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Multi-criteria decision making for photovoltaic alternatives: a case study in hot climate country

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ABSTRACT

Photovoltaic (PV) experiences significant growth and has been installed in many locations worldwide over the past decades. However, selecting the best alternative of PV system remains a problem in developing countries, often involving both stakeholders' interests and multiple objectives. This research proposes a multi-criteria decision making (MCDM) taking into account best-worst method (BWM) and VIKOR method for suitable PV alternatives. The combination provides high accuracy, faster data collection, and reliable performance compared to other methods. A case study in Tomia Island in Indonesia is used to evaluate the effectiveness of these approaches. The result shows that the best scenario is a full PV installation by combining two villages into one system. It offers the highest power and can be used not only for daily access to electricity but also to support economic activities such as tourism and aquaculture. Despite offering some economic benefits, hybrid alternatives that incorporate non-renewable energy as the main source of energy are less preferred by decision-makers due to low power generation and insignificant carbon reduction.

Keywords

Best-worst method;
Multi-criteria decision making;
Photovoltaic;
Renewable energy;
VIKOR method;

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1. Introduction

The world projected an increase in energy demand of 28% by 2040 [1]. From this figure, renewable energy consumption shows a progressive increase but is still far from catching up with petroleum and similar liquids as the highest energy consumption. As non-renewable energy is predicted to deteriorate soon, countries in Asia and Africa that are heavily dependent on fossil fuel need to seek alternative resources to accommodate growing energy demand.

Indonesia has abundant resources of renewable energy such as micro-hydro, geothermal, biomass, wind, and solar. The country's location in the equatorial area allows for a high intensity of daily solar energy production. It reaches approximately 4.8 kWh per square meter in the western part of the state and 5.1 kWh per square meter in the opposite area with a monthly variance of 9% [2]. Based on this condition, solar-based power plants are potentially installed in many isolated islands scattered across the country where some people are unable to access the electricity network grid provided by the government.

One of the potential locations for photovoltaic (PV) installation is Tomia island in the province of Southeast Sulawesi. It is part of the Wakatobi National Park listed in the UNESCO World Network of Biosphere Reserve

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Abbreviations

AHP	Analytic Hierarchy Process
ANP	Analytic Network Process
BWM	Best-Worst Method
DEMATEL	Decision Making Evaluation And Laboratory
ELECTRE	ELimination Et Choix Traduisant la REalité Grey Rational Analysis (GRA)
MADM	Multi-attribute Decision Making
MCDM	Multi-criteria Decision Making
MODM	Multi-objective Decision Making
PROMETHEE	Preference Ranking Organization METHod for Enrichment of Evaluations
PV	Photovoltaic
SAW	Simple Additive Weighting Stepwise Weight Assessment Ratio Analysis (SWARA)
TOPSIS	Technique for Order of Preference by Similarity to Ideal Solution
VIKOR	Vlse Kriterijumska Optimizacija i kompromisno Resenje
WPM	Weighted Product Model

(WNBR) for coral and sea faunas [3] and the UNESCO World Heritage tentative list [4]. Currently, the electricity in the area is supported by independent small diesel generators that have been purchased and maintained by local people. The generators can only supply electricity for approximately 5 hours per day, which is insufficient to accommodate daily activities. Considering the significance of the area and the urgency of electricity supply, PV installation may become one solution to the power shortage problem. In the longer term, PV development is expected not only to improve social welfare but also to support the area as a world-class research center and a laboratory for sustainability and marine life.

Prior to installation, a feasibility study is required, taking into account technical, financial, economic, and social considerations, to propose the best alternative to PV development. The process of decision-making should involve different stakeholders to address various issues including local regulation, technology adoption, social impact, and environmental issues [5] Collaboration between the parties aims to minimize conflicting objectives [6] and to provide an acceptable solution and a compromised framework for successful project delivery.

