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An integrated fuzzy optimal location selection model for setting up floating solar photovoltaic plant: Implications for energy sustainability in Bangladesh

Md. Zahidul Anam [a,b], A. B. M. Mainul Bari [a,*], Dipayan Basak [a], Md. Atik Foysal [c], Asif Raihan [d], Abu Reza Md. Towfiqul Islam [e]

[a] Department of Industrial and Production Engineering, Bangladesh University of Engineering and Technology, Dhaka 1000, Bangladesh
[b] Department of Operations and Supply Chain Management, American International University, Bangladesh, Dhaka, 1229, Bangladesh
[c] Department of Electrical and Electronic Engineering, Islamic University of Technology, Gazipur, 1704, Bangladesh
[d] Institute of Forestry and Environmental Sciences, University of Chittagong, Chittagong, 4331, Bangladesh
[e] Department of Disaster Management, Begum Rokeya University, Rangpur, 5404, Bangladesh

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ABSTRACT

Floating Solar Photovoltaic (FSPV) plants have emerged as a promising solution, harnessing solar energy while utilizing water bodies effectively, especially for emerging economy countries with limited land resources like Bangladesh. However, selecting an optimal location for such a solar plant requires a comprehensive evaluation of multiple criteria. This research, therefore, proposes a multi-criteria decision-making framework that integrates the Fuzzy Best Wort Method (F-BWM) and Fuzzy Combined Compromise Solution (F-CoCoSo) method to determine the optimal location for establishing a floating solar photovoltaic plant in Bangladesh. Through literature review and expert validation, ten key criteria were identified for suitable site selection for FSPV. Relative weights of the identified evaluation criteria were calculated using the F-BWM method. Following that, the F-CoCoSo approach was employed to rank the eight alternative potential sites in Bangladesh based on the F-BWM weights. The F-BWM result indicates that solar irradiance, terrain elevation, and conflicts over water access are the three most significant factors in selecting the site for FSPV installation. F-CoCoSo results identified the Kaptai Lake, located in southeastern Bangladesh, and Barapukuria Coal Mine's Lake, located in northwestern Bangladesh, as the two most preferable sites for installing FSPV plants. The research findings are expected to help academicians, policymakers, energy planners, and investors by offering a nuanced understanding of the significance of various technical, environmental, and social criteria for FSPV installation projects. Additionally, it offers a robust framework for site selection that enhances the efficiency, sustainability, and feasibility of FSPV projects in Bangladesh.

1. Introduction

The global energy market started to shrink since 2021 due to rapid economic recovery following the COVID-19 pandemic. However, the situation intensified significantly into a severe worldwide energy crisis due to the conflict between Russia and Ukraine in recent years. This polarization has put pressure on energy imports in different parts of the world, particularly in Bangladesh and other countries that are rapidly industrializing and experiencing economic growth [1]. In order to achieve the objective of the Paris Agreement, which is to keep the increase in global temperature to 1.5 °C over pre-industrial levels by the year 2100, a comprehensive transformation in the global energy production and consumption methods is necessary [2]. For Bangladesh to align with this target, it is crucial to transition from the conventional dependence on fossil fuels to sustainable renewable energy sources. Within this context, the implementation of floating solar photovoltaic (FSPV) technology emerges as a feasible option for sustainable energy generation in Bangladesh, aligning with the Sustainable Development Goals (SDGs). In recent times, Bangladesh has been putting efforts into increasing the installed capacity in power generation, but mostly, these

* Corresponding author.
E-mail addresses: 1018082110@ipe.buet.ac.bd, zahidul.anam@aiub.edu (Md.Z. Anam), mainul.ipe@gmail.com (A.B.M.M. Bari), dipayonbasak309@gmail.com (D. Basak), shuvo99@iut-dhaka.edu (Md.A. Foysal), asifraihan666@gmail.com (A. Raihan), towfiq_dm@brur.ac.bd (A.R.Md.T. Islam).

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are based on conventional sources like coal, natural gas, heavy fuel oil (HFO), etc. [3,4]. In order to tackle this issue, it is imperative for the country to augment the proliferation of renewable energy technologies (RET) within the energy sector.

Because floating solar power systems have so many benefits over their conventional land-based equivalents, there has been a noticeable increase in interest in these systems worldwide in recent years. The integration of the floating photovoltaic (FSPV) technique offers numerous benefits in terms of power production. According to Manolache et al. [5], FSPV offers 11 % higher generation efficiency compared to land-based ones. Besides, FSPVs aid in water preservation by reducing evaporation levels by as much as 70 % [6,7]. Moreover, they offer additional benefits, such as enhancing water quality by curbing algae proliferation, mitigating dust accumulation, minimizing maintenance costs, and conserving land resources [8].

When considering the global state of FSPV technology diffusion, it is still a relatively novel idea in many regions of the world. Although there have been some recent initiatives in Europe and China, the technology is still in its infancy and is addressing concerns such as the complexity of designing, building, and operating on water, uncertainty regarding environmental effects, particularly with regard to electrical safety, and mooring/anchoring issues [9]. In the context of Bangladesh, the country's abundant water surface area presents a unique opportunity for harnessing solar energy through floating solar installations.

Bangladesh receives high solar radiation most of the time of the year, which makes it a promising area for solar power generation [10,11]. However, due to the high population density in the country, there is an increasing conflict between the need to preserve the environment and the necessity of converting agricultural land or forests for FSPV installation sites [12,13]. It is noteworthy to highlight the abundance of open water reservoirs in Bangladesh, including lakes, rivers, and other aquatic systems, which together account for around 10 % of the country's total geographical area [14]. Thus, utilizing this extensive water resource for harnessing solar energy through floating solar plant installation presents a promising prospect to meet urban electricity demand sustainably and curb greenhouse gas (GHG) emissions in the country. Analysis by Islam et al. [13] also demonstrated that by utilizing only 10 % of the surface area of the 14 Lakes of the capital Dhaka, roughly 93.8 Gigawatt-Hour (GWh) power could be generated annually, proving the prospect of this renewable energy technology (RET) in this country.

In spite of its demonstrated potential, it has very little footprint in this country so far. A pilot project of a 10-kW FSPV plant was installed on a pond in the Bagerhat district [13]. Apart from that, the FSPV plant was installed in the Chapainawabganj district and connected to the national grid in 2023 with a generation capacity of only 2.30 MW, whereas IFC projects that the nation has the opportunity to produce approximately 11,000 Gigawatt peak (GWp) power from FSPV [15].

Bangladesh has set a goal for the production of RE, seeking to achieve 20 % RE in the overall energy mix by 2030 [16]. At present, renewable energy sources constitute only 4.44 % of the total installed power capacity, predominantly solar power [17]. Although the government has prioritized the power sector, it is largely fossil fuel-based. As a result, the goal is now more difficult and ambitious [18]. Among the country's energy sources, natural gas contributes 40 %, which is a great concern as Bangladesh's natural gas reserves are likely to be exhausted by about 2030 [19]. In this scenario, Bangladesh must emphasize FSPV, a promising renewable energy source, as part of its global commitment to a low-carbon development path.

Several recent studies have been conducted focusing on site selection for floating solar installations. Deveci et al. [20] introduced a model named LAAW and RAFSI, based on fuzzy rough numbers, to identify appropriate locations for floating solar installations, highlighting the efficacy of fuzzy rough numbers in handling uncertainty and enhancing decision-making precision. Gökmener et al. [21] performed a location appraisal study using a fuzzy sine trigonometric-based Ordinal Priority Approach (OPA). Göllü [22] employed the Analytical Hierarchy Process (AHP) and Ordered Weighted Averaging (OWA) for the evaluation as well as the ranking of suitable locations for FSPV deployment in Turkey. Karipoğlu et al. [23] carried out a suitability analysis for FSPV locations using a GIS-Fuzzy AHP hybrid approach. Nebey et al. [24] utilized GIS and AHP to identify the most favorable water body in the Amhara region of Ethiopia for FSPV installations. Vagiona et al. [25] employed an Entropy-based Weight Method (EWM), AHP, and the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) to rank suitable locations for offshore solar farms (OSF). Di Grazia & Tina [26] conducted a study for Italy using Geographic Information Systems (GIS) and Multi-Criteria Decision Analysis (MCDA) to allocate FSPV optimally. Zubair et al. [27] utilized the AHP method to compare factors like solar irradiance, land storage, and energy, determining the optimal FSPV location in Pakistan.

