Renewable and Sustainable Energy Reviews 215 (2025) 115545

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Strategic site selection methodology for small modular reactors: A case study in Türkiye

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ARTICLE INFO

Keywords:
Multi-criteria decision making
Picture fuzzy set
Site selection
Small modular reactor
Sustainability

ABSTRACT

Selecting the optimal site for Small Modular Reactors (SMRs) ensures operational efficiency and safety and aligns with growing energy demands and environmental goals. Given the unique challenges of climate change and the need for sustainable energy solutions, this study's innovative approach provides critical insights for making informed decisions that balance economic, environmental, and social factors. This study introduces a novel hybrid multi-criteria decision-making (MCDM) approach for selecting optimal sites for SMR in Türkiye. The proposed methodology integrates Picture Fuzzy SWARA (PiF-SWARA) and Picture Fuzzy WASPAS (PiF-WASPAS) techniques to address site selection's complexities by evaluating criteria weights and alternative scores. PiF-SWARA is employed to determine the relative importance of five main criteria and 28 sub-criteria, providing a nuanced understanding of each criterion's impact. Subsequently, PiF-WASPAS ranks the alternative sites based on these weighted criteria. This approach ensures a robust evaluation by accommodating various uncertainties inherent in the decision-making process. The case study applied to Türkiye demonstrates the effectiveness of this method in identifying the most suitable locations for SMRs, highlighting its potential to advance the strategic planning of nuclear energy infrastructure. The study provides valuable insights for policymakers and stakeholders involved in energy planning and development.

1. Introduction

Abbreviations

SMR	Small Modular Reactors
MCDM	Multi-criteria decision-making
SWARA	Step-Wise Weight Assessment Ratio Analysis
WASPAS	Weighted Aggregated Sum Product Assessment
PiF-SWARA	Picture Fuzzy SWARA
PiF-WASPAS	Picture Fuzzy WASPAS
NPP	Nuclear power plant
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
AHP	Analytical Hierarchy Process
TOPSIS	Technique for Order Preference by Similarity
IFS	Intuitionistic fuzzy set
FS	Fuzzy set
PFWA	Picture Fuzzy Weighted Arithmetic
PiFN	Picture fuzzy numbers
WSM	Weighted sum model
WPM	Weighted product model

Global energy demand continues to rise with population growth, urbanization, and technological advancements. In response, policymakers actively seek sustainable, zero-emission power generation pathways to ensure energy security and environmental stewardship. Among the emerging solutions, thermal plasma-assisted systems have garnered significant attention due to their potential to minimize pollutant emissions to near-zero levels [1]. Thermal plasma, characterized by its high energy density and thermal equilibrium between heavy

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https://doi.org/10.1016/j.rser.2025.115545
Received 12 August 2024; Received in revised form 6 February 2025; Accepted 23 February 2025
Available online 6 March 2025
1364-0321/

particles and electrons, provides an effective platform for waste-to-energy conversion through pyrolysis, enabling the production of clean, high-temperature outputs [2,3]. Such systems highlight how innovative technologies can contribute to a cleaner energy mix.

While thermal plasma-assisted systems represent one promising avenue, other low-carbon innovations are also gaining traction. Small Modular Reactors (SMRs), for example, offer scalable, flexible, and relatively safer nuclear energy solutions with significantly reduced greenhouse gas emissions. However, despite their advantages, a critical gap exists in the strategic selection of SMR sites. Addressing this gap ensures that SMRs are not only technically and economically viable but also socially acceptable and environmentally sound, thereby complementing broader zero-emission strategies in the energy sector.

Distributed generation refers to small-scale power sources that generate electricity close to the distribution network, playing a crucial role in modern energy systems. SMRs, a type of distributed generation, are emerging as a pivotal solution in this landscape [4]. These reactors are designed to be compact, scalable, and capable of being deployed closer to the point of use, which enhances grid stability and reduces transmission losses. As energy systems evolve, they face significant challenges such as outages, high costs, and the need for greater efficiency and sustainability. Integrated smart energy systems, which combine various energy sources, are expected to overcome these challenges by optimizing energy use and minimizing waste [5].

SMRs, which can be integrated into these smart energy systems, offer continuous power generation and are ideally suited to cover the grid's base load [5]. Compared to traditional nuclear power plants (NPPs), SMRs are safer, more cost-effective, and more flexible. Their modular design allows for shorter construction times and the ability to scale capacity according to demand [6]. With a maximum capacity of 300 MW [7,8], SMRs require less land and can be seamlessly integrated into existing electrical networks, reducing the environmental and logistical challenges associated with large-scale NPPs [9].

Beyond electricity generation, SMRs provide additional benefits, such as reducing greenhouse gas emissions, supplying heat and power for resource extraction and heavy industry, and supporting the production of hydrogen and district heating [10]. Their transportability and adaptability make them ideal for use in remote or isolated areas where traditional energy infrastructure may be impractical [4]. Moreover, SMRs can be used in various applications, enhancing the resilience and versatility of the energy grid [11]. Given these numerous advantages, SMRs are poised to play a key role in the future of energy generation, offering economic and environmental benefits.

1.1. Research motivation

When planning for new energy infrastructure, particularly nuclear power, the choice of location becomes a critical factor that can influence the long-term success and safety of the project. The selection of a power plant's site is a strategic decision that significantly influences a country's energy policy and overall infrastructure planning [12]. When it comes to nuclear facilities, including SMRs, the purpose of site selection is to identify a location that can be safely designed and operated while meeting stringent radiological and safety requirements [13]. Given that SMRs are an emerging technology, their site selection process must account for numerous factors, including environmental, societal, and technological considerations. For instance, climate change plays a crucial role in site selection, as it may lead to environmental hazards and operational disruptions due to extreme weather events [14]. Moreover, the impact on surrounding communities and the need for enhanced security measures are essential components of this decision-making process [15]. Therefore, selecting a suitable site for SMRs involves a comprehensive evaluation of environmental conditions, societal factors, and potential natural disasters, all of which have far-reaching consequences.

This study aims to address the gap in the existing literature by introducing a novel hybrid MCDM approach for selecting the optimal site for SMRs in Türkiye. As a developing country with growing energy demands, Türkiye faces a critical challenge in determining the most appropriate locations for power plants that will meet its future energy needs [12]. This study applies MCDM methods to the SMR site selection problem for the first time in the literature, offering a systematic approach to this complex issue. Specifically, the study proposes using picture fuzzy (PiF) SWARA to determine the weights of five main criteria and 28 sub-criteria, followed by applying picture fuzzy WASPAS to evaluate and rank alternative sites based on these weighted criteria.

This study aims to address the current gap in the literature by examining the SMR site selection process from a strategic sustainability perspective. In doing so, it seeks to answer two key research questions.

- How can sustainability principles be effectively integrated into the SMR site selection process?
- How can the decision-making process for SMR site selection be enhanced using a fuzzy-based framework?

In light of these questions, the primary motivations of the study are as follows: A comprehensive set of criteria is considered to determine the most suitable SMR location from a sustainability perspective and an innovative hybrid MCDM methodology, which integrates fuzzy logic for flexible criteria weighting and robust alternative ranking across varying conditions, is proposed.

The main contributions of this study are threefold: (i) It pioneers the use of a hybrid MCDM approach to determine the most suitable SMR site, marking the first application of MCDM methods in this context. (ii) The study identifies five main criteria and 28 sub-criteria within a sustainability framework, encompassing infrastructure, geography, energy, safety, and social factors. (iii) The integration of the SWARA and WASPAS methods within a picture fuzzy environment provides an innovative framework for decision-making in SMR site selection, with PiF-SWARA used for criteria weighting and PiF-WASPAS applied to rank the alternative sites based on these criteria. This approach offers a robust, comprehensive solution to the complex challenge of SMR site selection, contributing valuable insights to nuclear energy planning.

Section 2 provides a summary of the relevant literature. The theoretical background of this study is explained in Section 3. Section 4 details the application of the PiF-SWARA and PiF-WASPAS methods used to determine the criteria weights and evaluate the alternative sites. Section 5 presents a case study on SMR site selection in Türkiye. Section 6 discusses the results of the analysis, and Section 6 concludes with final remarks and suggestions for future research.

1.2. Literature review

A detailed literature analysis has been conducted and is presented in this section to ascertain the studies that will serve as the base for the research and the uniqueness and contribution of this study to the body of relevant literature. The SCOPUS database has been utilized to look through books, papers, and conference proceedings that might be used as study references. The PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) technique has been employed to perform an exhaustive and methodical search of the literature [16]. PRISMA has been an increasingly popular tool among academics for conducting thorough literature reviews in recent years. The PRISMA technique was developed by Moher et al. [16], and it offers more structured methods and lessens the chance of bias while conducting literature analysis. The search process for literature was conducted between August 01, 2024 and August 11, 2024 utilizing the keywords presented in Table 1, resulting in 58 articles in the SCOPUS platform.