There are decision-making models that specifically adopt multi-criteria operations in different fields from engineering, mathematics, environment, and many others. Multi-criteria decision making (MCDM) aims to cope with a set of problems by generating the best possible alternative through structuring operations and trade-offs. This research evaluates the ideal PV model by combining two MCDM models, the best-worst method (BWM) and VIKOR technique. The objective of BWM is to produce a relative weight of the criteria, while VIKOR technique ranks the criteria for generating the best alternative. The aim of integrating these methods is to improve the weighting score, reduce the set of pairwise comparisons that result in fewer questionnaires, and improve ranking accuracy [7]. This multi-criteria optimization, through a combination of BWM and VIKOR technique, proposes novelty in decision making and fills the gap in the body of knowledge that remains uncovered in previous studies. This combination can be adopted in similar context studies or across fields due to its general characteristics and straightforward implementation.

The rest of this paper is organized as follows: section 2 will discuss MCDM and its relationship to the selection of renewable energy models, section 3 will further examine the condition of the case study in Tomia island, section 4 will show the operation of the method in this research, and section 5 will elaborate on the operation of the BWM and VIKOR technique in detail. Last, a conclusion and a recommendation will be provided for further research development.

2. Multi-criteria decision making

MCDM is a technique used to decide multiple alternatives by considering qualitative and/or quantitative criteria. Some researchers have categorized MCDM into two types, including Multi-Objective Decision Making (MODM) or Multi-Attribute Decision Making (MADM). The definition of alternatives distinguished the two approaches [8]. Nowadays, many academics and researchers are trying to combine both MCDM categories in order to find the optimum method for a specific case study context. This research adopts a categorization that has been published in previous literature [9,10]. The details of this MCDM are shown in Table 1.

MADM processes predetermined alternatives by comparing each alternative attribute. Literature shows the classification of MADM methods which considers pairwise comparison, scoring, and outranking [11,12]. MADM is highly dependent on the judgment of experts or decision-makers in presenting their preferences against criteria and gain a fair perspective plays a significant role in achieving the minimum reliability score for further processing [13]. MODM suggests that a set of unbiased functions must be optimized prior to the identification of alternatives [8]. Methods in MODM use extensive mathematical modeling for optimization and involve a wide range of alternatives. MODM offers the best continuous alternative, close to decision-maker aspiration [14]. Some academics have attempted to combine MADM and MODM methods to generate a comprehensive decision-making result [15].

The MADM approaches discussed in this paper have been successfully adopted in various sectors and research fields, including the energy sector, as one of the most suitable methods for problem-solving. Saaty [16] firstly introduced the Analytical Hierarchy Process (AHP) which proposes a hierarchical structure and a pairwise comparison to evaluate the project and the complex decision making, taking into account multiple criteria.

Mastrocinque et al. [21] has adopted AHP to develop a sustainable supply chain in the renewable energy sector, particularly related to PV installations. Many publications also use this method in various fields, including technology selection in renewable energy [22], renewable energy alternatives [24], and energy policy [23]. Recently, AHP combined with Geographical information systems (GIS) was used to determine off-shore wind farms' location in Turkey [25].

The Analytic Network Process (ANP) was further developed by Saaty [37] to cope with the mutual dependence of attributes. Similar to AHP, this method works well when combined with other MCDM approaches such as Decision Making Trial and Evaluation Laboratory Model (DEMATEL), Technique for Order Preference by Similarity to Ideal Solutions (TOPSIS), and VlseKriterijumska Optimizacija I Kompromisno Resenje (VIKOR). For instance, both ANP and DEMATEL combined to select renewable energy resources in Turkey from the investor perspective [17]. While fuzzy ANP and fuzzy VIKOR adopted to select the optimal location of the PV system in China [38].