Several studies have been conducted in Bangladesh regarding the feasibility and potential of FSPV. Shatil et al. [28] examined the feasibility of installing floating solar panels in Chalan Beel Lake in Bangladesh, comparing conversion costs with other countries. Ahmad & Rahman [29] and Chowdhury et al. [30] delved into the potential and feasibility of an FSPV plant in Bangladesh's Kaptai Lake, considering factors such as location potential, environmental impact, and financial aspects. Rahman et al. [31] highlighted the absence of a scientific evaluation system in Bangladesh's government for assessing location suitability for Solar PV projects. The study employed the Delphi method alongside AHP to identify criteria and their respective weights for analyzing the suitability of a solar energy park's location in Bangladesh. Nevertheless, the study was confined to land-based solar plants. Since site selection for FSPV involves more criteria to consider [32], criteria for selecting a suitable location for FSPV in Bangladesh have not been evaluated and prioritized so far. In another study, Islam & Halim [33] analyzed the FSPV potential of 14 lakes in Dhaka, the capital of Bangladesh. However, the evaluation was conducted considering only climate factors. Non-climate factors (such as proximity to the nearest substation, ecological sensitivity of the water bodies, availability for use, etc.) and the relative importance of the factors were not incorporated in this evaluation. Moreover, the location study evaluated the water bodies of only one district out of a total of 64 districts in Bangladesh, where the climatic factors do not vary significantly. Therefore, as far as the authors are aware, no previous literature comprehensively evaluates the factors influencing location selection for FSPV installation in Bangladesh and determines suitable locations based on these factors.

To improve the framework's robustness, it is recommended that two or more multiple-criteria methods be hybridized [34]. Thus, two MCDM methods, the Fuzzy Best-Worst Method (F-BWM) and the Fuzzy Combined Compromise Solution (F-CoCoSo), were used together in this research to identify the most suitable site for establishing FSPV in Bangladesh. The proposed approach of combining F-BWM and F-CoCoSo has been previously used in various contexts. For instance, this integrated approach (F-BWM and F-CoCoSo) has been utilized in supplier selection within the reverse supply chain [35], gateway selection in fog-enabled Internet of Things [36], addressing the construction project scheduling issue [37], examining the execution of Industry 4.0 in the mobility industry [38], and so on. Nonetheless, this current research represents the first application of this hybrid method to tackle the location selection problem.

When many factors require pairwise comparisons, decision-makers face a challenge in prioritizing criteria. This is because inconsistent expert judgment results in inaccurate conclusions [39]. Rezaei [40] presented the BWM approach as a solution to this problem, making the pairwise comparison process more logical. This approach takes less time than existing MCDM techniques and yields more consistent results [41, 42]. The reasons for using BWM in this study are its benefits over other multi-criteria methods: It provides a flexible environment for decision-making, decreases the number of comparisons between pairs, and maintains consistency in the opinions of experts. Nonetheless, a great deal of uncertainty and ambiguity is included in human judgments. Therefore, Fuzzy judgments are used with BWM for pairwise comparisons, giving decision-makers (DMs) greater freedom and producing more satisfactory outcomes. Thus, this study uses fuzzy set theory linked with BWM (F-BWM) [43]. Since its invention, BWM and fuzzy sets have been employed together in various contexts. Ajripour & Hanne [44] used F-BWM to evaluate and prioritize strategic management models for small and medium-sized manufacturing companies. Karimi et al. [45] used F-BWM for maintenance assessment in hospitals. Other decision contexts where F-BWM is found include the evaluation of supplier selection factors for paper manufacturers [46], occupational risk assessment [47], analyzing the challenges to adopting blockchain technologies in supply chain management [48], assessing the drivers for carbon regulatory policies (CRP) execution in the industrial supply chain [49], and so on. Numerous location selection studies have also used the F-BWM methodology [50,51].

Again, F-CoCoSo has been used in this study to evaluate alternatives. The CoCoSo method was first introduced by Yazdani et al. [52] in 2019. It combines the ideas of WASPAS (weighted aggregated sum product assessment), MEW (multiplicative exponential weighting), and SAW (simple additive weighting), making the method a powerful, reliable, and stable decision-making technique for analyzing complex information with respect to group expert feedback [52]. The F-CoCoSo method has been proven effective in different contexts. Zolfani et al. [53] utilized CoCoSo in conjunction with BWM to tackle challenges related to supplier selection. Maghsoodi et al. [54] employed BWM and MULTIMOORA (Multiple Objective Optimization on the basis of Ratio Analysis plus Full Multiplicative Form) alongside CoCoSo for resource selection in interior building applications. Cui et al. [55] identified internet adoption obstacles in the manufacturing industry using CoCoSo and Fuzzy SWARA (Stepwise Weight Assessment Ratio Analysis). Deveci et al. [56] developed a real-time traffic management model using F-CoCoSo. Thus, this method is proven to be feasible for solving actual decision-making problems like location selection problems in the present study.

In this research, the F-BWM and F-CoCoSo techniques are employed together as an integrated approach. F-BWM and F-CoCoSo methods have been used together to incorporate the subjective judgments of the DMs. F-BWM offers a structured way of prioritizing criteria based on their relative influence on the decision, while F-CoCoSo enables simultaneous optimization of multiple criteria. Collectively, they provide a comprehensive structure for conducting decision analysis, guaranteeing that all pertinent factors are taken into account and optimized. Thus, F-BWM and F-CoCoSo complement each other by presenting a comprehensive and robust approach to analyzing complex decision-making problems [57].

The key contribution of the proposed study is that it identifies the key evaluation criteria for suitable location selection among the potential waterbodies of Bangladesh for installing FSPV plants. Various research studies have been conducted on location selection for FSPV in the context of other countries, such as Turkey, China, Korea, and Greece. Still, no one has comprehensively conducted it in the context of Bangladesh despite its remarkable potential. The purpose of this study is to bridge the gap in the literature through the application of MCDM methodology and is expected to provide an efficient framework for policymakers, energy planners, and investors to utilize in selecting suitable sites for establishing FSPV systems for an emerging economy like Bangladesh.

2. Problem definition

Floating solar PV plants entail the installation of solar photovoltaic panels on floating platforms over water bodies, such as lakes, reservoirs, and oceans, instead of on traditional land or building surfaces [58]. Due to adverse terrain conditions or scarcity of land area that make conventional ground-mounted PV systems impractical, FSPVs are gradually becoming well-liked compared to land-based systems, especially in countries facing land constraint problems [58]. FSPVs provide beneficial advantages such as lowering evaporation and algal development [59]. Also, the cooling effect of water enhances panel performance. FSPVs are easy to install and deploy; they offer modularity, enabling faster installations [20].

This site selection study offers vital information for future refinement and design of FSPV systems. The study can be a starting point for assessing the prospect of FSPV, the suitability of water bodies, and grid integration. The findings of this study could influence the future development of FSPV projects in other emerging economy countries like Bangladesh.

2.1. Criteria for the site selection

For this study, three experts with extensive experience in the area of solar energy in Bangladesh have been chosen. First, eight major critical issues are identified from an extensive review of the literature. The location selection criteria were explored in the existing literature published between 2015 and 2024, accessible in the Google Scholar and Scopus databases. Some of the key terms used for identifying the major criteria are: "criteria/factors/attributes for location/site selection for floating solar power plant" OR "criteria/factors/attributes for location/site selection for floating solar PV" OR "evaluation criteria for selecting location/site for floating solar power plant." The resulting criteria are then forwarded to experts for validation (in the form of a survey questionnaire) in the context of Bangladesh. The survey questionnaire has been presented in Appendix A of the supplementary materials file.

After validation, two more factors are added, named 'proximity to the grid' and 'ecological sensitivity', with the existing eight factors identified from the literature. The list of the final ten evaluation criteria identified for location selection of FSPV in Bangladesh, based on literature review and expert feedback, is presented in Table 1. Table B1 in Appendix B concisely explains each criterion.

2.2. Potential FSPV sites

Despite the fact that FSPV is becoming more and more popular around the world as a feasible renewable energy (RE) alternative, the technology is still in its infancy and is not yet widely used in Bangladesh. Over 90 % of Bangladesh's area is flat, primarily dedicated to agricultural purposes, and it is interlaced with numerous rivers [66]. The country itself is a delta created by the sediment from the Ganges-Brahmaputra rivers [67]. There is no available land in the nation for constructing large PV power plants. However, most of the perennial marshland has sufficient area for building large-scale FSPV plants. Bangladesh is home to a variety of freshwater wetlands, which include 373 haors and 6300 beels (lakes) [68]. Furthermore, it must be acknowledged that the location-specific information that is important for FSPV installation is not available for all the water bodies of the country.