Papers directly connected to the subject area are found after the literature search by defining inclusion and exclusion criteria. The goal is to select comparable studies to serve as the investigation's starting point and allow for comparing the results. The inclusion and exclusion criteria

Table 1
Keywords for literature review.

Keywords	# of paper
(TITLE-ABS-KEY ("Small Modular Reactor") AND TITLE-ABS-KEY ("site selection"))	13
(TITLE-ABS-KEY ("Small Modular Reactor") AND TITLE-ABS-KEY ("location selection"))	0
(TITLE-ABS-KEY ("Modular Reactor") AND TITLE-ABS-KEY ("site selection"))	15
(TITLE-ABS-KEY ("Modular Reactor") AND TITLE-ABS-KEY (site) AND TITLE-ABS-KEY (selection))	20
(TITLE-ABS-KEY ("Modular Reactor") AND TITLE-ABS-KEY (location) AND TITLE-ABS-KEY (selection))	6
(TITLE-ABS-KEY ("small Reactor") AND TITLE-ABS-KEY (site) AND TITLE-ABS-KEY (selection))	4

for the papers are displayed in Table 2.

When the papers found during the literature search are filtered using the criteria in Tables 2 and it is seen that 15 of them could be used as references for this study. Table 3 has been added to show the differences between these studies and our research and how they contribute to the literature.

In addition, a summary of some papers we have reached via literature search that directly guided and contributed to our study is given below. Shrestha et al. [11] presented a novel approach for choosing appropriate locations for small modular reactor (SMR) power generation units based on fuzzy AHP (FAHP) and the analytical hierarchy process (AHP). Preferable locations are defined by taking into account location-dependent factors such as transmission lines, switching stations, electrical and non-electrical loads, present and retiring generation, and renewable energy generation. Leite Maia et al. [20] suggest an MCDM method for choosing the location of small reactor compartment temporary storage facilities, emphasizing the Brazilian scenario. Almalki et al. [22] suggests implementing a two-stage procedure for assessing geographic factors in Saskatchewan's small modular reactor (SMR) site selection with (i) identifying potential site locations based only on available geographic, economic, and logistical data and (ii) honing the potential locations based on social norms, political will, and public perceptions. Shrestha et al. [4] presented a structure utilizing the AHP and Fuzzy AHP algorithms. To create a ranking system for selecting appropriate locations for SMR power generation units, the proposed model considers location-dependent factors such as transmission lines, switching stations, electrical and non-electrical loads, and existing and retiring generation.

The papers in Table 3, which were most similar to this study and could form a basis, have been examined in detail. First of all, when the relevant literature was scanned in detail, it was observed that a limited number of studies had been found. The first thing that stands out about the papers is that SMR site selection concept studies have generally been conducted in Canada. Mathematical modeling has been a frequently used method for SMR, as in other facility location problems. Although a small part of the studies is carried out based on MCDM methods, the repeated use of the same methods is noticeable. Besides, it has been determined that fuzzy logic, one of the best ways to reflect uncertainty in decision-making problems, has yet to find enough space in current studies, and no calculation has been conducted with extended fuzzy numbers.

Table 2
The inclusion and exclusion criteria for literature review.

Inclusion Criteria	Exclusion Criteria
The studies include site selection initiatives for the small modular reactor facilities	Studies whose full text could not be reached
The studies include the location selection in considering small modular reactor facilities	Studies that do not explicitly mention the method used and the results
The studies include the site selection in considering small reactor facilities	Studies that are written in languages other than English

However, unlike all studies reviewed in the literature, this study addresses the issue of which site should be selected for an SMR in Türkiye for the first time by using a hybrid MCDM methodology under a fuzzy environment. In addition, a novel fuzzy hybrid MCDM method has been adopted in methodological terms, enabling the simultaneous evaluation of many conflicting criteria. Picture fuzzy sets, an extended form of ordinary fuzzy sets, have been utilized to transfer the assessment of the experts consulted in the study to the findings in a linguistically accurate manner and as close to reality as feasible.

When the papers conducted are examined in general, no study has been found that addresses the SMR site selection problem in this detail for Türkiye and adopts a unique fuzzy hybrid MCDM approach, as in this study. At this point, our study will be a first in the literature in terms of the level of detail, the focal study area, and the method adopted, and it will serve as a guide for researchers who want to study this topic. Unlike all the studies examined in the literature, for the first time in this paper, the SMR location selection problem for Türkiye has been addressed, and a detailed evaluation structure has been created within this scope. In terms of methodology, for the first time, the hybrid MCDM approach, which consists of SWARA and WASPAS methods, has been modeled within the framework of picture fuzzy sets. Using the flexibility and advantages provided by picture fuzzy sets, the practical and reasonable steps of SWARA and WASPAS methods in determining the criterion weights and ranking the alternatives have been utilized. The ranking of the alternatives is obtained successfully.

1.3. Theoretical background

Picture fuzzy sets, introduced by Cuong and Kreinovich in Ref. [25], serve as an advanced extension of intuitionistic fuzzy sets (IFSs). They are particularly beneficial when multiple response options, such as yes, no, abstain, and reject, are available, making them ideal for voting processes. Traditional IFSs are limited in scenarios where decision-makers may need to distribute probabilities across these varied responses [26]. Picture fuzzy sets improve upon traditional fuzzy sets (FSs) and IFSs by incorporating a more comprehensive range of response possibilities, thus better handling uncertainty and imprecision [25]. The theory of Picture fuzzy sets includes operators that extend the concepts of FSs and IFSs, making them particularly useful for managing ambiguous and uncertain information, especially in MCDM contexts [27,28].

Picture fuzzy numbers (PiFNs) provide a detailed representation of fuzzy and uncertain data, minimizing information loss in practical decision-making. Despite their benefits, there is still a scarcity of research on resilience evaluation using picture-fuzzy information. Picture fuzzy sets offer a more precise and comprehensive method for expressing evaluation information than FSs and IFSs, particularly when decision-makers must consider four response types: for, against, neutral, and refusal [29]. In essence, Picture fuzzy sets extend the capabilities of FSs, IFSs, and hesitant fuzzy sets by encompassing a broader array of responses, providing a more nuanced and accurate framework for tackling complex decision-making scenarios [30]. Basic definitions of Picture fuzzy sets are elaborated in Refs. [25,26,31].

Definition 1. Picture fuzzy set of the universe of discourse U.

$$\widetilde{A}_p = \left\{ \langle u, \left(\mu_{\widetilde{A}_p}(u), I_{\widetilde{A}_p}(u), \nu_{\widetilde{A}_p}(u) \right) \middle| u \in U \right\} \tag{1}$$

membership degree of element u:

$$\mu_{\widetilde{A}_p}(u) : U \rightarrow [0, 1] \tag{2}$$

indeterminacy degree of element u:

$$I_{\widetilde{A}_p}(u) : U \rightarrow [0, 1] \tag{3}$$

Table 3
Literature review results.

#	Author(s)	Aim	Adopted Methods	Country	Paper Type
1	Chmielewska-Śmietanko et al. (2024) [17]	to address interdisciplinary research on Poland's nuclear energy development.	Review Paper	Poland	Article
2	Temiz and Dincer (2024) [5]	to create a solar and small modular reactor-based system for multigeneration.	Simulation	Turkiye, Spain, Japan, USA, Canada	Article
3	Luo et al. (2023) [18]	to minimize the overall cost of heating by locating a small nuclear reactor facility	System Dynamics	China	Proceeding
4	Shrestha et al. (2022) [11]	to choose appropriate sites for SMR power generation units.	AHP, Fuzzy AHP	Canada	Article
5	Liu et al.(2022) [19]	to provide a small modular reactor siting model with optimization assistance to help with timing, size, and siting decisions.	Interval two-stage stochastic programming	Canada	Article
6	Leite Maia et al. (2022) [20]	to suggest a multi-criteria decision-making process for choosing the location of the reactor compartment interim storage facility	AHP	Brazil	Proceeding
7	Xiaoyue et al. (2021) [15]	to create a climate-focused strategy for SMR site recognition to find possible locations that work well for SMR placement.	Fuzzy AHP, Fuzzy TOPSIS	Canada	Article
8	Luo et al. (2021) [7]	to suggest an SMR siting model with constraints for regional electric power system planning.	Interval linear programming, chance-constrained programming, and mixed-integer programming	Canada	Article
9	Gao et al. (2021) [21]	to develop an SMR positioning model that takes into account the multiple complexities of the power system	Multistage stochastic programming, Chance-constrained programming	Canada	Article
10	Zhang et al. (2020) [10]	to examine the SMRs' development process, technical attributes, and possible uses	Review Paper	–	Article
11	Devanand et al. (2019) [9]	to develop a new mathematical methodology for assessing possible land locations for modular NPP.	Mixed Integer Non-linear Programming	Singapore	Article
12	Almalki et al. (2019) [22]	to concentrate on the objective geographic factors while choosing an SMR site	Fuzzy AHP, Geospatial Analysis	Canada	Article
13	Shrestha et al. (2018) [4]	to provide a rating system for selecting appropriate sites for SMR power-producing units.	AHP, Fuzzy AHP	Canada	Proceeding
14	Zhang et al. (2018) [23]	to find possible SMR sites in Saskatchewan using the multi-criteria decision analysis method	Multi-criteria analysis	Canada	Article
15	Wang et al. (2018) [24]	to examine the SMR emergency planning zone's classification system using feedback from conventional nuclear power plants	Conditional probability approach	China	Proceeding

non-membership degree of element u:

$$v_{\tilde{A}_p}(u) : U \rightarrow [0,1] \tag{4}$$

$$\mu_{\tilde{A}_p}(u) + I_{\tilde{A}_p}(u) + v_{\tilde{A}_p}(u) \leq 1 \tag{5}$$