Nowadays, the BWM becomes the latest MCDM approach, capable in minimizing the inconsistency of previous techniques and reducing the number of pair-

Table 1: Adoption of MCDM in energy research project

Type of MCDM	Category	Method	References
Multi-Attribute Decision Making	Pairwise comparison-based method	AHP, ANP, DEMATEL, BWM	[17–25]
	Outranking-based method	PROMETHEE, ELECTRE	[26–30]
	Scoring-based method	TOPSIS, VIKOR, SAW, WPM	[31,32]
Multi-Objective Decision Making		e-constraint, goal programming, weighting method	[33,34]
Combination of MADM and MODM		Goal programming-TOPSIS	[15]
		AHP-Goal programming	[35]
		VIKOR-Linear Programming	[36]

wise comparisons [7]. By performing this method, participants will complete the survey in a shorter time. This method also allows for easier data processing to generate a weighting score for research team members. Previous research conducted by Kheybari et al. [19] has attempted to locate the best site for bioethanol production facilities in Iran using this technique.

The outranking model in MADM may include elimination and choice expressing reality (ELECTRE), and preference ranking organization method for enrichment of evaluations (PROMETHEE). Both methods propose a broad perception for decision-makers by processing cases involving multiple alternatives but limited criteria. These concepts have been widely used to evaluate options in the energy sector. Wu et al. [27] has adopted PROMETHEE to determine the optimal selection of the parabolic trough concentrating solar power (PT-CSPP) in China. The author suggested a sensitivity analysis and a comparative analysis ensure the feasibility of the proposed framework. On the other hand, ELECTRE was used in the selection of site for renewable energy sources in Turkey considering geographical conditions and energy production [29], the selection of offshore wind power stations [26], investment analysis for energy resources [28], and policy assessment of renewable energy [30].

In the scoring-based method of MCDM, VIKOR and TOPSIS are two approaches extensively used in the energy sector as alternatives for decision making. These methods adopt aggregating functions but use different ranking and normalization techniques to delete units of criteria [39]. VIKOR adopts linear scaling, and the normalized values do not correlate with the evaluation unit of criteria, while TOPSIS utilizes vector scaling and the normalized values may differ from the assessment unit on the investigated criterion [40]. Some scholars used the VIKOR method for hydro energy storage plants [40]. Some scholars have used the VIKOR method for hydro energy storage plants [41], or the selection of renewable energy sources. Academics have used the TOPSIS method to rank renewable energy supply systems [31] and to prioritize low-carbon energy sources[42]. Some researchers have even proposed a combination of TOPSIS and VIKOR or Taguchi [32,43].

Despite extensive methods of MCDM applied in the energy sector, some limited scholars combine BWM and VIKOR method to evaluate the best alternative for PV installations. In this paper, the author will show how to assign the weighting of the criteria using BWM and perform scoring with VIKOR method in order to gain the ranking of alternatives for the PV installation in the case study. Many other disciplines can adopt this combination to provide an alternative solution during the initial and planning stages.

3. The case study

Tomia is located in the center of Wakatobi National Park, part of the Wakatobi Regency. It is located approximately 100 km southeast of the Sulawesi mainland (see Table 2). Wakatobi area is one of the centers of marine biodiversity in the world, comprising Indonesia, Malaysia, the Philippines, and stretching until the Solomon Islands.

More than 70% of the world's coral species, six species of marine turtle, and over 2,000 species of reef fish are found in this area. This location is one of the ideal places for renewable energy installations, not only to improve people's well-being by increasing access to electricity, but also to lower the risks of transporting and storing liquid fuel that could harm the environment. According to the SolarGIS database, the location shows a high level of solar irradiation reaching 2,016 kWh/m² of annual global in-plane irradiation.

The PV installation focuses on five villages in Tomiaisland (see Figure 1). Four villages consist of Kahianga, Wawotimu, Kulati, and Dete are in Tomia Timur district, while the village of Lamanggau is in Tomia Induk district. A primary daylight survey showed that most of the villages have minimum access to electricity ranging from four to twelve hours per day and are supplied by either self-owned diesel generators, a communal diesel generator, or private resort nearby the village. Self-owned diesel generators and a communal diesel are in decent condition, but lack maintenance due to limited equipment and technical knowledge. People are required to pay a subscription fee for accessing electricity

Table 2: A general description of the case study

Regency	Wakatobi
Province	Southeast Sulawesi
Size	47.10 km²
Population	± 15.789 inhabitants
Social condition	Low-income households
Main activities	Fishing
Topography	Low-slope and some hills
Average rainfall	0,4–288,2 mm

at US$4.5 per cycle. Some of the cycles are thirteen days, while others may be up to one month per cycle.

