a high degree of agreement on its suitability due to its advanced infrastructure and strong renewable energy potential. Similarly, Konya remains a top contender, ranking either first or second, reinforcing its reliability as a viable site. The methods also largely align with Trabzon, which consistently ranks as the least favorable location due to potential logistical challenges. The strong agreement across methods further validates the robustness of the proposed approach, confirming its effectiveness in supporting strategic data center site selection.

## 4. Discussion

This paper presents a comprehensive approach to selecting data center locations focusing on integrating renewable energy, offering valuable insights for companies and policymakers. The analysis divides the main criteria—environmental, accessibility, economic, social, and renewable energy—into detailed sub-criteria based on a thorough literature review and expert input. Six alternative locations from various regions of Türkiye are evaluated, each with unique characteristics related to renewable energy use and field capacity.

The weights of the sub-criteria obtained through the PiF-SWARA method reveal the relative importance of various factors in the decision-making process. Seismic Intensity (C13) and Availability of Water Resources (C11) are highlighted as the most influential, with final weights of 0.0588 and 0.0580, respectively. This emphasis on environmental safety and resource availability aligns with existing research prioritizing these factors for operational resilience and sustainability [68,69]. The high weight of the Availability of Water Resources indicates the critical need for water in cooling and operational processes, which is corroborated by literature highlighting water as a crucial criterion for data center locations [70,71]. Similarly, the significant weight of Seismic Intensity reflects the importance of earthquake resilience, given Turkiye's seismic activity [2].

The prominence of Carbon Emissions (C15) with a final weight of 0.0537 underscores growing environmental concerns, consistent with recent studies advocating for reduced carbon footprints in infrastructure projects [72,73]. Other environmental criteria, such as Conflicts with Reserves and Natural Parks (C12), Climate (C14), and Environmental Impact of Renewable Energy Infrastructure (C58), also receive substantial weight, emphasizing the need for minimizing environmental impacts and achieving sustainability goals [74].

Among renewable energy criteria, Annual Average Sunshine Duration (C51) holds the highest weight (0.0536), reflecting Türkiye's significant solar potential [75]. The weights assigned to Annual Total Solar Radiation (C52), Wind Energy Density (C53), and Environmental Impact of Renewable Energy Infrastructure (C58) further highlight the importance of incorporating renewable energy considerations into site selection. Other factors, such as Geothermal Energy Potential (C54), Wave Energy Potential (C55), Hydroelectric Energy Potential (C56), and Biomass Energy Potential (C57), are also considered, reinforcing the need to evaluate a broad range of renewable energy options [76].

The significant weight given to Proximity to Telecommunications Networks (C21) [6] and Proximity to Renewable Energy Sources (C27) [77] further emphasizes the crucial role of connectivity and renewable energy integration in enhancing data center performance and sustainability. This finding aligns with contemporary research on integrating telecommunications and renewable energy for optimized data center operations. Conversely, criteria like Proximity to Main Road Access (C23) and Proximity to Railway (C24) receive lower weights, reflecting their lesser impact than environmental and energy considerations. These findings illustrate the increasing importance of renewable energy and environmental factors in data center location selection, consistent with current literature and best practices.

As a result of the evaluation with the PiF-VIKOR method, İzmir and

**Table 11**
Results of comparative analysis.

| | Proposed Approach | TOPSIS | SAW | WASPAS | WISP |
|---|---|---|---|---|---|
| Konya | **2** | 1 | 2 | 2 | 2 |
| Izmir | **1** | 2 | 1 | 1 | 1 |
| Trabzon | **5** | 6 | 6 | 6 | 6 |
| Antalya | **3** | 3 | 4 | 4 | 4 |
| Sanliurfa | **4** | 5 | 3 | 3 | 3 |
| Canakkale | **6** | 4 | 5 | 5 | 5 |
| **Rs** | – | 0.77 | 0.88 | 0.88 | 0.88 |

Konya emerged as the top two choices, with İzmir leading and Konya following closely. This outcome reflects the cities' strategic advantages regarding infrastructure, accessibility, and alignment with sustainability goals. İzmir's prominence in this ranking can be attributed to its robust infrastructure and strategic location. As a major economic hub, İzmir offers a well-developed transportation network, including ports and airports, facilitating efficient connectivity. The city's commitment to sustainability and renewable energy integration further enhances its appeal as a prime location for data centers. Konya's strong performance in the evaluation highlights its potential as a viable alternative for data center establishment. The city's expansive land availability and favorable environmental conditions provide a solid foundation for infrastructure development. Konya's emphasis on sustainable practices and renewable energy sources aligns with the growing demand for eco-friendly data center solutions.

To validate the practical relevance of the proposed methodology, real-world data from renewable energy reports [78] and development plans [79] are utilized to assess six alternative locations in Türkiye. The evaluation considered renewable energy potential, land availability, infrastructure, and accessibility, ensuring the rankings reflected actual site conditions. Additionally, expert consultations were conducted with renewable energy professionals, data center operators, and academics specializing in energy systems, who validated the feasibility of the selected locations and the reliability of the decision-making process. The results demonstrated that locations with strong solar and wind energy potential, along with well-developed infrastructure, ranked higher, consistent with industry trends and ongoing data center investments in Türkiye. The correlation between the proposed rankings and real-world data further confirms the practical applicability of the methodology, supporting its effectiveness in strategic site selection for data centers.