The Asian Development Bank (ADB) has reported Barapukuria pit

Table 1
List of finalized criteria for FSPV site/location selection in Bangladesh.

Major criteria	Code	Source
Terrain elevation	C1	[21,23,32,60,61,62], Expert Feedback
Solar irradiance	C2	[32,62,63], Expert Feedback
Rainfall	C3	[32,64], Expert Feedback
Air temperature	C4	[20,23], Expert Feedback
Humidity	C5	[32,62], Expert Feedback
Ecological sensitivity	C6	Expert Feedback
Wind speed	C7	[20,32,62], Expert Feedback
Water surface area	C8	[23,65], Expert Feedback
Proximity to the grid	C9	Expert Feedback
Conflict over water use	C10	[21,32]; Expert feedback

lakes in Dinajpur (45.9 MW), Jhenidah's Joydia Lake (9.1 MW), and Jashore's Bukbhara Lake (6.0 MW) to be very suitable for installing FSPV after a feasibility study [69]. Floating solar power plants in these areas can ensure dual use of water bodies by generating electricity and supporting aquaculture in the same place [63]. In another feasibility study, the International Finance Corporation (IFC), keen to boost investment in Bangladesh's RE, studied 323 water bodies larger than 25 acres and identified 10 with a total potential of 10.8 GWp solar power [15]. Of them, the lakes at Barapukuria Coal Mine and Kaptai Hydro Power have generating capacities of 20 MWp and 10,372 MWp, respectively. The remaining eight water bodies - Joydia Baor, Baluhar Baor, Marjat Baor, Katgara Beel, Bergobindopur Baor, Bukhbara Baor, Majdia Baor, and Jhapa Baor - can produce between 27 and 83 MWp [15]. This program is a component of the $172 billion climate-smart investment opportunity offered by IFC between 2018 and 2030 [15].

Kaptai Lake, located in the southeastern part of the country, has been studied in several feasibility analyses as a potential site for generating energy from floating photovoltaic (FSPV) installations [29,30,70]. As the largest man-made lake in Bangladesh, it covers an area of approximately 777 square kilometers [30]. While part of the lake is utilized by a hydroelectric power plant (HPP), the remaining extensive surface area is unused. This provides ample space for FSPV systems without competing with land resources [70].

Hatirjheel Lake and Dhanmondi Lake, two of the few man-made reservoirs in the capital Dhaka, are deemed suitable sites for FSPV in several studies ([63]; M. I. [13,71]). The lakes harbor residential and commercial infrastructure. The urban location makes them more accessible for maintenance and monitoring and facilitates integration with the city's grid system, which can contribute sustainably to the high energy demand of the capital.

Hakaluki Marsh Wetland (Haor), located in the northeastern part of Bangladesh, is the largest freshwater wetland in the country [72]. According to the techno-economic assessment by Kowsar et al. [68], it is large enough to accommodate a 50 MW floating solar power plant project. From the literature and feasibility assessments, eight potential sites are selected as alternatives in this study. They are presented in Table 2, along with their location-specific coordinates, solar irradiance, and average wind speed.

The maps of the eight potential site locations in Bangladesh considered for the study are presented in Fig. 1, with the site areas highlighted in red.

Table 2
List of potential sites for establishing FSPV plant in Bangladesh.

Potential site	Code	Coordinates	Solar irradiance (kwh/m2)	Average wind speed (m/s)
Kaptai Lake	S1	22.6602° N, 92.2035° E	1750	3.4
Hatirjheel Lake	S2	23.7703° N, 90.4151° E	1639	1.9
Hakaluki marsh wetland	S3	24.6725° N, 92.0548° E	1657	1.7
Barapukuria Coal Mine's Lake	S4	25.5387° N, 88.9689° E	1630	2.74
Joydia Lake	S5	23.4460° N, 88.9322° E	1698	3.08
Jhanpa Lake	S6	22.9852° N, 89.1578° E	1705	3.3
Dhanmondi Lake	S7	23.7473° N, 90.3783° E	1648	1.87
Bukbhara Lake	S8	23.1766° N, 89.11750° E	1702	3.23

Note: The data on solar irradiance is from the World Bank Group. (2014). *Global Solar Atlas*. Retrieved June 6, 2024, from https://globalsolaratlas.info/map. The data on average wind speed is from the World Bank Group. (2014). *Global Wind Atlas*. Retrieved June 6, 2024, from https://globalwindatlas.info/map.

3. Methodology

An integrated method combining F-BWM and F-CoCoSo has been used in this study. Within the scope of this study, the F-BWM technique was first employed to determine the criteria weights. Then, the F-CoCoSo technique is used to prioritize the potential sites based on the weight of the determined criteria. The design of the study has been illustrated in Fig. 2 below.

Expert feedback is collected in three stages in this study. Initially, expert opinion feedback is gathered to verify the relevance of the identified site selection criteria in the context of Bangladesh and the inclusion of any new relevant criteria (if suggested by the experts). Furthermore, feedback is also collected for F-BWM and F-CoCoSo analysis. Throughout the survey, Google Forms has been utilized to collect expert feedback.

In this study, three experts (following Ecer & Pamucar [57]) were chosen using the purposive sampling technique [73,74]. This sampling technique enables researchers to obtain input from experts who are more likely to respond to a questionnaire [75,76]. The criteria for selecting the experts include having a minimum of 10 years of work experience in the field of solar energy in Bangladesh, having knowledge of floating solar energy, and having a proper understanding of the questionnaire presented through Google Forms, among others. The profiles of the three experts who provided their opinions in the three stages of the present research are presented in Table 3.

3.1. Fuzzy best-worst method (F-BWM)

In 1965, Professor L. A. Zadeh introduced fuzzy set theory as an expansion of classical set theory that could address real-world issues in an uncertain scenario [77].

A fuzzy number $\widetilde{a}$ from real number set R is expressed as a triangular fuzzy number (TFN) if its membership function, $\mu_{\widetilde{a}}(x) : R \to [0, 1]$. This can be expressed as Eq. (1).

$$\widetilde{\mu}_a(x) = \begin{cases} 0, & x < l \\ \dfrac{x-l}{m-l}, & l \le x < m \\ \dfrac{u-x}{u-m}, & m \le x \le u \\ 0, & x > u \end{cases} \tag{1}$$

where l, m, and u denotes the lower, middle, and upper value of the support of $\tilde{a}$, respectively. All these 3 are crisp numbers $(-\infty < l \le m \le u < \infty)$. A triangular fuzzy number TFN can be expressed as a triplet $(l,\ m, u)$. The basic laws of operation of triangular fuzzy numbers are presented in [78]. The graded mean integration representation (GMIR) $R(\widetilde{a})$ of a TFN $\widetilde{a}$ provides the ranking of TFN as presented in Eq. (2). [79].

$$R(\widetilde{a}_i) = \frac{l_i + 4m_i + u_i}{6} \tag{2}$$

In the fuzzy environment, the linguistic input from the experts is converted to corresponding fuzzy numbers. The rules for transforming linguistic input to fuzzy numbers are provided in Table 4.

The stepwise procedure of the F-BWM method is presented below [43]:

Step 1: Determination of the site selection criteria for the FSPV power plant in Bangladesh. A team of experts from relevant fields identifies a list of criteria for site selection.

Step 2: Selecting the best and the worst criteria. From the list of criteria identified in Step 1, the best criterion (C_B) and the worst criterion (C_W) are selected from the feedback of DMs.