Based on the primary survey by the research team members, three villages (Wawotimu, Kulati, and Lamanggau) out of five villages, have a sufficient electricity supply for each house. In contrast, less than 97% can only access electricity in the other two villages due to limited generator capacity. The average daily energy consumption for each village is estimated at 87.6 kWh for Kahianga (available for 6 hours), 65.92 kWh for Wawotimu (available for 4 hours), 49 kWh for Kulati (available for 4 hours), 52.36 kWh for Dete (available for 4 hours), and 350 kWh for Lamanggau (available for 12 hours). However, the primary survey found complex troubleshooting with the existing transmission network in Kahianga that could disrupt future PV installation and interconnection. Therefore, an alternative installation by taking into account the integration of the distribution network between Kahianga and Wawotimu as a nearby village considered as one of the PV scenarios.

4. Research methodology

This research follows three-stage approaches, taking into account the BWM and VIKOR approach to achieve the research objectives. First, alternative PV installation is generated before identifying the criteria for evaluation. The research carried out a decision matrix to provide a weighting score for each criterion based on expert judgment. VIKOR technique will then test the criteria and rank the best alternative PV installation in the case study. The research framework is illustrated in Figure 2.

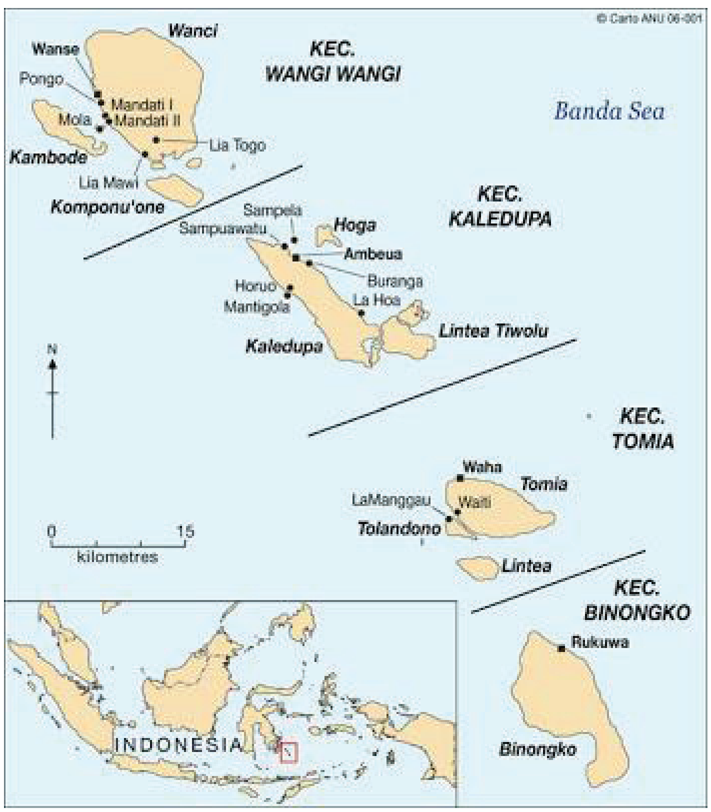

Figure 1: location of the case study
Source: Stacey [44]

Figure 2: research framework

4.1. Best-worst method

This method aims to reduce some issues from the previous pair-wise comparison method including AHP, ANP, and other approaches related to inconsistency, data comparison, and timely completion. Researchers and academics have adopted this method in various contexts and sectors, such as energy efficiency building [45], airport evaluation [46], port performance [47], and residential grid storage technology [48].

Based on Rezaei [7] formulation, the BWMis performed by carrying out the following steps.