The results show that although there are difficulties in decision-making processes, MCDM methods are a suitable tool for solving such problems [80]. Theoretically, this study contributes to the literature by further developing the application of picture fuzzy set theory in MCDM. Picture fuzzy sets are particularly suitable for representing uncertainty, hesitation, and imprecision in expert judgments. Using PiF-SWARA for weighting and PiF-VIKOR for ranking, the research demonstrates how subjective expert judgments can be transformed into robust, mathematically based decisions, particularly in complex infrastructure planning scenarios. Operationally, the proposed framework assists decision-makers in evaluating multiple data center site alternatives while considering critical sustainability-related parameters. The integration of renewable energy criteria with multiple factors ensures a holistic and practical solution. The results provide clear guidance for prioritizing sites aligned with long-term sustainability goals, providing actionable insights for public and private sector stakeholders involved in digital infrastructure development.

## 5. Conclusion

The present study introduces a pioneering approach to data center site selection, which integrates a comprehensive set of criteria and sub-criteria, particularly emphasizing renewable energy factors. By utilizing the PiF-SWARA methodology to ascertain the weights of each criterion, the research offers a comprehensive and meticulous evaluation framework that emphasizes the pivotal role of renewable energy sources, such as solar and wind potential, while concurrently underscoring the relevance of conventional considerations, including infrastructure and operational costs. Combining the PiF-SWARA and PiF-VIKOR methodologies to evaluate and prioritize prospective data center locations establishes an MCDM framework. The proposed framework enhances precision in evaluation processes and addresses such decisions' inherent uncertainty and complexity by incorporating picture fuzzy sets. This methodology's emphasis on renewable energy represents a significant shift towards sustainability, aligning site selection processes with contemporary environmental and economic imperatives.

The PiF-VIKOR evaluation identified İzmir as the optimal location for a renewable energy-integrated data center, attributed to its robust infrastructure, extensive transportation networks, and significant investments in data center facilities. This result is attributed to the city's well-developed infrastructure, strong connectivity through its extensive transportation network, and significant renewable energy potential, particularly in solar and wind power. Additionally, İzmir benefits from a highly skilled workforce and a dynamic economic environment, making it an attractive destination for sustainable data center investments. Konya ranked second, offering vast land availability and high solar energy potential, making it a strong candidate for sustainable data center operations. However, its limited proximity to coastal transportation routes may pose logistical challenges. Both cities present compelling opportunities, with İzmir's advanced infrastructure and Konya's favorable environmental conditions as key advantages.

In addition, this study significantly contributes to the field of site selection by providing a more detailed and comprehensive analysis that considers the interrelationship between environmental sustainability and operational efficiency. Overall, in light of the research questions and the gap in the literature on how to integrate renewable energy into the data center site selection process, how to integrate sustainability principles, and how to apply the fuzzy-based framework with an expanded set of criteria, the main motivations of the study can be summarized as follows: A comprehensive set of criteria has been defined to select the most suitable data center location with a renewable energy integration and sustainability perspective, and a novel hybrid MCDM methodology has been developed that combines expert opinions with flexible criterion weighting and fuzzy logic under changing conditions. This study contributes to the literature by providing a robust MCDM tool for data center location selection with sustainable renewable energy integration and the proposed innovative approach. In addition, this study addresses the inherent uncertainties in the decision-making process and is unique in its ability to assess Turkiye's data center location selection process in light of comprehensive criteria. Therefore, this study proposes new and important contributions in terms of the proposed hybrid methodology and its application. Incorporating sophisticated MCDM methodologies guarantees that the decision-making process is comprehensive and adaptable to varying contextual circumstances and priorities. This research provides valuable insights for policymakers, businesses, and stakeholders involved in developing data centers. Furthermore, the proposed methodology facilitates more informed and sustainable decisions. It is a foundation for future studies to optimize site selection in other sectors where renewable energy plays a pivotal role. As the demand for energy-efficient and environmentally responsible data centers continues to grow, it will be necessary to apply such advanced decision-making frameworks to drive sustainable growth and innovation in this sector.

While the proposed PiF-SWARA–PiF-VIKOR framework offers a systematic and comprehensive approach for selecting data center locations with integrated renewable energy considerations, certain limitations should be noted. The reliance on expert evaluations introduces inherent subjectivity, which may persist even when processed through picture-fuzzy logic. Additionally, the model is built upon static data reflecting current renewable energy potential, infrastructure, and socio-economic conditions; however, these factors may evolve due to policy shifts, technological innovations, or environmental changes. The current study is also limited in geographical scope, focusing solely on six alternatives within Türkiye. Therefore, its generalizability to other countries or regions with different regulatory structures and energy landscapes remains to be explored.

Future research could address these limitations by adopting dynamic weighting mechanisms that respond to changing environmental, political, and technological conditions. Expanding the expert pool to include broader stakeholder representation may also enhance the robustness of the evaluation process. Additionally, the integration of machine learning techniques could support more adaptive and data-driven decision-making, allowing the model to adjust to real-time data and emerging trends automatically. These extensions would further strengthen the proposed framework's practical relevance and global applicability.

## CRediT authorship contribution statement

**Ertugrul Ayyildiz:** Writing – original draft, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Betul Yildirim:** Writing – original draft, Visualization, Validation, Methodology, Investigation, Data curation. **Nezir Aydin:** Writing – review & editing, Writing – original draft, Supervision, Resources, Project administration, Methodology.

## 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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