$\mu_{\tilde{A}_p}(u), v_{\tilde{A}_p}(u)$ and $I_{\tilde{A}_p}(u)$ are membership degree, non-membership degree, and indeterminacy degree of u to $\tilde{A}_p$, respectively. Based on these values, the degree of refusal can be calculated.

refusal degree of element u:

$$\chi_{\tilde{A}_p} = 1 - \left(\mu_{\tilde{A}_p}(u) + v_{\tilde{A}_p}(u) + I_{\tilde{A}_p}(u)\right) \tag{6}$$

Definition 2. Basic mathematical operations on two PiFNs $\widetilde{A}_p = \left(\mu_{\tilde{A}_p}, I_{\tilde{A}_p}, v_{\tilde{A}_p}\right)$ and $\widetilde{B}_p = \left(\mu_{\tilde{B}_p}, I_{\tilde{B}_p}, v_{\tilde{B}_p}\right)$ [32,33].

addition:

$$\widetilde{A}_p \oplus \widetilde{B}_p = \left\{\mu_{\tilde{A}_p} + \mu_{\tilde{B}_p} - \mu_{\tilde{A}_p}\mu_{\tilde{B}_p}, I_{\tilde{A}_p}I_{\tilde{B}_p}, v_{\tilde{A}_p}v_{\tilde{B}_p}\right\} \tag{7}$$

multiplication:

$$\widetilde{A}_p \otimes \widetilde{B}_p = \left\{\mu_{\tilde{A}_p}\mu_{\tilde{B}_p}, I_{\tilde{A}_p}I_{\tilde{B}_p}, v_{\tilde{A}_p} + v_{\tilde{B}_p} - v_{\tilde{A}_p}v_{\tilde{B}_p}\right\} \tag{8}$$

scalar power:

$$\widetilde{A}_p^{\lambda} = \left\{\mu_{\tilde{A}_p}^{\lambda}, I_{\tilde{A}_p}^{\lambda}, \left(1 - \left(1 - v_{\tilde{A}_p}\right)^{\lambda}\right)\right\} \tag{9}$$

scalar multiplication:

$$\lambda \cdot \widetilde{A}_p = \left\{\left(1 - \left(1 - \mu_{\tilde{A}_p}\right)^{\lambda}\right), I_{\tilde{A}_p}^{\lambda}, v_{\tilde{A}_p}^{\lambda}\right\} \tag{10}$$

Definition 3. Picture Fuzzy Weighted Arithmetic (PFWA) operator is given below concerning $w = (w_1, w_2, \ldots, w_n)$; $0 \leq w_j \leq 1$; $\sum_{j=1}^{n} w_j = 1$.

$$\text{PFWA}_w\left(\widetilde{A}_1, \ldots \widetilde{A}_i, \ldots, \widetilde{A}_n\right) = \left\{1 - \prod_{j=1}^{n}\left(1 - \mu_{\tilde{A}_j}\right)^{w_j}, \prod_{j=1}^{n} I_{\tilde{A}_j}^{w_j}, \prod_{j=1}^{n} v_{\tilde{A}_j}^{w_j}\right\} \tag{11}$$

Here $\widetilde{A}_i = \left(\mu_{\tilde{A}_j}, I_{\tilde{A}_j}, v_{\tilde{A}_j}\right)$ are PiFNs and w_i is the importance assigned to each PiFN.

Definition 4. The score function for a PiFN $\widetilde{A}_p = \left(\mu_{\tilde{A}_p}, I_{\tilde{A}_p}, v_{\tilde{A}_p}\right)$.

$$\text{Score}\left(\widetilde{A}_p\right) = \left(2\mu_{\tilde{A}_p} - v_{\tilde{A}_p} - \frac{I_{\tilde{A}_p}}{2}\right) \tag{12}$$

2. The proposed methodology

This study presents an innovative approach to selecting the optimal location for a modular reactor by integrating the WASPAS and SWARA methods within a picture-fuzzy environment for the first time. This novel methodology offers a comprehensive framework for tackling complex MCDM problems. In the proposed methodology, we employ PiF-SWARA and PiF-WASPAS to evaluate and determine the optimal location for an SMR. The process begins with applying PiF-SWARA to establish the relative importance of criteria via pairwise comparisons. PiF-SWARA is utilized to determine the relative importance of each criterion by allowing experts to express their preferences in terms of picture fuzzy numbers, thus capturing a wider range of opinions, including agreement, disagreement, neutrality, and refusal. Subsequently, PiF-WASPAS is applied to rank the alternative locations based on the weighted criteria, combining both additive and multiplicative approaches to provide a comprehensive assessment. Utilizing Picture Fuzzy Sets provides a more detailed representation of membership, non-membership, and indeterminacy values, thereby increasing the accuracy and reliability of the decision-making process. Fig. 1 illustrates the flowchart of the proposed methodology.

2.1. Picture fuzzy SWARA

SWARA is an MCDM method designed to determine the criteria weights and rank them in order of importance. Originally developed by Ref. [34], SWARA is a decision-maker-oriented method that emphasizes subjective judgment, allowing decision-makers to prioritize criteria based on current conditions. This method places a strong emphasis on the role of experts, who are crucial in providing the subjective inputs necessary to assign weights to the criteria [35,36].The critical feature of SWARA is its reliance on expert opinions to establish the relative importance of each criterion. In this study, we utilize the PiF-SWARA approach to determine the importance weights of both main and sub-criteria at each hierarchical level. The PiF-SWARA methodology involves the following steps. Here are the parameters for PiF-SWARA.

C_i: Each criterion to be evaluated

k_j: Comparative significance, capturing how the current criterion compares to the previous one.

q_j: Recalculated weight, an intermediate step in deriving the final weight.

w_j: Final normalized weight for criterion j.

n: Total number of criteria.

Step 1. Create an initial decision matrix by gathering expert assessments for each criterion, utilizing the linguistic terms provided in Table 4.
Step 2. Aggregate the expert evaluations via the PFWA operator to form a picture fuzzy decision matrix, reflecting the varied linguistic inputs as picture fuzzy values.
Step 3. Calculate the crisp score values.
Step 4. Rank the criteria in descending order based on their crisp score values.
Step 5. Determine the comparative significance of each criterion by calculating the difference in score values between the current criterion (j) and the previous one (j-1).
Step 6. Compute the comparative coefficient.

Table 4
Linguistic terms for PiF-SWARA.

Linguistic Terms	PiFNs (μ, I, ν)
VHI-Very High Importance	(0.9, 0.01, 0.05)
HI-High Importance	(0.75, 0.05, 0.1)
MHI-Medium High Importance	(0.65, 0.07, 0.25)
MI-Medium Importance	(0.5, 0.1, 0.4)
MLI-Medium Low Importance	(0.35, 0.07, 0.5)
LI-Low Importance	(0.25, 0.05, 0.6)
VLI-Very Low Importance	(0.1, 0.01, 0.85)