Step 1. Establish a set of criteria for evaluation as ($C_1, C_2, C_3 \dots C_n$)

Step 2. Determine the best and worst criteria by taking into account expert judgments without conducting a comparison.

Step 3. Best-to-Others vector which is generated based on a number from one to nine determining which one is the best criterion among any other criteria.

$$A_B = (a_{B1}, a_{B2}, a_{B3}, \dots, a_{Bn}) \tag{1}$$

where a_{Bj} denotes the preference of the best criterion B over criterion j and $a_{BB} = 1$.

Step 4. Others-to-Worst vector is regulated based on similar treatment on Step 3 using a number from one to nine to produce the other criteria over the worst criteria:

$$A_W = (a_{1W}, a_{2W}, a_{3W}, \dots, a_{nW})^T \tag{2}$$

where a_{jW} denotes the preference of the criterion j over the worst criterion W and clearly that $a_{WW} = 1$.

Step 5. Optimal weights will be obtained ($w_1^*, w_2^*, \dots, w_n^*$) by calculating the following optimization problem. It aims to find the weights such that the maximum deviation for all j is minimized.

$$\begin{aligned} & \min \max_j \left\{ \left| w_B - a_{Bj} w_j \right|, \left| w_j - a_{jW} W_W \right| \right\} \\ & \text{s.t.} \\ & \sum_j w_j = 1 \\ & w_j \geq 0; \text{ for all j} \end{aligned} \tag{3}$$

The min-max model from the previous equation proceeds into the following formula:

$$\begin{aligned} & \hat{m}\text{in } ^L \\ & \left| w_B - a_{Bj} w_j \right| \leq \xi^L, \text{for all } j \\ & \left| w_j - a_{jW} W_W \right| \leq \xi^L, \text{for all } j \\ & \sum_j w_j = 1 \\ & w_j \geq 0; \text{ for all } j \end{aligned} \tag{4}$$

Using the model (4), the optimal weights (($w_1^*, w_2^*, \dots, w_n^*$) and optimal objective function value from $min\xi^{L*}$ are generated. Based on Rezaei [49], the value of $min\xi^{L*}$ can be used to show the consistency level of pairwise comparisons, if it is far from zero, then it denotes a low level of consistency.

4.2. VIKOR technique

VIKOR was developed in 1998 to optimize complex decision-making by taking into account a multi-criteria analysis [50]. This technique evaluates alternatives according to the available criteria and also provides a compromise ranking based on the measure of "closeness" to the "ideal" solution.

The research expands the compromise ranking of multi-criteria measurement using aggregate functions [39]:

$$\begin{aligned} & L_{pj} = \left\{ \sum_{i=1}^{n} \left[w_i \left(f_i^* - f_{ij} \right) / \left(f_i^* - f_i^- \right) \right]^p \right\}^{1/p} \\ & 1 \leq p \leq \infty, j = 1, 2, \dots, J \end{aligned} \tag{5}$$

Where L_{1j} (as S_j in Eq. (6)) and $L_{\infty j}$ (as R_j in Eq. (7)) are used to formulate ranking measures.

VIKOR technique uses the following steps [50,51].

Step 1. Determine the best f_i^* and the worst f_i^- values of all criterion functions, $i = 1,2, ..., n$. If, the ith function represents a benefit then $f_i^* = \max_j f_{ij}$ and $f_i^- = \min_j f_{ij}$. On the other hand, when ith function represents cost then $f_i^* = \min_j f_{ij}$ and $f_i^- = \max_j f_{ij}$. This study selects attributes of benefits and cost based on stakeholders' input. Benefit attributes consist of Power, Economic rate of return, and CO_2 Reduction, with the higher value is more desirable. On the other hand, Cost of Energy and Operation and maintenance as cost attributes expected to have lower values.

Step 2. Compute the values S_j and R_j, $j = 1,2,...,J$ by the relations

$$S_j = \sum_{i=1}^{n} w_i \frac{\left(f_i^* - f_{ij} \right)}{\left(f_i^* - f_i^- \right)} \tag{6}$$

$$R_j = \max_i \left[w_i \frac{\left(f_i^* - f_{ij} \right)}{\left(f_i^* - f_i^- \right)} \right] \tag{7}$$

Where w_i denotes the weight of each criterion and f_{ij} is the score of alternative i based on criterion j.