Fig. 1. (a) Kaptai Lake (S1)

Fig. 1. (b) Hatirjheel Lake (S2)

Fig. 1. (c) Hakaluki marsh wetland (S3)

Fig. 1. (d) Barapukuria Coal Mine's Lake (S4)

Fig. 1. (e) Joydia Lake (S5)

Fig. 1. (f) Jhanpa Lake (S6)


Fig. 1. (g) Dhanmondi Lake (S7)

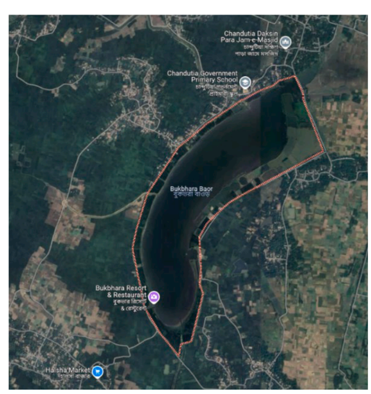

Fig. 1. (h) Bukbhara Lake

Fig. 1. Maps of the eight potential sites in Bangladesh for setting up the FSPV plant.
Note: Maps are from Google Earth. (2024). *Google Earth Map*. Retrieved December 12, 2024, from https://earth.google.com/

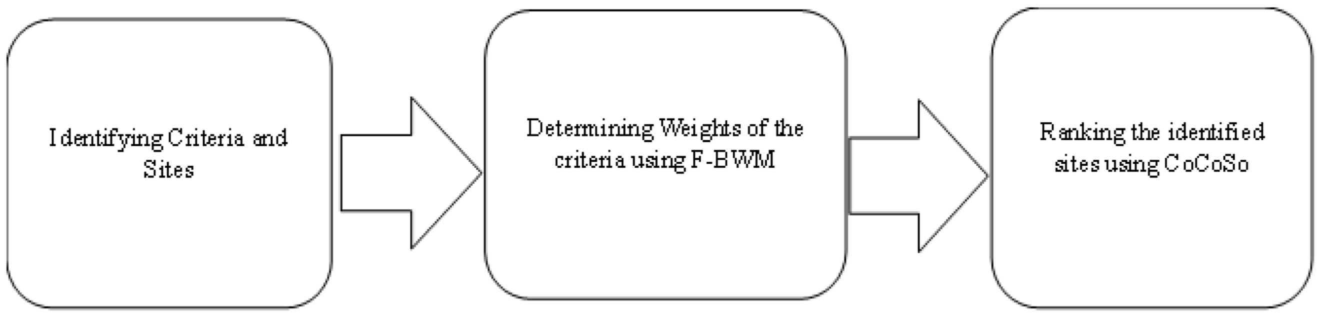

Fig. 2. Design of the study.

Table 3
Profile overview of the experts who participated in the questionnaire of the study.

Respondent	Designation	Years of Experience	Education level
DM1	Manager	17 years	Postgraduate
DM2	Project Director	10 years	Postgraduate
DM3	Manager	12 years	Graduate

Step 3: Pairwise comparison of the C_B and C_W, with respect to other criteria. The comparative influence of C_B over the rest of the criteria and the comparative influence of the rest of the criteria over C_W are provided with the help of Table 4 by the experts. $\widetilde{\widetilde{A}}_B = (\widetilde{\widetilde{a}}_{B1}, \widetilde{\widetilde{a}}_{B2}, \ldots, \widetilde{\widetilde{a}}_{BN})$ is known as fuzzy Best-to-Others (*BO*) vector and $\widetilde{\widetilde{A}}_w = (\widetilde{\widetilde{a}}_{1w}, \widetilde{\widetilde{a}}_{2w}, \ldots, \widetilde{\widetilde{a}}_{nw})$ is called a fuzzy Others-to-Worst (OW) vector.
Step 4: Determination of the optimal fuzzy weights of the identified criteria: From the BO and OW vectors, a nonlinearly constrained optimization problem can be developed, which is presented in the model (3).

$$\min \widetilde{\xi}^* \text{ s.t.} \begin{cases} \left| \dfrac{l_B^w, m_B^w, u_B^w}{l_j^w, m_j^w, u_j^w} - l_{Bj}, m_{Bj}, u_{Bj} \right| \le (k^*, k^*, k^*) \\ \left| \dfrac{l_j^w, m_j^w, u_j^w}{l_W^w, m_W^w, u_W^w} - l_{jW}, m_{jW}, u_{jW} \right| \le (k^*, k^*, k^*) \\ \sum_j R(\widetilde{w}_j) = 1 \\ l_j^w \le m_j^w \le u_j^w \\ l_j^w \ge 0 \\ j = 1, 2, \ldots, n \end{cases} \tag{3}$$

where $\widetilde{\widetilde{\xi}} = \left(l^\xi, m^\xi, u^\xi\right) : l^\xi \le m^\xi \le u^\xi$ and $\xi^* = (k^*, k^*, k^*); k^* \le l^\xi$.
By solving model (3), optimal fuzzy weights $\widetilde{w}^* = (\widetilde{w}_1^*, \widetilde{w}_2^*, \ldots, \widetilde{w}_n^*)$ can be obtained. Following that, the crisp weights are obtained by defuzzification of fuzzy weights using the GMIR Eq. (2). Finally, the consistency ratio (CR= ξ^*/CI) is calculated such that a CR value below 0.1 is acceptable [80].

3.2. Fuzzy combined compromise solution (F-CoCoSo)

The CoCoSo method combines SAW (Simple Additive Weighting) and WEP (Weighted Electoral Potential) methods for Multi-Criteria Decision Making (MCDM) [81]. This method is a comprehensive solution, addressing the strengths of other consensus approaches [82]. Compared to other MCDM methods, CoCoSo is more stable, reliable, and robust in terms of ranking alternatives [83]. For incorporating DM's preferences, the F-CoCoSo method utilizes a fuzzy linguistic scale provided in Table 5.

The stepwise procedure of the F-CoCoSo method to rank sort alternative sites based on their criteria weights is presented as follows [84, 85]:

Step 1. Develop the fuzzy decision matrix ($\widetilde{Z}$) as shown in Eq. (4).

$$\widetilde{Z} = [\widetilde{z}_{ij}]_{kxn} = \begin{bmatrix} \widetilde{z}_{11} & \ldots & \widetilde{z}_{1n} \\ \vdots & \ddots & \vdots \\ \widetilde{z}_{k1} & \ldots & \widetilde{z}_{kn} \end{bmatrix} \tag{4}$$

Where $\widetilde{z}_{ij} = \left(z_{ij}^l, z_{ij}^m, z_{ij}^u\right)$ is the fuzzy value of the *i*. alternative to the *j*. criteria.

Step 2. Prepare normalized fuzzy decision matrix ($\widetilde{R}$) using Eq. (5) (for non-beneficial criteria) and Eq. (6) (for beneficial criteria).

$$\widetilde{R} = [\widetilde{r}_{ij}]_{kxn} = \widetilde{\widetilde{r}}_{ij} = \left(r_{ij}^l, r_{ij}^m, r_{ij}^u\right) = \frac{\max(\widetilde{z}_{ij}) - \widetilde{z}_{ij}}{\max(\widetilde{z}_{ij}) - \min(\widetilde{z}_{ij})} = \left(\frac{\max\left(z_{ij}^u\right) - z_{ij}^u}{\max\left(z_{ij}^u\right) - \min\left(z_{ij}^l\right)}, \frac{\max\left(z_{ij}^u\right) - z_{ij}^m}{\max\left(z_{ij}^u\right) - \min\left(z_{ij}^l\right)}, \frac{\max\left(z_{ij}^u\right) - z_{ij}^l}{\max\left(z_{ij}^u\right) - \min\left(z_{ij}^l\right)}\right) \tag{5}$$

$$\widetilde{R} = [\widetilde{r}_{ij}]_{kxn} = \widetilde{r}_{ij} = \left(r^l_{ij}, r^m_{ij}, r^u_{ij}\right) = \frac{\widetilde{z}_{ij} - \min(\widetilde{z}_{ij})}{\max(\widetilde{z}_{ij}) - \min(\widetilde{z}_{ij})} = \left(\frac{z^l_{ij} - \min\left(z^l_{ij}\right)}{\max\left(z^u_{ij}\right) - \min\left(z^l_{ij}\right)}, \frac{z^m_{ij} - \min\left(z^l_{ij}\right)}{\max\left(z^u_{ij}\right) - \min\left(z^l_{ij}\right)}, \frac{z^{il}_{ij} - \min\left(z^l_{ij}\right)}{\max\left(z^u_{ij}\right) - \min\left(z^l_{ij}\right)}\right) \tag{6}$$

Step 3. Determine the sum of comparability arrays $(\widetilde{S}_i)$ and the sum of power weights $(\widetilde{P}_i)$ of the comparability arrays using Eq. (7) and Eq. (8), respectively.

$$\widetilde{S}_i = \left(S^l_i, S^m_i, S^u_i\right) = \left(\sum_{j=1}^{n} \widetilde{w}_{jc}\widetilde{r}_{ij}\right) = \left(\sum_{j=1}^{n} w^l_{jc} r^l_{ij}, \sum_{j=1}^{n} w^m_{jc} r^m_{ij}, \sum_{j=1}^{n} w^u_{jc} r^u_{ij}\right) \tag{7}$$

$$\widetilde{P}_i = \left(P^l_i, P^m_i, P^u_i\right) = \sum_{j=1}^{n} (\widetilde{r}_{ij})^{\widetilde{w}_{jc}} = \left(\sum_{j=1}^{n} \left(r^l_{ij}\right)^{w^u_{jc}}, \sum_{j=1}^{n} \left(r^m_{ij}\right)^{w^m_{jc}}, \sum_{j=1}^{n} \left(r^u_{ij}\right)^{w^l_{jc}}\right) \tag{8}$$