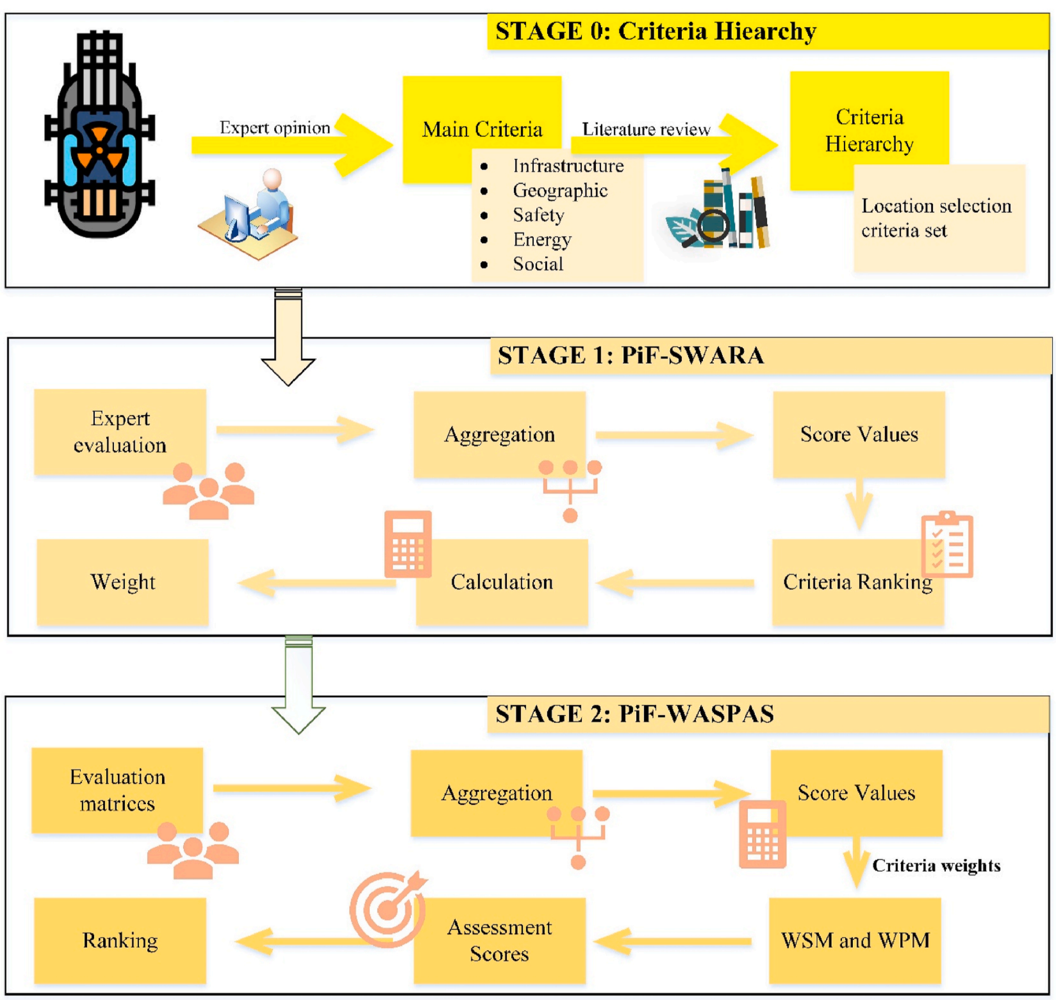

Fig. 1. Flowchart of the proposed methodology.

$$k_j = \begin{cases} 1, j = 1 \\ s_j + 1, j > 1 \end{cases} \tag{13}$$

Step 7. Estimate the recalculated weights.

$$q_j = \begin{cases} 1, j = 1 \\ \dfrac{q_{(j-1)}}{k_j}, j > 1 \end{cases} \tag{14}$$

Step 8. Finalize the criteria weights, ensuring the sum of weights corresponds to the total number of criteria *n*.

$$w_j = \frac{q_j}{\sum_{j=1}^{n} q_j} \tag{15}$$

2.2. Picture fuzzy WASPAS

For the modular reactor site selection study, we employed the MCDM method WASPAS, which Zavadskas introduced [37,38]. WASPAS combines two well-established MCDM techniques: the weighted sum model (WSM) and the weighted product model (WPM) [39–41]. This hybrid approach is often applied to MCDM problems and can be extended with various fuzzy set theories [42], including Picture fuzzy sets [43]. The WSM aspect of WASPAS calculates the overall score of each alternative as a weighted sum of attribute values. In contrast, the WPM aspect mitigates the impact of subpar attribute values by raising each attribute's value to a power equal to its corresponding weight [44]. In our study, picture fuzzy numbers are utilized to determine the weights used in the WASPAS method, allowing for a more nuanced representation of uncertainty and expert opinion. The detailed steps of the PiF-WASPAS methodology are outlined below.

Step 1. Construct a picture fuzzy evaluation matrix using the linguistic terms in Table 5 to assess the options based on the given criteria.

$\widetilde{Y}_{ij}^{k}$ denotes the picture fuzzy evaluation value of the alternative *i* according to criterion *j* by expert *k*.

Step 2. Aggregate the expert opinions by applying the PFWA operator, considering each expert's weight. $\widetilde{X}_{ij}$ is the aggregated evaluation of alternative *i* according to criterion *j*.
Step 3. Calculate crisp score values aggregated evaluations. X_{ij} shows the crisp equivalent of $\widetilde{X}_{ij}$.
Step 4. Normalize the decision matrix based on criteria type.

For benefit criteria;

$$r_{ij} = \frac{X_{ij}}{\max_j X_{ij}} \tag{16}$$

For cost criteria;

$$r_{ij} = \frac{\min_j X_{ij}}{X_{ij}} \tag{17}$$

Step 5. Compute the weighted sum model (Q^1) for alternatives.

$$Q_i^1 = \sum_{j=1}^{n} w_j\, r_{ij} \tag{18}$$

Step 6. Compute the weighted product model (Q^2) for alternatives.

$$Q_i^2 = \prod_{j=1}^{n} r_{ij}{}^{w_j} \tag{19}$$

Step 7. Determine the threshold value (λ) and combine the weighted sum model and weighted product models using λ.

$$Q_j = \lambda Q_i^1 + (1 - \lambda) Q_i^2 \tag{20}$$

λ takes values between 0 and 1. When $\lambda = 1$, the decision is made solely based on the WSM, and when $\lambda = 0$, it relies entirely on the WPM. Choosing $\lambda = 0.5$ assigns equal weight to both models, ensuring the final score is an unbiased combination of the additive (WSM) and multiplicative (WPM) approaches. This default value is commonly adopted in the literature [45–47] to maintain a balanced integration of both models. However, λ can be adjusted based on decision-maker preferences or specific problem contexts.

Step 8. Rank the alternatives in descending order based on their score values.

Table 5
Linguistic terms for PiF-WASPAS.

Linguistic Terms	PiFNs $(\boldsymbol{\mu}, \boldsymbol{I}, \boldsymbol{\nu})$
VH-Very High	(0.90, 0.01, 0.05)
H-High	(0.75, 0.05, 0.15)
MH-Moderately High	(0.60, 0.05, 0.30)
F-Fair	(0.50, 0.10, 0.40)
ML-Moderately Low	(0.30, 0.05, 0.60)
L-Low	(0.20, 0.05, 0.70)
VL-Very Low	(0.10, 0.01, 0.80)

3. Real case application in Türkiye

Türkiye, a rapidly developing country with a population exceeding 85 million, is grappling with escalating energy demands, making the selection of optimal power plant sites a pressing issue. As the nation strives to enhance its energy infrastructure, identifying suitable locations for SMRs becomes crucial. This study addresses this challenge by focusing on the strategic selection of SMR sites within Türkiye [12]. Choosing an appropriate power plant location requires careful consideration of various factors, including safety, geographic conditions, and social impact. For instance, sufficient water resources are essential for both power plant operations and cooling systems, while high population density poses potential safety risks due to adverse effects on nearby communities [48]. Moreover, avoiding sites near seismic fault lines is vital to mitigate the risk of earthquakes and enhance overall safety [9]. Fig. 2 provides a comprehensive overview of the main and sub-criteria used in this study to evaluate potential SMR locations.

Five main criteria and 28 sub-criteria were determined from the sustainability perspective, with experts' views and NPP and SMR literature for the problem being handled, as explained in Table 6.

Site selection for nuclear facilities is essential for the safe establishment and operation of these facilities [49]. Thus, suitable alternative sites for SMRs should be determined by considering many of the criteria in Table 6. At this stage, we have determined five alternative sites from different areas of Türkiye based on previously determined regions and chosen for the nuclear power plant location in Türkiye by the Ministry of Energy and Natural Resources and the Turkish Atomic Energy Authority. These alternatives (see Fig. 3) are relatively far from active fault lines and have a large land area.