Step 4. Determine three fuzzy assessment scores using Eq (9)-(11) presented below.

$$\widetilde{f}_{ia} = \left(f^l_{ia}, f^m_{ia}, f^u_{ia}\right) = \frac{\widetilde{P}_i + \widetilde{S}_i}{\sum_{i=1}^{k}(\widetilde{P}_i + \widetilde{S}_i)} = \left(\frac{P^l_i + S^l_i}{\sum_{i=1}^{k}\left(P^u_i + S^u_i\right)}, \frac{P^m_i + S^m_i}{\sum_{i=1}^{k}\left(P^m_i + S^m_i\right)}, \frac{P^u_i + S^u_i}{\sum_{i=1}^{k}\left(P^l_i + S^l_i\right)}\right) \tag{9}$$

$$\widetilde{f}_{ib} = \left(f^l_{ib}, f^m_{ib}, f^u_{ib}\right) = \frac{\widetilde{S}_i}{\min(\widetilde{S}_i)} + \frac{\widetilde{P}_i}{\min(\widetilde{P}_i)} = \left(\frac{S^l_i}{\min(S^l_i)} + \frac{P^l_i}{\min(P^l_i)}, \frac{S^m_i}{\min(S^l_i)} + \frac{P^m_i}{\min(P^l_i)}, \frac{S^u_i}{\min(S^l_i)} + \frac{P^u_i}{\min(P^l_i)}\right) \tag{10}$$

$$\widetilde{f}_{ic} = \left(f^l_{ic'}, f^m_{ic}, f^u_{ic}\right) = \frac{\lambda(\widetilde{S}_i) + (1-\lambda)(\widetilde{P}_i)}{\lambda\max(\widetilde{S}_i) + (1-\lambda)\max(\widetilde{P}_i)} = \left(\frac{\lambda\left(S^l_i\right) + (1-\lambda)\left(P^l_i\right)}{\lambda\max\left(S^u_i\right) + (1-\lambda)\max\left(P^u_i\right)}, \frac{\lambda\left(S^m_i\right) + (1-\lambda)\left(P^m_i\right)}{\lambda\max\left(S^u_i\right) + (1-\lambda)\max\left(P^u_i\right)}, \frac{\lambda\left(S^u_i\right) + (1-\lambda)\left(P^u_i\right)}{\lambda\max\left(S^u_i\right) + (1-\lambda)\max\left(P^u_i\right)}\right) \tag{11}$$

In Eq. (11), λ is typically considered as 0.5. DMs may also calculate the value of λ.

Step 5. Calculate the net assessment scores.

Fuzzy assessment scores are transformed into net evaluation scores with the help of Eq. (12)-(14).

$$f_{ia} = \frac{f^l_{ia} + f^m_{ia} + f^u_{ia}}{3} \tag{12}$$

$$f_{ib} = \frac{f^l_{ib} + f^m_{ib} + f^u_{ib}}{3} \tag{13}$$

$$f_{ic} = \frac{f^l_{ic} + f^m_{ic} + f^u_{ic}}{3} \tag{14}$$

Step 6. Determine the crips evaluation scores to obtain the final scores (f_i) for each site with the help of Eq. (15).

$$f_i = (f_{ia}f_{ib}f_{ic})^{1/3} + \left(\frac{f_{ia} + f_{ib} + f_{ic}}{3}\right) \tag{15}$$

The site receiving the highest weight is the best among the alternatives.

4. Calculations and results

The calculations and results for determining criteria weight using the F-BWM method and ranking alternatives using the F-CoCoSo technique are provided in the following two subsections.

4.1. Determination of criteria weights using the F-BWM method

Three experts from the field of solar energy in Bangladesh identified the best and worst criteria and their comparative influence with respect to other criteria for selecting suitable sites for FSPV establishment in Bangladesh based on linguistic variables. The linguistic variables are then converted to corresponding TFNs using Table 4. The TFNs of each expert's BO vector and OW vectors are presented in Table C1 and Table C2 of Appendix C (in the supplementary materials file), respectively.

Afterward, based on the TFNs, the model (3) of F-BWM is implemented using Python, and the fuzzy weights are calculated for each DM. The fuzzy weights and consistency ratio of each DM are presented in Table 6.

Next, the fuzzy scores are aggregated and converted to crisp scores using Eq. (2) of defuzzification. This provides the ranking of the weights, which are presented in Table 7, along with the aggregated fuzzy weight and crisp weight.

Table 4
Rules for transforming the linguistic inputs of DMs.

Linguistic terms	Membership function
Equally important (E)	(1,1,1)
Weakly important (WI)	(2/3,1, 3/2)
Fairly important (FI)	(3/2,2, 5/2)
Very important (VI)	(5/2,3, 7/2)
Absolutely important (AI)	(7/2,4, 9/2)

Table 5
Fuzzy linguistic scale for evaluating sites using F-CoCoSo [57].

Linguistic terms	Membership function
Extremely low (EL)	(1/2,1, 3/2)
Very low (VL)	(1, 3/2, 2)
Low (L)	(3/2,2, 5/2)
Medium (M)	(2, 5/2,3)
High (H)	(5/2,3, 7/2)
very high (VH)	(3, 7/2, 4)
Extremely high (EH)	(7/2,4, 9/2)
Perfect (P)	(4, 9/2, 5)

Table 6
Fuzzy weights of the criteria determined by F-BWM.

Criteria Code	Expert 1 $CR = 0.0914$	Expert 2 $CR = 0.0910$	Expert 3 $CR = 0.0887$
C1	0.0518,0.0877,0.2983	0.0689,0.1057,0.2072	0.0513,0.0696,0.5592
C2	0.0522,0.0875,0.3459	0.0517,0.0704,0.3309	0.0596,0.0881,0.4776
C3	0.0102,0.0157,0.3765	0.0620,0.0963,0.1384	0.0422,0.0556,0.1562
C4	0.0504,0.0841,0.3137	0.0730,0.0919,0.1023	0.0344,0.0512,0.1911
C5	0.0408,0.0631,0.1415	0.0483,0.0724,0.1376	0.0379,0.0575,0.1479
C6	0.0502,0.0802,0.2115	0.0742,0.0870,0.3779	0.0383,0.0535,0.3986
C7	0.0438,0.0732,0.1445	0.0449,0.0556,0.1666	0.0406,0.0581,0.1628
C8	0.0480,0.0818,0.2333	0.0504,0.0854,0.2193	0.0327,0.0590,0.2169
C9	0.0493,0.0809,0.2668	0.0479,0.0565,0.1811	0.0506,0.0514,0.4409
C10	0.0537,0.0847,0.2590	0.0562,0.0909,0.3097	0.0354,0.0631,0.3943

Table 7
Final weight and ranking of the site selection criteria.

Criteria	Fuzzy weight	Crisp weight	Rank
Terrain elevation (C1)	0.0573,0.0876,0.3549	0.1272	2
Solar irradiance (C2)	0.0545,0.0820,0.3848	0.1279	1
Rainfall (C3)	0.0381,0.0559,0.2237	0.0809	8
Air temperature (C4)	0.0526,0.0757,0.2023	0.0930	7
Humidity (C5)	0.0423,0.0643,0.1423	0.0737	10
Ecological sensitivity (C6)	0.0542,0.0736,0.3293	0.1130	4
Wind speed (C7)	0.0431,0.0623,0.1579	0.0751	9
Water surface area (C8)	0.0437,0.0754,0.2231	0.0948	6
Proximity to grid (C9)	0.0493,0.0629,0.2963	0.0996	5
Conflict over water use (C10)	0.0484,0.0796,0.3210	0.1147	3

4.2. *Evaluation of sites using the F-CoCoSo method*

In this study, three experts participated to assess the eight selected sites with respect to the ten key selection criteria. The assessments obtained from the three experts with the help of Table 5 are presented in Table D1 of Appendix D of the supplementary materials file.

The linguistic inputs are converted to fuzzy values, as shown in Table 5. The arithmetic average of the matrices that correspond to the experts' evaluation is calculated to find the initial aggregated matrix, which is presented in Table D2 of Appendix D. Following that, Eq. (5) is used for normalizing the non-useful criteria C3, C4, C5, C6, C7, C9, C10 and Eq. (6) is used for normalizing the useful criteria C1, C2, C8. The decision matrix after normalization is presented in Table 8.

Then, the fuzzy sum of power weight ($\widetilde{P}_i$) and fuzzy sum of comparability array ($\widetilde{S}_i$) for each alternative site are calculated using Eq. (7) and Eq. (8), which are shown in Table 9.

For each site, three fuzzy evaluation scores are calculated with the help of Eq. (9)-(11). The scores are presented in Table 10.

From the fuzzy evaluation scores, crisp evaluation scores and, thereby, the final scores (f_i) are determined using Eq. (12)-(15). The crisp evaluation score, final score, and the resulting rank are shown in Table 11.

Table 9
The fuzzy sum of weighted comparability ($\widetilde{S}_i$) and power weight ($\widetilde{P}_i$).

Alternatives	$\widetilde{S}_i$	$\widetilde{P}_i$
S1	0.2980, 0.5281, 2.4176	8.8496, 9.7636, 9.9375
S2	0.1969, 0.3632, 1.6713	7.8730, 9.5021, 9.7618
S3	0.2813, 0.4995, 2.2520	8.7027, 9.7056, 9.8784
S4	0.2900, 0.5235, 2.4066	8.6979, 9.7501, 9.9460
S5	0.2747, 0.5034, 2.2388	8.3586, 9.6460, 9.8595
S6	0.2582, 0.4866, 2.2618	8.4860, 9.6869, 9.8813
S7	0.1821, 0.2312, 0.2865	7.5584, 9.4309, 9.7166
S8	0.2179, 0.4088, 1.8198	8.0367, 9.5647, 9.7960

Table 10
Fuzzy appraisal scores.

Alternatives	$\widetilde{f}_{ia}$	$\widetilde{f}_{ib}$	$\widetilde{f}_{ic}$
S1	0.2980, 0.5281, 2.4176	2.8069, 3.3193, 9.4613	0.7398, 0.8324, 0.9993
S2	0.1969, 0.3632, 1.6713	2.1229, 2.5784, 6.8380	0.6527, 0.7979, 0.9247
S3	0.2813, 0.4995, 2.2520	2.6957, 3.1896, 8.8771	0.7266, 0.8254, 0.9811
S4	0.2900, 0.5235, 2.4066	2.7427, 3.2980, 9.4235	0.7269, 0.8309, 0.9991
S5	0.2747, 0.5034, 2.2388	2.6140, 3.2003, 8.8290	0.6982, 0.8209, 0.9785
S6	0.2582, 0.4866, 2.2618	2.5400, 3.1318, 8.9116	0.7072, 0.8228, 0.9821
S7	0.1821, 0.2312, 0.2865	2.0, 2.0, 2.0	0.6260, 0.7814, 0.8090
S8	0.2179, 0.4088, 1.8198	2.2598, 2.7822, 7.3602	0.6676, 0.8066, 0.9395

5. Discussion

In the present research, F-BWM was employed to calculate the weights of the location selection criteria, and F-CoCoSo was employed to rank the potential sites for FSPV. The final scores of the evaluation criteria determined using F-BWM (from Table 7) are presented in Fig. 3 in descending order for better visualization.

Table 8
Decision matrix after normalization.

Criteria	S1	S2	S3	S4	S5	S6	S7	S8
C1	0.64, 0.76, 0.88	0.421, 0.578, 0.736	0.5, 0.714, 0.928	0.52, 0.64, 0.76	0.4, 0.55, 0.7	0.2, 0.35, 0.5	0.380, 0.523, 0.666	0.210, 0.368, 0.526
C2	0.72, 0.84, 0.96	0.631, 0.789, 0.947	0.571, 0.785, 1	0.76, 0.88, 1	0.7, 0.85, 1	0.35, 0.5, 0.65	0.523, 0.666, 0.809	0.631, 0.789, 0.947
C3	0.36, 0.48, 0.6	0.157, 0.315, 0.473	0.071, 0.285, 0.5	0.32, 0.44, 0.56	0.35, 0.5, 0.65	0.3, 0.45, 0.6	0.238, 0.380, 0.523	0.263, 0.421, 0.578
C4	0.36, 0.48, 0.6	0.052, 0.210, 0.368	0.142, 0.357, 0.571	0.56, 0.68, 0.8	0.45, 0.6, 0.75	0.5, 0.65, 0.8	0.142, 0.285, 0.428	0.473, 0.631, 0.789
C5	0.28, 0.4, 0.52	0, 0.157, 0.315	0, 0.214, 0.428	0.44, 0.56, 0.68	0.2, 0.35, 0.5	0, 0.15, 0.3	0.095, 0.238, 0.380	0.157, 0.315, 0.473
C6	0.76, 0.88, 1	0.473, 0.631, 0.789	0.5, 0.714, 0.928	0.6, 0.72, 0.84	0.4, 0.55, 0.7	0.5, 0.65, 0.8	0, 0.142, 0.285	0, 0.157, 0.315
C7	0.76, 0.88, 1	0.263, 0.421, 0.578	0.571, 0.785, 1	0.68, 0.8, 0.92	0.4, 0.55, 0.7	0.3, 0.45, 0.6	0, 0.142, 0.285	0.210, 0.368, 0.526
C8	0.16, 0.28, 0.4	0, 0.157, 0.315	0.071, 0.285, 0.5	0, 0.12, 0.24	0, 0.15, 0.3	0, 0.15, 0.3	0.285, 0.428, 0.571	0.315, 0.473, 0.631
C9	0.56, 0.68, 0.8	0.052, 0.210, 0.368	0.5, 0.714, 0.928	0.48, 0.6, 0.72	0.05, 0.2, 0.5	0.050, 0.2, 0.35	0.142, 0.285, 0.428	0, 0.157, 0.315
C10	0.64, 0.76, 0.88	0.368, 0.526, 0.684	0.5, 0.714, 0.928	0.64, 0.76, 0.88	0.55, 0.7, 0.85	0.35, 0.5, 0.65	0, 0.142, 0.285	0.368, 0.526, 0.684

Table 11
Crisp evaluation scores and ranking.

Alternatives	f_{ia}	f_{ib}	f_{ic}	f_i	Ranking
S1	0.1350	5.1958	0.8571	2.9067	1
S2	0.1249	3.8464	0.7917	2.3124	7
S3	0.1329	4.9208	0.8443	2.7866	3
S4	0.1343	5.1547	0.8523	2.8860	2
S5	0.1313	4.8811	0.8325	2.7595	4
S6	0.1320	4.8611	0.8374	2.7567	5
S7	0.1160	2	0.7388	1.5071	8
S8	0.1269	4.1341	0.8046	2.4388	6

Results of F-BWMs provide critical pieces of information. Before discussing F-BWM results, it is noteworthy to mention that the consistency ratio for F-BWM results is found to be below 0.1 for all the DMs, which proves the consistency of the input data [80].

According to the F-BWM findings, solar irradiance (C2) is found to be the most significant factor for site selection for FSPV in Bangladesh due to having the maximum weight (0.1279). This is not surprising since solar irradiation has emerged as the most important criterion in several studies [21,23,32,25]. Countries situated in low-latitude regions with higher solar irradiation benefit more from solar energy [86]. Being located in a low latitude region (between 20°34′ and 26°38′ North), Bangladesh lies in a favorable location for capturing solar energy [87]. After solar irradiance, terrain elevation (C2) got the second-highest score in the F-BWM result, followed by conflict over water use (C10). The study by Deveci et al. [20] also found the rank of elevation right after solar irradiation in terms of the influence in selecting the site for FSPV. According to experts, conflict regarding water use is the third most weighted criterion in Bangladesh. This implies that the competition and potential conflicts over the use of water bodies for FSPV installations, as opposed to other purposes such as commercial activities, recreational uses, or environmental concerns, greatly influence the selection of sites for FSPV installations. On the other hand, relative humidity (C5) received the lowest weight, implying that among the ten key criteria, it has the lowest impact on selecting the site for FSPV installation. This is also in line with existing literature. Recent research by Melek et al. [32] also identified the humidity of the air as the least influential technical criterion for selecting a suitable site for FSPV. Ecological sensitivity (C6), proximity to the grid (C9), water surface area (C8), air temperature (C4), rainfall (C3), and wind speed (C7) lie in descending order in terms of their influence in selecting the location for FSPV in Bangladesh.