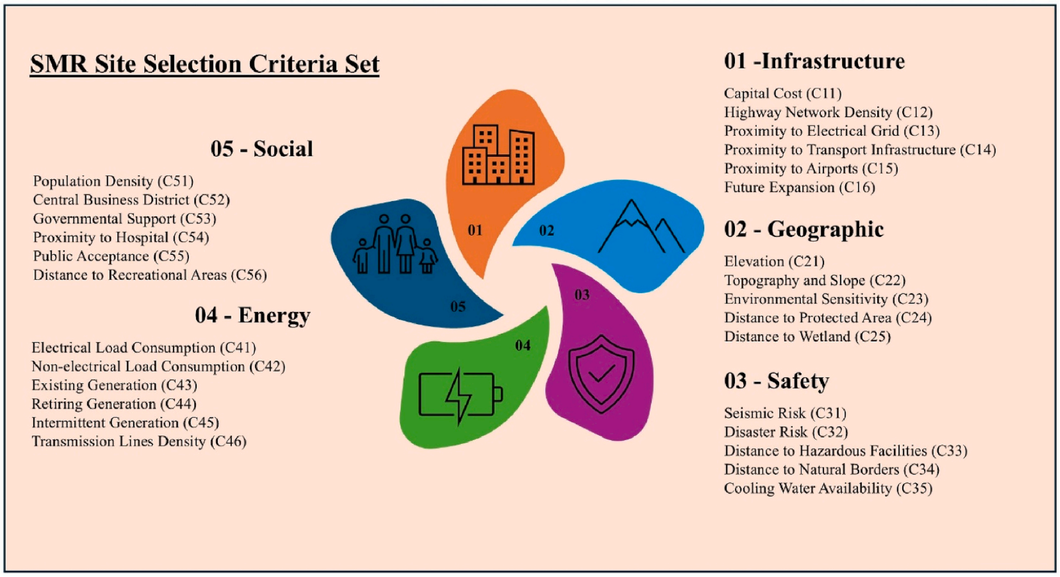

Fig. 2. Main criteria and sub-criteria.

3.1. *Calculation of criteria weights with PiF-SWARA*

In this section, criteria weights were decided by four expert evaluations. In the first step, experts evaluate the main criteria and the sub-criteria using the linguistic terms in Table 4. The experts' assessment of the main criteria is shown in Table 7.

Then, the PiF-SWARA method is applied, and the main criteria weights are calculated, as shown in Fig. 4.

According to Fig. 4, the main criteria weights obtained with the PiF-SWARA method demonstrate that safety and infrastructure are the most important criteria for SMR site selection. Safety is vital in site selection as SMRs contain many important applications and data. Possible dangers and threats create negative processes for the digital security of governments and the public. In addition, the importance of infrastructure-related factors for these facilities is evident. Experts selected the least important factor, which is social. However, it was realized that social and energy criteria weights are very close.

And then, the same experts evaluate the sub-criteria, as drawn in Table 8. The PiF-SWARA method was applied step by step to calculate the local weights of the sub-criteria. The final weights of the sub-criteria are calculated by multiplying the weights of the main criteria with the consistent sub-criteria weights, as presented in Table 9.

According to the weight of the sub-criteria related to the main "Safety" criterion (see Table 7), "Seismic Risk (C31)", "Disaster Risk (C32)" and "Cooling Water Availability (C35)" are the most important criteria. Addressing these criteria effectively ensures that SMRs are sited in locations that meet technical and safety requirements and contribute to sustainable and efficient energy production. The outcomes of this research are expected to support Türkiye's energy strategy by providing actionable insights into optimal SMR site selection, ultimately contributing to the country's long-term energy security and environmental sustainability.

3.2. *Calculation of alternative scores with PiF-WASPAS*

The scores of alternative sites were calculated by integrating the criteria weights obtained with PiF-SWARA into the PiF-WASPAS method. For this purpose, five different alternative sites in Türkiye, shown in Fig. 3, were evaluated by the proposed approach.

The first step in evaluating alternative sites includes constructing a decision matrix, which facilitates assessing decisions based on the linguistic terms outlined in Table 3. PiF-WASPAS method allows a thorough and precise evaluation of the alternative locations by considering multiple criteria and their respective importance. The criteria-alternative assessment is shown in Table A1 in the Appendix.

After converting the linguistic terms into PiFNs, using the aggregated values, Q_j values were calculated, and the alternatives were ranked in descending order based on their score values, as shown in Table 10. λ is set to 0.5 to combine the weighted sum and weighted product models.

According to Table 10, *A1-Seydişehir* is determined as the best alternative site for SMR in Türkiye. This alternative is flat and expandable land, especially away from the active fault line, close to water resources, and with good infrastructure opportunities, as it is located in the Mediterranean Region Lakes region. The *A5-Kırıkkale* was selected as the second most important alternative. *A4-İğneada* was determined as the worst location for an SMR site. The safety and infrastructure criteria are the most essential features that put this station in the background.

3.3. *Sensitivity analysis*

In this study, sensitivity analysis was conducted by examining changes in the threshold value. As highlighted in Step 5, while Equation (20) provides a recommended approach for calculating the coefficient λ, it can also be assigned a crisp value within the range of 0.1–1.0 in increments of 0.1. The first part of the sensitivity analysis explores the impact of varying the coefficient λ, as presented in Table 11.

This approach demonstrates the robustness of the decision-making process. The final rankings of all alternatives across different threshold values are presented in Fig. 5.

The impact of threshold values on the rankings of potential SMR locations is evaluated through sensitivity analysis, which is crucial due to the differing outcomes generated by the weighted sum and weighted product models. As depicted in Fig. 5, A1 consistently emerges as the top choice across all scenarios, underscoring its robustness as the most viable site for SMR deployment. This stability is critical for ensuring the safety and efficiency of the reactor. Conversely, A5 consistently ranks last, reinforcing the reliability of the results. The observed variations in rankings with different threshold values highlight the model's sensitivity, ensuring that the SMR site selection process remains adaptable and dependable under varying conditions.

3.4. *Comparative analysis*

This subsection compares the proposed approach with three

Table 6
Definitions of sub-criteria.

Sub-criteria	Definitions	Source
Capital Cost (C11)	The cost of constructing the SMR plant	[9]
Highway Network Density (C12)	The availability and accessibility of significant highways near the site	[15]
Proximity to Electrical Grid (C13)	The distance to the nearest connection point to the electrical grid	[49]
Proximity to Transport Infrastructure (C14)	The accessibility of various transportation modes	[49]
Proximity to Airports (C15)	The distance to the nearest airport,	[50]
Future Expansion (C16)	The availability of land and resources for the potential future deployment of additional SMR modules	Expert view
Elevation (C21)	The site's elevation above sea level and its susceptibility to flooding	[49]
Topography and Slope (C22)	The physical characteristics of the land influencing the suitability for SMR module placement and foundation construction	[49]
Environmental Sensitivity (C23)	The presence of sensitive ecosystems, protected areas, or endangered species in the vicinity	[49]
Distance to Protected Area (C24)	The distance to national parks, wildlife reserves, or other protected areas	[48]
Distance to Wetland (C25)	The proximity to wetlands and water bodies impacts potential hydrological and ecological disruptions	[48]
Seismic Risk (C31)	The likelihood and potential severity of earthquakes in the region	[9]
Disaster Risk (C32)	The susceptibility of the site to various natural disasters like floods, landslides, or wildfires	[51]
Distance to Hazardous Facilities (C33)	The proximity to industrial plants, chemical facilities, or other hazardous sites poses potential risks to the SMR and necessitates additional safety measures.	[49]
Distance to Natural Borders (C34)	The distance to national borders or coastlines influences security considerations and potential geopolitical complexities.	[49]
Cooling Water Availability (C35)	The availability of sufficient water resources for cooling the SMR is crucial for its safe and efficient operation.	[9]
Electrical Load Consumption (C41)	The amount of electricity consumed in the region indicates the potential demand.	[11]
Non-electrical Load Consumption (C42)	The demand for energy for non-electrical purposes, such as district heating or industrial processes	[11]
Existing Generation (C43)	The presence of other power plants in the area influences the need for additional generation capacity and potential grid connection challenges.	[11]
Retiring Generation (C44)	The number of power plants nearing retirement in the region presents opportunities for the SMR to replace aging infrastructure and provide cleaner energy.	[11]
Intermittent Generation (C45)	The level of renewable energy generation from sources like wind and solar affects grid stability.	[11]
Transmission Lines Density (C46)	The availability and capacity of existing transmission infrastructure	[15]
Population Density (C51)	The number of people living in the vicinity affects safety considerations, emergency planning, and potential social impacts.	[9]
Central Business District (C52)	The distance to major economic centers influences access to skilled labor and supporting infrastructure.	[51]
Governmental Support (C53)	The level of support and cooperation from local and national authorities	Expert View
Proximity to Hospital (C54)	The distance to healthcare facilities is essential for emergency response	Expert View
Public Acceptance (C55)	The level of support from the local community	[12]
Distance to Recreational Areas (C56)	The proximity to parks, natural areas, or tourist destinations affects potential visual and environmental impacts.	Expert View

commonly used MCDM methods: SAW (Simple Additive Weighting) (Afshari et al., 2010), EDAS (Evaluation based on Distance from Average Solution) (Ghorabaee et al., 2015), and CODAS (Combinative Distance-Based Assessment) (Keshavarz Ghorabaee et al., 2016). The goal of this comparison is twofold: to assess the accuracy and efficiency of the proposed method and to identify its relative advantages and limitations. To ensure a fair comparison, the rankings derived from each method were defuzzified, and Spearman's rank correlation coefficient (r_s) was calculated to gauge the strength of the relationship between the results of the proposed method and those of the other approaches. The final rankings, along with the computed correlation coefficients, are presented in Table 12.