In the next stage, the F-CoCoSo technique was used to prioritize the selected potential sites for installing FSPV in Bangladesh in terms of the eight selection criteria after determining F-BWM criteria weights. Fig 4

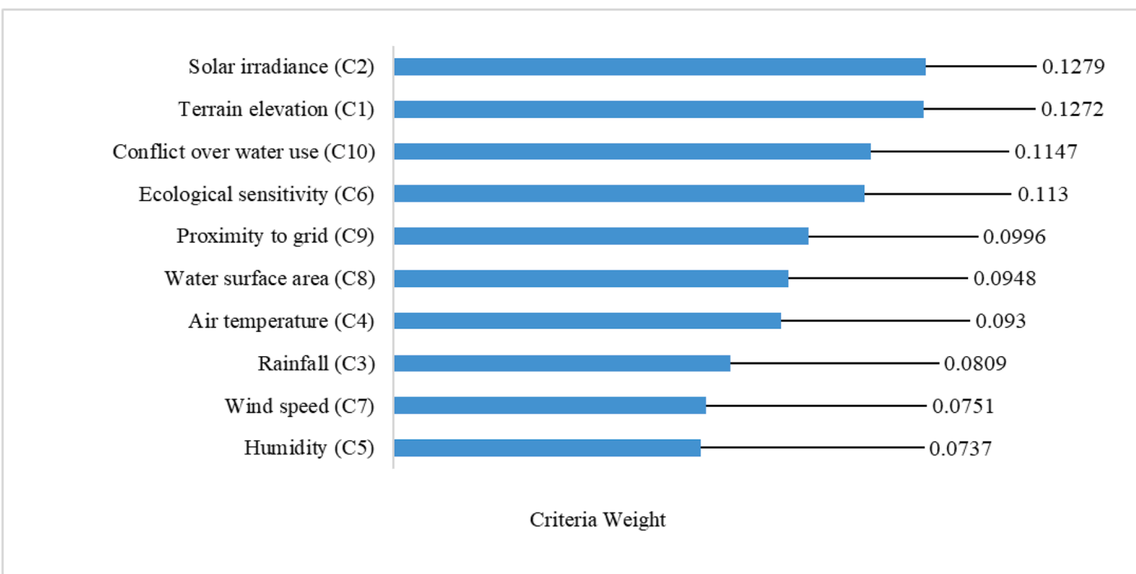

Fig. 3. Weight of the site selection criteria for FSPV obtained from F-BWM.

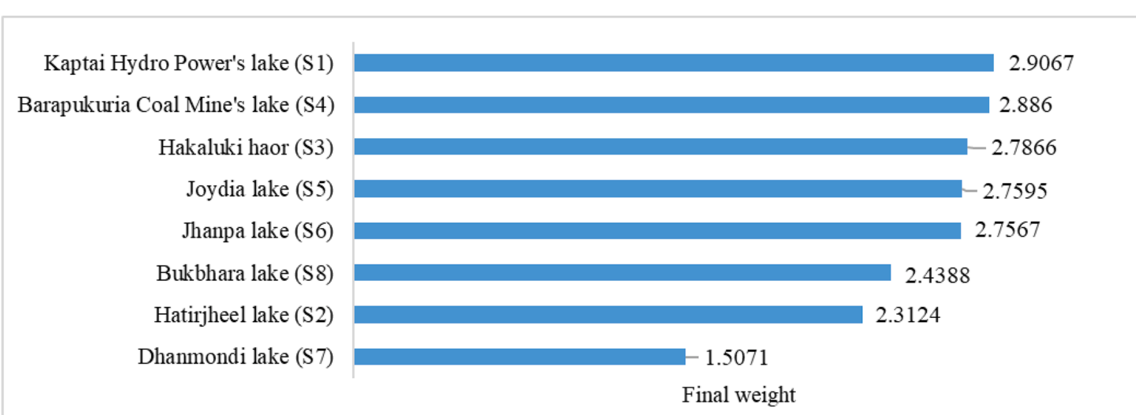

Fig. 4. The final weight of the eight alternative sites for FSPV installation in Bangladesh.

presents the site rankings obtained from the F-CoCoSo result.

This finding sheds significant light on the subject. As shown in Fig 4, the most suitable location is Kaptai Lake (S1), located in the Rangamati district of Bangladesh, due to receiving the highest F-CoCoSo score (2.9067) among the eight sites. According to Faruqui et al. [63], the attachment of the existing Hydro Power Plant (HPP) in Kaptai Lake supports the cause of FSPV establishment, which is already proven to be successful in many countries. During the summer season, temperatures are higher than at other times of the year, leading to increased evaporation. As a result, HPP's power generation capability significantly decreases during summer [70]. On the other hand, FSPV systems can produce the most electricity during this summer period [88]. Additionally, the shading provided by FSPV considerably reduces evaporation loss around the plant, which ultimately supports HPP production [70]. This way, running the Kaptai Hydropower Plant (HPP) alongside the FSPV system can provide a balanced energy supply year-round, as demonstrated by the findings of Faruqui et al. [63]. The study identified Kaptai Lake as the most suitable site for economic evaluation.

Barapukuria Coal Mine's Lake (S4), located in Dinajpur district, ranks second (2.8860) in terms of suitability. This outcome is consistent with a recent feasibility assessment by the International Finance Corporation (IFC). After conducting a study on 323 water bodies in Bangladesh, the IFC discovered the maximum solar PV potential in Kaptai Lake (10,372 Megawatt peak) and the second highest potential in Barapukuria (20 Megawatt peak) [15].

Conversely, Dhanmondi Lake (S7) has received the lowest weight (1.5071) in the F-CoCoSo result, implying that it is the least suitable site for installing FSPV among the eight selected potential sites in Bangladesh. In the study by Faruqui et al. [63], Dhanmondi Lake is identified as having the least potential for electricity generation, which is in line with the present research findings. Dhanmondi Lake, with its limited space for solar panel installation and its urban setting that contributes to significant shading, serves as a recreational hub and hosts a sensitive ecosystem that could be adversely affected by large-scale solar projects [63].

The literature review reveals that, so far, no research has been conducted in Bangladesh on suitable location selection for FSPV. Karipoğlu et al. [23] investigated suitable locations in the context of Turkey, where the ecological impact was ranked fourth and terrain elevation was ranked third. On the other hand, the results of the present research also ranked ecological sensitivity fourth but ranked terrain elevation second. Therefore, the ranking or weighting of the evaluation criteria may vary slightly depending on the country being studied and the panel of experts conducting the evaluation.

It is important to note that the study considered eight potential sites in Bangladesh based on previous literature and feasibility assessments. To comprehensively evaluate the large-scale applicability of the proposed model across the country, several constraints must be considered. Scaling up may impact local aquatic ecosystems, particularly concerning water quality and biodiversity of the particular area. A comprehensive assessment of environmental impact is critical for future large-scale FSPV projects [89]. Technological challenges may include material degradation due to prolonged exposure to harsh weather and variations in system efficiency across different climatic regions [90]. The potential for synergy with other technologies, such as hydropower infrastructure, irrigation systems, and rooftop solar photovoltaic systems, could enhance cost-efficiency and resource utilization in the long term [91, 92]. Furthermore, conflicts over water use and public resistance vary to different degrees across different regions. Community engagement and awareness programs are essential to ensure social support. Additionally, the initial cost of setting up FSPV on water and the supporting infrastructure varies by location, depending on geographic conditions. In the future, location-specific cost-benefit analyses could be conducted to determine whether to transition from traditional energy sources to FSPV. Addressing these points is crucial for the FSPV model's scalability and its contribution to sustainable energy transitions throughout Bangladesh.

5.1. Theoretical implications

The present study has several implications for researchers from a theoretical perspective. First, this study focused on the suitable location selection for installing FSPV in Bangladesh based on key selection criteria, which is a field that has been unexplored before, particularly for an emerging economy like Bangladesh. The present study can lead to the development of more refined models for selecting suitable sites for FSPV installations.

Secondly, this study identified various criteria for location selection based on a literature review and experts' feedback. Following that, the research identifies the relative importance of those identified site selection criteria with the help of the F-BWM method, which holds theoretical significance for researchers working on the development of renewable energy for an emerging economy like Bangladesh. This research can offer valuable insights into the suitability factors that experts can prioritize for analysis. Since this is the initial attempt to identify suitable locations for FSPV in Bangladesh, this study can serve as a foundation for researchers to assess location suitability for FSPV in any specific region of the country. Additionally, the application of such a multiple-criteria decision-making approach for FSPV location selection study is not so common for other countries of emerging economies either. The adoption of such an approach can improve the quality of assessment for researchers to perform in similar emerging economy countries.