The correlation coefficients exceed 0.6, indicating a strong agreement between the rankings generated by the proposed method and the reference methods. This outcome validates both the reliability and robustness of the proposed approach. This comparative analysis offers more profound insights into its performance and practical utility by illustrating how it performs alongside established methods.

Furthermore, these findings hold particular significance for the problem of modular reactor site selection, where safety, sustainability, and stakeholder acceptance are paramount. The high-rank correlation coefficients demonstrate that the proposed method, which integrates fuzzy logic and a tailored set of criteria, produces results that are broadly consistent with established MCDM approaches. For nuclear and SMR projects—where the cost of poor site selection can be substantial—the ability to confirm that different methods converge on a similar conclusion helps build confidence among policymakers, regulators, and community stakeholders. By revealing a strong agreement across multiple decision-making frameworks, this analysis underscores the robustness of the proposed approach.

4. Discussion

This paper proposes a methodical approach to selecting the optimal site SMRs in Türkiye, emphasizing the importance of various criteria and sub-criteria in the evaluation process. Key findings indicate that "safety" and "infrastructure" emerged as the most critical criteria for SMR site selection, while "social" factors were deemed less significant. This prioritization is consistent with the operational requirements of SMR facilities, where mitigating risks associated with natural disasters and ensuring robust infrastructure are paramount. The "safety" criterion, encompassing risks such as seismic activity and disaster potential, is crucial as any failure in this area could lead to catastrophic outcomes. Likewise, infrastructure factors like proximity to transportation and cooling water resources are vital for the efficient operation and sustainability of SMRs.

With their significantly lower radioactive inventory, SMRs are scalable nuclear power plant designs that promise to lower investment risks through incremental capacity expansion, become more standardized and result in cost reductions through accelerated learning effects, and allay fears of catastrophic events [52]. Incorporating nuclear safety into the entire lifespan and stressing its significance during the design stage and in the national regulatory framework is crucial for designers, vendors, and nuclear regulators [53]. Simpler designs, improved safety and dependability, the capacity to perform on a balanced power market, power generation for a larger range of consumers, and applications such as district heating, water desalination, and commercial hydrogen production are just a few of the expected advantages that the SMRs provide [54]. Concerns about possible safety hazards and the environmental effects of treating nuclear waste influence decisions about the future of nuclear energy in addition to goals for climate mitigation and economic feasibility [55].

SMRs should prioritize the implementation of intrinsic and/or engineered safety features, safety systems, and procedures that can prevent reactor core damage or major off-site releases and restore the facility to a safe state [56]. SMRs are critical infrastructures and can be

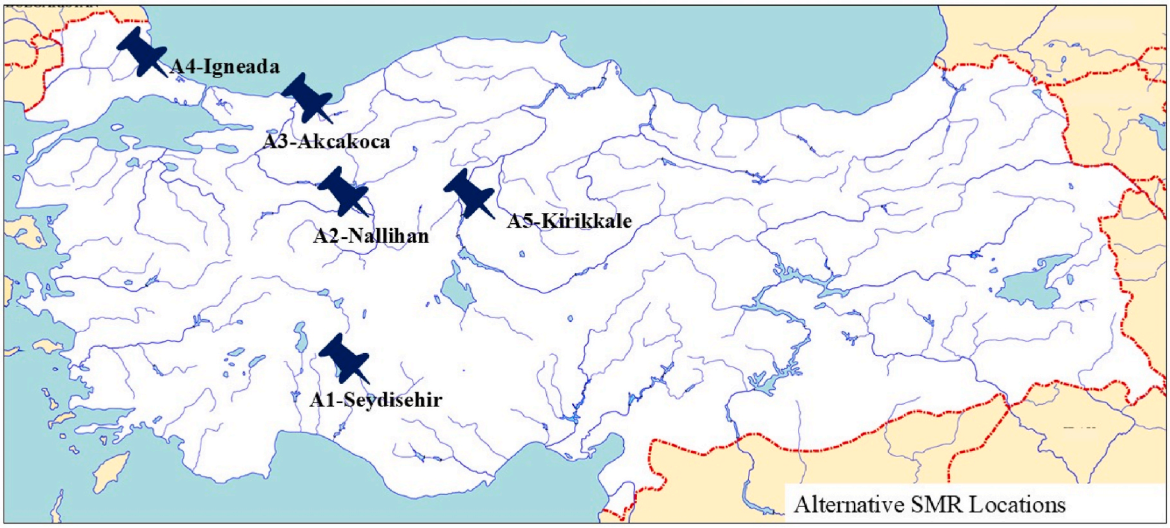

Fig. 3. Alternative locations.

Table 7
Expert evaluations for main criteria.

PiF-SWARA				
	E1	E2	E3	E4
Infrastructure	HI	VHI	VHI	HI
Geographic	VHI	HI	HI	HI
Safety	VHI	VHI	VHI	VHI
Energy	MHI	MHI	MHI	MHI
Social	MLI	MHI	MHI	HI

developed for use in remote areas. Therefore, terrorist attacks and other malicious acts should also be considered when addressing security. Regarding natural disasters and cyber security, resilience and redundancy measures are given extra importance in site selection [53].

One of the main concerns about nuclear deployment in developing countries is that these countries generally have a less mature regulatory regime compared to advanced industrial countries and require very stringent requirements on plant reliability and safety performance [52]. SMRs can more readily satisfy the need for higher levels of safety by incorporating extra layers of "defense in depth" and optimizing the usage of passive and inherent safety measures [52]. Improved site compatibility, the use of cutting-edge passive safety measures, lower initial construction costs, and lower inventories on both the main and secondary sides of the reactor system are some of the specific benefits that SMRs have over their bigger counterparts [57]. The location of SMRs is heavily influenced by technical considerations, such as security and safety. SMRs are appealing alternatives for power generation because of their improved safety features as compared to conventional reactors, and they have sophisticated passive safety features that minimize primary and secondary-side inventory and lower construction capital costs [57,58].

The analysis highlighted "Seismic Risk (C31)", "Disaster Risk (C32)", and "Cooling Water Availability (C35)" as the most significant subcriteria under the "safety" criterion. The importance of these factors aligns with prior research emphasizing the necessity of avoiding locations with high earthquake or natural disaster risks and ensuring reliable access to cooling water [6,40]. Furthermore, the "Distance from Protected Area (C24)" under the "Geographic" criterion also received substantial weight, reflecting the need to avoid ecologically sensitive areas such as national parks and wetlands to minimize environmental impact [46].

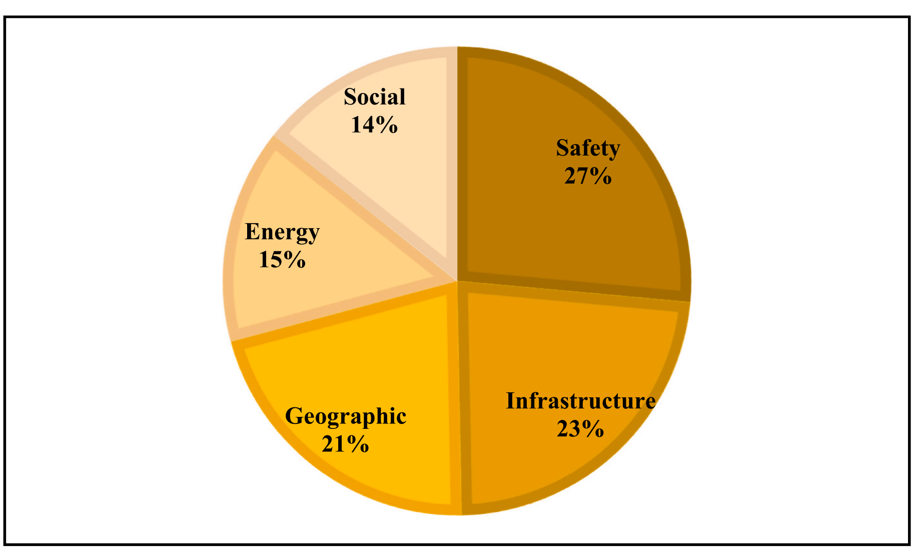

Fig. 4. Main criteria weights.

Table 8
Expert evaluations for sub-criteria.