5.2. Practical implications

The present study represents pioneering research on site selection for FSPV in Bangladesh, making it the first approach in the context of Bangladesh. It presents a multifaceted practical contribution for emerging economy countries like Bangladesh, which aims to enhance the proportion of renewable energy in its energy blend. It addresses the crucial need to identify suitable locations for floating photovoltaic (FSPV) systems. The research employs a hybrid MCDM methodology, combining the F-BWM and F-CoCoSo methods. This integrated approach enables a systematic and comprehensive evaluation of various parameters in the FSPV site selection problem.

According to the results of the research, the factor that mostly affects the judgment of where the FSPV plant should be placed is the solar irradiation of the location. Bangladesh has seen numerous land-based solar plant projects benefiting from its favorable geographic conditions for solar irradiation [93]. However, it faces challenges due to land use conflicts arising from its high population density [94]. As a result of this, the country has not been quite able to exploit the potential of high solar irradiance [87]. It is important to note that Bangladesh, often referred to as a 'riverine country,' possesses a considerable number of unused water bodies, presenting an opportunity to harness this untapped potential fully through floating solar PV technology [14].

Currently, location suitability analysis for solar energy projects is not based on any scientific evaluation system, resulting in decisions that are largely dependent on assumptions [31]. By considering key techno-socioeconomic-environmental parameters, this study provides a holistic assessment of the factors to consider for project managers when selecting an optimized location. This will lead to more rational decisions and make projects more viable and sustainable. Hence, the study can assist policymakers and DMs in better grasping the important aspects to consider when choosing a location for RE projects, which is essential to effectively implementing these projects in countries with limited resources, such as Bangladesh. Additionally, it offers practitioners insightful information on the relative importance of various site selection factors of FSPV.

Bangladesh's economy is expanding, largely due to the country's ready-made garment (RMG) sector [33]. In the last decade, garment exports have consistently constituted 80–85 % of Bangladesh's overall export portfolio, achieving a total of $47 billion in 2023 [95]. The European Green Deal targets a continent-wide transition to emission-free products by 2050 [96]. In accordance with this objective, European purchasers are urging RMG supplier factories in Bangladesh to switch to renewable energy sources [97]. To stay competitive in the global market and maintain economic growth in the post-COVID era, it is imperative to adopt favorable renewable technologies like FSPV for countries with growing economies [98]. In this regard, this study can provide policymakers with a baseline for more assessments, which can be region-specific to identify other potential locations for FSPV to realize the complete potential of this technology in this country and to encourage investments.

Through the identification of optimal sites for FSPV installations, this study can contribute to the effective and optimized allocation of resources for countries with limited resources. This guarantees that investments are channeled toward locations with the highest energy generation potential, minimizing wasted effort and financial expenditure. In addition, choosing the most suitable locations can maximize energy output by FSPV, which is crucial for fulfilling energy needs, particularly in areas where land availability for conventional land-based solar setups is limited. Through the provision of grants, loans, and technical assistance, the World Bank is actively promoting the development of renewable energy (RE) in developing nations such as Bangladesh, frequently in collaboration with other international donors and financial organizations [99]. These programs are designed to help these countries lessen the effects of climate change, improve energy access, and transition to cleaner energy sources [99]. The study can be crucial for optimizing the use of these foreign investments in RE by maximizing energy output and utilizing water bodies efficiently. Also, a strategic location selection study will enable more informed decision-making, providing data-driven insights for policymakers and investors about where to allocate resources and reducing the risk of funding.

5.3. Sustainability implications

The research significantly impacts the progression of multiple Sustainable Development Goals (SDGs), bolstering efforts towards global sustainable development and climate action initiatives. By identifying optimal sites for FSPV installations, the research aids in increasing the ratio of RE within the energy portfolio of emerging economy countries such as Bangladesh. In this way, FSPV can emerge as a sustainable and cost-effective source of clean energy, bolstering the nation's endeavors to secure widespread access to dependable and contemporary energy services in accordance with SDG 7 (affordable and clean energy) [100, 101].

The research contains several environmental insights as well. By encouraging the generation of low-carbon energy and lowering greenhouse gas emissions, FSPV is vital in fighting climate change [100]. This study aligns with SDG 13 (climate action) by facilitating the dissemination of renewable energy technologies, thereby aiding worldwide endeavors to combat the adverse effects of environmental degradation [101]. In addition, by covering water bodies with solar panels, FSPV installations shield water from direct sunlight exposure, effectively lowering evaporation rates [59]. This advantage of water conservation helps to achieve SDG 6′s target 6.4 (ensuring efficient use and conservation of water resources) [101]. Grid-connected FSPV plants can support the energy needs of manufacturing industries and agriculture, leading to a transformation in sustainable production practices in emerging economy countries [102]. This benefit promotes responsible consumption and production practices (SDG 12) [101]. This can further contribute to the sustainable expansion of the economy, which is in line with SDG 8 (Decent Work and Economic Growth) [101].

6. Conclusions

Bangladesh is a densely populated country that is striving to maximize its limited resources and transform its energy portfolio sustainably to maintain its current economic growth. In this regard, it is crucial to identify a suitable site for establishing Floating Photovoltaic (FSPV) systems, considering the relevant factors, in order to reduce the challenge of land acquisition by utilizing the unused abundant water bodies. This study aimed to develop a framework for selecting suitable locations for setting up FSPV systems in emerging economy countries like Bangladesh, using the triangular fuzzy BWM method and fuzzy CoCoSo technique.

Ten key criteria for site selection connected to various aspects were identified based on a literature review and a survey form provided to the experts in the solar energy sector. A consistent questionnaire was then conducted for the F-BWM method, resulting in comparative weights for each location appraisal criterion. The weighting of location evaluation criteria using the F-BWM method indicates that solar irradiance, topographic elevation, and conflicts over water use significantly impact selecting a suitable location for FSPV among the ten key criteria.

Following this, eight water bodies were considered as alternatives, which were shortlisted from previous literature and feasibility studies conducted in different locations in Bangladesh. DMs completed another survey form to assess each identified location based on the site selection criteria. Subsequently, a consensus analysis was done using the F-CoCoSo method for the selected sites. According to the F-CoCoSo results, although the weights seem close to each other, Kaptai Lake, located in southeastern Bangladesh, was found to be the most feasible site, followed by Barapukuria coal mine's Lake, located in northwestern Bangladesh, as the second most suitable site among the eight identified sites for installing an FSPV plant.

This study is expected to provide a robust framework for site selection, enhancing the efficiency, sustainability, and feasibility of FSPV projects on water bodies. Additionally, the findings will contribute to a better understanding of the significance of various technical, environmental, and social criteria for FSPV and other renewable energy plant installation projects in emerging economy countries like Bangladesh.

This study does, however, have certain drawbacks. For example, it relies on the subjective input from DMs, particularly for the F-BWM and the F-CoCoSo methods. Consequently, there is a probability that the outcomes are subjectively biased. Moreover, the study only examined ten key selection criteria, and additional relevant criteria could be identified and included in the context of emerging economies like Bangladesh to observe their impact on the outcomes. Furthermore, the site-specific parameters used as selection criteria are continually changing, which means that the results of this study may not be accurate and usable after a long time.

However, the study expands the scope for further research. The findings presented in this study provide a foundation for future research and could be strengthened by validation through practical implementation and continuous monitoring. Additionally, potential researchers can apply the hybrid F-BWM and F-CoCoSo method-based framework (which has been utilized in this research) to investigate the solar energy sector or other RE sectors in different countries. Furthermore, various advanced fuzzy sets, including Interval-valued Intuitionistic Fuzzy Sets, α-cut Interval-based Fuzzy Sets, Interval Type-2 Fuzzy Sets, Fermatean fuzzy numbers, Z-number-based Fuzzy Sets, Neutrosophic Fuzzy Sets, Hesitant Fuzzy Sets, etc., can be used in the future to translate the linguistic input from the expert into corresponding fuzzy representation for better interpretation of the subjective judgment. These various advanced fuzzy sets can offer more nuanced ways of handling uncertainty and imprecision in decision-making.

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CRediT authorship contribution statement

Md. Zahidul Anam: Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **A. B. M. Mainul Bari:** Writing – review & editing, Visualization, Validation, Supervision, Project administration, Methodology, Investigation, Conceptualization. **Dipayan Basak:** Writing – original draft, Investigation, Data curation. **Md. Atik Foysal:** Writing – original draft, Validation, Investigation. **Asif Raihan:** Writing – review & editing, Visualization, Validation. **Abu Reza Md. Towfiqul Islam:** Writing – review & editing, Visualization, Validation.

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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Supplementary materials

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Data availability

All data used in this research are provided either in the manuscript or in the supplementary materials file

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