Sub-criteria/Experts	E1	E2	E3	E4
Capital Cost (C11)	MHI	HI	MHI	LI
Highway Network Density (C12)	MI	MHI	MHI	MHI
Proximity To Electrical Grid (C13)	MHI	VHI	MHI	MHI
Proximity To Transport Infrastructure (C14)	MI	HI	MHI	MHI
Proximity To Airports (C15)	MI	MHI	MLI	HI
Future Expansion Availability (C16)	HI	HI	MLI	MHI
Elevation And Flood Level (C21)	MHI	VHI	MHI	MI
Topography And Slope (C22)	MLI	HI	MHI	LI
Environmental Sensitivity (C23)	MHI	MHI	MHI	MHI
Distance From Protected Area (C24)	HI	HI	MHI	HI
Distance From Wetland (C25)	MHI	HI	MHI	MHI
Seismic Risk (C31)	VHI	VHI	VHI	VHI
Disaster Risk (C32)	VHI	VHI	HI	HI
Distance to Hazardous Facilities (C33)	HI	HI	HI	HI
Distance to Natural Borders (C34)	MI	MHI	MHI	MHI
Cooling Water Availability (C35)	HI	VHI	HI	MHI
Electrical Load Consumption (C41)	HI	HI	MHI	LI
Non-electrical Load Consumption (C42)	HI	MHI	MI	LI
Existing Generation (C43)	MHI	HI	MHI	LI
Retiring Generation (C44)	MI	MHI	MI	MI
Intermittent Generation (C45)	MI	MHI	MHI	MI
Transmission Lines Density (C46)	MHI	VHI	MHI	MHI
Population Density (C51)	MHI	VHI	HI	HI
Central Business District (C52)	MI	MHI	MLI	MI
Governmental Support (C53)	HI	HI	MLI	HI
Proximity to Hospital (C54)	MI	HI	MLI	HI
Public Acceptance (C55)	MHI	HI	MLI	MI
Distance to Recreational Areas (C56)	MI	MHI	HI	MI

Table 9
Sub-criteria weights.

Sub-Criteria	Local Weight	Final Weight	Rank
Capital Cost (C11)	0.1546	0.0359	12
Highway Network Density (C12)	0.1515	0.0352	13
Proximity To Electrical Grid (C13)	0.2089	0.0485	6
Proximity To Transport Infrastructure (C14)	0.1663	0.0386	11
Proximity To Airports (C15)	0.1453	0.0338	15
Future Expansion Availability (C16)	0.1733	0.0403	9
Elevation And Flood Level (C21)	0.2245	0.0474	7
Topography And Slope (C22)	0.1528	0.0323	18
Environmental Sensitivity (C23)	0.1865	0.0394	10
Distance From Protected Area (C24)	0.2333	0.0493	4
Distance From Wetland (C25)	0.2028	0.0429	8
Seismic Risk (C31)	0.2587	0.0684	**1**
Disaster Risk (C32)	0.2271	0.0601	**2**
Distance to Hazardous Facilities (C33)	0.1835	0.0486	5
Distance to Natural Borders (C34)	0.1328	0.0351	14
Cooling Water Availability (C35)	0.1979	0.0524	**3**
Electrical Load Consumption (C41)	0.1805	0.0268	19
Non-electrical Load Consumption (C42)	0.1511	0.0225	23
Existing Generation (C43)	0.1652	0.0246	21
Retiring Generation (C44)	0.1335	0.0198	27
Intermittent Generation (C45)	0.1476	0.0219	25
Transmission Lines Density (C46)	0.2221	0.0330	17
Population Density (C51)	0.2324	0.0332	16
Central Business District (C52)	0.1195	0.0171	28
Governmental Support (C53)	0.1870	0.0268	20
Proximity to Hospital (C54)	0.1610	0.0230	22
Public Acceptance (C55)	0.1462	0.0209	26
Distance to Recreational Areas (C56)	0.1539	0.0220	24

Among the evaluated alternatives, A1-Seydişehir was identified as the most suitable site for SMR facilities in Türkiye. Located centrally in the Mediterranean Lakes Region, A1-Seydişehir benefits from proximity to water resources, a favorable distance from protected areas, and a high potential for future expansion. Despite Türkiye's status as an earthquake-prone region, the evaluated sites did not significantly differ in seismic risk, indicating that other factors may weigh more heavily in

Table 10
Ranking of alternatives.

	Weighted sum	Weighted product	Final score	Rank
A1-Seydişehir	0.785	0.800	0.793	**1**
A2-Nallıhan	0.739	0.747	0.743	3
A3-Akçakoca	0.744	0.716	0.730	4
A4-İğneada	0.680	0.596	0.638	5
A5-Kırıkkale	0.742	0.745	0.743	2

Table 11
Final scores of alternatives for different coefficients.

	A1	A2	A3	A4	A5
λ=0	0.800	0.747	0.716	0.596	0.745
λ=0.1	0.799	0.746	0.719	0.604	0.744
λ=0.2	0.797	0.745	0.722	0.613	0.744
λ=0.3	0.796	0.745	0.725	0.621	0.744
λ=0.4	0.794	0.744	0.728	0.630	0.744
λ=0.5	0.793	0.743	0.730	0.638	0.743
λ=0.6	0.791	0.742	0.733	0.646	0.743
λ=0.7	0.790	0.742	0.736	0.655	0.743
λ=0.8	0.788	0.741	0.739	0.663	0.743
λ=0.9	0.787	0.740	0.741	0.672	0.742
λ=1	0.785	0.739	0.744	0.680	0.742

the final decision (see Table A1 in Appendix). Conversely, A4-İğneada was ranked the least favorable option, primarily due to its inferior performance in infrastructure-related sub-criteria. The selection of Seydişehir (A1) as the most suitable site illustrates the efficacy of the proposed methodology and demonstrates its capacity to evaluate and rank alternative sites with precision.

These findings underscore the critical role of "safety" and "infrastructure" in the site selection process for SMRs. The results emphasize the need for careful consideration of these factors to ensure the selection of a site that meets operational and safety requirements, thereby supporting Türkiye's strategic energy needs and enhancing its long-term energy security. This robustness is essential in SMR deployment, where safety and infrastructure considerations must be carefully balanced against other factors, such as geographic and environmental impacts.

The sensitivity analysis further confirmed the model's stability and demonstrated that the proposed methodology is adaptable and reliable across various decision-making scenarios. The consistent ranking of Seydişehir as the top choice, irrespective of changes in the coefficient λ, reinforces its suitability as the preferred site for SMR installation in Turkiye. The proposed methodology's adaptability and consistent performance are critical in ensuring that the selected site can meet Turkiye's energy demands while minimizing potential risks.

Conversely, İğneada's low ranking (A4) underscores the pivotal role of infrastructure in site selection. The region's deficiencies in infrastructure-related sub-criteria illustrate the potential obstacles to selecting a site that does not fully align with the rigorous operational demands of SMRs. This finding reinforces the imperative for policymakers to prioritize infrastructure development in prospective SMR sites to ensure these facilities' safety and efficient operation.

It is important to note that the results are not validated through conventional laboratory experiments or large-scale simulations, as the study focuses on a decision-making framework built upon expert input and literature-driven criteria. This approach is consistent with established MCDM practices, where complex, context-specific decisions—such as SMR site selection—rely on synthesizing expert judgments, regulatory standards, and documented best practices. Although no direct test setups or simulation data are provided, the robustness and reliability of the outcomes are enhanced through carefully selecting criteria, using a fuzzy-based aggregation methodology to manage uncertainty and the application of sensitivity analyses.

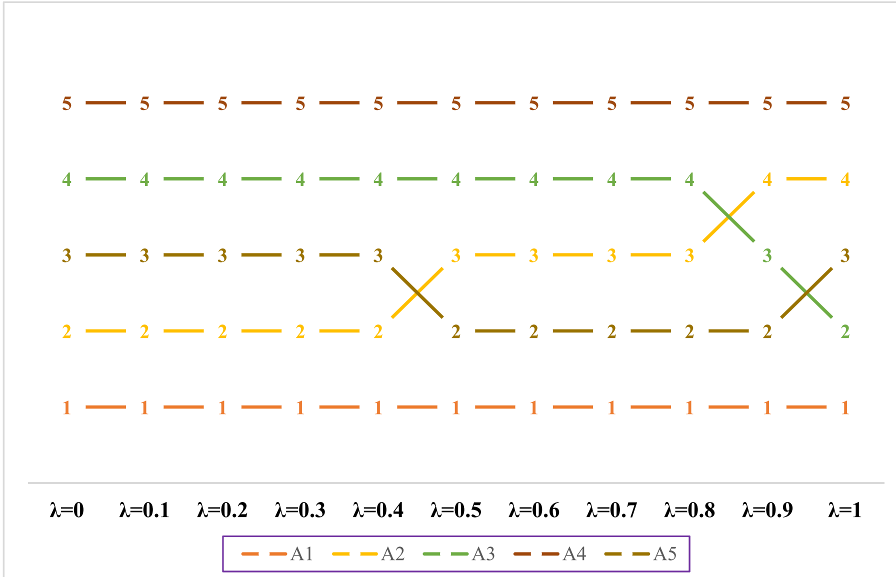

Fig. 5. Results of sensitivity analysis.

Table 12
Results of comparative analysis.

	Proposed Approach	SAW	EDAS	CODAS
A1-Seydişehir	**1**	1	1	**1**
A2-Nallıhan	**3**	4	4	3
A3-Akçakoca	**4**	2	2	2
A4-İğneada	**5**	5	5	5
A5-Kırıkkale	**2**	3	3	4
Rs		0.7	0.7	0.6

5. Conclusion

Planning for new energy infrastructure, especially nuclear power, makes site selection crucial since it might affect the project's long-term safety and success. The strategic choice of where to locate a power plant significantly impacts a nation's energy policy and overall infrastructure planning. SMRs are perfect for covering the basic load of the grid since they provide continuous power generation. SMRs are more flexible, safer, and more affordable than conventional nuclear power stations (NPPs). Their modular design makes shorter building timeframes and capacity scaling in response to demand possible. With their advantages for the economy and the environment, SMRs are positioned to play a significant part in energy generation in the future. Finding a location that can be safely developed and operated while satisfying strict radiological and safety standards is the aim of site selection for SMRs. Since SMRs are a new technology, several factors, such as technological, sociological, and environmental factors, must be taken into account while choosing a site. As a result, choosing a good location for SMRs requires a thorough assessment of the social, environmental, and natural disaster risks—all of which have significant ramifications. Considering all these situations, this study employs a comprehensive methodology to identify optimal locations for SMRs in Turkiye. This novel approach integrates a hybrid MCDM framework that combines PiF-SWARA and PiF-WASPAS techniques. The methodology has been devised to address the inherent complexities and uncertainties associated with selecting an appropriate location, ensuring a balanced evaluation of the economic, environmental, and social factors involved in such a decision.

The study's findings highlight the importance of two primary criteria in selecting SMR sites: "safety" and "infrastructure." The research identifies several key sub-criteria as essential considerations for ensuring the safe and efficient operation of SMRs. These include seismic risk, disaster risk, and the availability of cooling water. The case study, conducted in Türkiye, effectively validates the efficacy of the proposed methodology. The analysis reveals that Seydişehir possesses the most favorable geographical attributes and robust infrastructure, becoming the optimal location for SMR deployment. Moreover, sensitivity analysis substantiates the reliability and stability of the site selection process, even under conditions of uncertainty.

Overall, this study contributes to the field of energy planning by providing a robust and adaptable framework for SMR site selection. Applying PiF-SWARA and PiF-WASPAS methods offers a systematic approach to evaluating multiple criteria, allowing for informed decision-making that balances economic, environmental, and social factors. The findings are particularly relevant for policymakers and stakeholders in Türkiye, offering actionable insights to guide the strategic planning of nuclear energy infrastructure. By prioritizing safety and infrastructure, this study supports the country's energy strategy and contributes to its long-term energy security and environmental sustainability.

Despite these contributions, several research gaps remain. For instance, future studies could incorporate dynamic criteria weights that reflect changing policy priorities, technological advancements, and evolving environmental conditions. Additionally, more extensive stakeholder engagement could be included to capture diverse perspectives better and improve public acceptance. Advanced computational techniques like machine learning may also be integrated to refine data processing and prediction capabilities. By pursuing these research directions, further improvements in SMR site selection can be achieved, ultimately contributing to a more resilient, sustainable, and acceptable nuclear energy infrastructure.

Further research might extend the SMR site selection process by including factors like geopolitical stability. This would create a more comprehensive evaluation framework. Incorporating dynamic environmental data, such as real-time seismic activity and climate projections, would facilitate implementing a more adaptive site assessment process, allowing for the incorporation of changing conditions. The methodology could be extended to other regions and energy technologies (for example, renewable energy plants), thus broadening its applicability. Advanced uncertainty modeling techniques, such as Monte Carlo simulations, could further enhance sensitivity analysis, facilitating a more robust assessment of site selection outcomes.

CRediT authorship contribution statement

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

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.

Appendix

Table A1
Expert evaluations for alternative locations

Criteria/Alternatives	E1					E2					E3					E4				
	A1	A2	A3	A4	A5	A1	A2	A3	A4	A5	A1	A2	A3	A4	A5	A1	A2	A3	A4	A5
Capital Cost (C11)	H	VH	H	MH	H	L	F	MH	VH	F	F	F	F	F	F	VH	H	ML	F	H
Highway Network Density (C12)	H	H	VH	F	MH	F	MH	ML	L	F	ML	MH	F	H	VH	VH	ML	L	L	MH
Proximity To Electrical Grid (C13)	VH	VH	VH	H	VH	F	F	F	ML	ML	MH	MH	MH	ML	MH	H	H	MH	MH	MH
Proximity To Transport Infrastructure (C14)	VH	H	VH	F	H	F	H	ML	L	F	ML	H	MH	MH	MH	MH	H	VH	F	ML
Proximity To Airports (C15)	F	H	MH	H	VH	L	F	ML	MH	VH	MH	H	H	H	VH	H	H	ML	MH	L
Future Expansion Availability (C16)	VH	H	H	MH	VH	H	H	ML	M	H	H	H	H	F	H	F	ML	F	F	H
Elevation (C21)	VH	VH	VH	H	VH	ML	ML	MH	MH	L	H	MH	ML	ML	MH	MH	MH	VL	VL	ML
Topography And Slope (C22)	VH	H	MH	H	VH	MH	ML	MH	MH	H	VH	MH	ML	ML	F	H	MH	ML	F	ML
Environmental Sensitivity (C23)	MH	H	MH	VH	H	MH	H	H	VH	ML	MH	F	F	F	MH	H	H	L	VL	H
Distance From Protected Area (C24)	VH	H	H	VH	H	MH	MH	ML	VL	H	MH	MH	MH	MH	MH	MH	MH	L	VL	H
Distance From Wetland (C25)	VH	VH	H	VH	H	MH	H	ML	VL	MH	F	F	F	F	F	H	H	VL	VL	F
Seismic Risk (C31)	VH	VH	H	MH	VH	MH	H	ML	L	ML	H	MH	MH	H	H	H	MH	VL	L	MH
Disaster Risk (C32)	VH	H	MH	MH	VH	ML	MH	MH	ML	L	F	F	F	F	F	VH	VH	VL	L	MH
Distance to Hazardous Facilities (C33)	H	MH	H	VH	MH	F	ML	ML	F	ML	F	F	F	F	F	H	VL	F	VH	L
Distance to Natural Borders (C34)	VH	VH	MH	VH	VH	H	MH	L	VL	H	VH	VH	F	L	VH	VH	VH	H	VL	ML
Cooling Water Availability (C35)	VH	H	VH	VH	MH	L	L	VH	VH	H	L	L	H	H	MH	L	H	ML	ML	ML
Electrical Load Consumption (C41)	MH	H	VH	H	H	MH	ML	MH	L	H	F	F	F	F	F	H	VH	F	ML	ML
Non-electrical Load Consumption (C42)	H	MH	VH	H	H	MH	ML	MH	L	H	F	F	F	F	F	H	VH	ML	ML	L
Existing Generation (C43)	VH	VH	VH	H	VH	ML	L	MH	L	H	F	F	F	F	F	VH	VH	F	MH	MH
Retiring Generation (C44)	VH	VH	VH	H	VH	L	L	MH	L	MH	F	F	F	F	F	MH	H	ML	L	F
Intermittent Generation (C45)	H	VH	VH	MH	VH	MH	ML	MH	MH	L	F	F	F	F	F	MH	MH	MH	H	H
Transmission Lines Density (C46)	VH	H	VH	H	VH	M	L	M	L	MH	F	F	F	F	F	VH	VH	H	MH	H
Population Density (C51)	VH	H	MH	VH	H	MH	ML	MH	L	M	L	H	MH	MH	MH	VL	VL	F	F	ML
Central Business District (C52)	VH	H	VH	H	MH	L	M	MH	ML	M	L	H	H	H	H	H	VH	MH	MH	F
Governmental Support (C53)	H	VH	H	H	VH	ML	ML	ML	MH	H	F	F	F	F	F	VH	F	MH	VH	F
Proximity to Hospital (C54)	H	VH	H	MH	H	H	H	M	MH	M	F	F	F	F	F	H	VH	H	MH	MH
Public Acceptance (C55)	H	H	H	MH	VH	L	M	VL	VL	M	H	H	L	L	H	H	ML	L	L	H
Distance to Recreational Areas (C56)	H	MH	H	VH	MH	M	MH	VL	VL	M	F	F	F	F	F	H	MH	VL	VL	F

Data availability

The data supporting this study's findings are available from the corresponding author upon reasonable request.

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