Step 3. When the value S_j and R_j have been obtained, the values Q_j, $j=1,2,3,...,J$ will be evaluated based on the following formula:

$$Q_j = v \frac{\left(S_j - S^* \right)}{\left(S^- - S^* \right)} + (1 - v) \frac{\left(R_j - R^* \right)}{\left(R^- - R^* \right)} \tag{8}$$

Where, $S^* = \min_j S_j, S^- = \max_j S_j, R^* = \min_j R_j, R^- = \max_j R_j$ and v is proposed as the majority of criteria. The value of is ranging from 0 to 1, but 0.5 is taken in this study.

Step 4. Alternatives will be ranked based on the values of *S, R,* and Q which are structured in decreasing order. The best rank (alternative $A^{(1)}$) is selected based on the measure of Q when two conditions are met:

a. Acceptable advantage. $Q\ (A^{(2)})$ - $(A^{(1)}) \geq DQ$, where alternative $A^{(2)}$ is placed second by Q; $DQ = 1/\ (J - 1)$; J is the available alternatives in the project.

b. Acceptable stability. Alternative $A^{(1)}$ placed first by S or/and R. This strategy provides a stable outcome when voting occurred by majority rule (when $v > 0.5$ is needed), or by consensus ($v \approx 0.5$), or by veto ($v < 0.5$).

When the process fails to fulfill satisfying conditions, a set of compromise solution will be proposed as follows.

c. Alternative $A^{(1)}$ and $A^{(2)}$ when condition number (b) is failed, or

d. Alternative $A^{(1)}, A^{(2)},..., A^{(M)}$ when condition number (a) is failed. $A^{(M)}$ is measured through the relation $Q\ (A^{(M)}) - Q(A^{(1)}) < DQ$ for maximum M.

5. Result and discussion

In this section, each alternative scenario is evaluated based on BWM and VIKOR methods to determine the optimum alternative for installation. Subsequently, sensitivity analysis will be used to evaluate certain parameters that could contribute to the research output. Research findings will then be compared with previous literature studies and suggested recommendations for future research direction.

5.1. Alternative scenario for PV installation

The PV scenario in this research was developed by considering the electricity demand of the current households and the future energy usage of approximately 400 kW for all villages. This research generates four alternative scenarios including full PV installation on every five villages, hybrid installation, full PV installation with two integrated villages, and hybrid installation with two integrated villages.

In the first scenario, the research will install PV system in each village. This scenario proposes low emission because of unused diesel fuel, offers clean energy usage, and suggests the lowest operation and maintenance cost compared to other scenarios. However, this scenario requires a large area, leading to higher initial costs and cost of energy. In the second scenario, the PV system will only be installed in Kulati and Dete villages, while the rest of the villages will combine both PV and diesel generators. This scenario offers the lowest cost of energy but compromises the operation and maintenance by more than 100% of the previous one due to the enormous consumption of diesel generators. However, this alternative provides the lowest reduction in CO_2 among other scenarios.

The third scenario suggests that PV is only installed in four villages (Kahianga, Dete, Kulati, and Lamanggau). Unlike the first scenario, Wawotimu electricity will be supported by PV in Kahianga due to their proximity, to reduce investment costs. This scenario offers the highest power and potentially be used beyond daily activities including but not limited to tourism and aquaculture. Last, the fourth scenario suggests PV in Kulati and Dete villages while electricity from the remaining villages supplied by the hybrid system. This system generates adequate power for daily activities with minimum cost of energy and offers a high economic rate of return. However, this alternative consumes the highest operation and maintenance costs. The details of the PV alternatives and the attributes are shown in Table 3.

5.2. Criteria weighting based on best-worst method

This research proposes five criteria to evaluate the best alternative for PV installations in the case study. These criteria (See Table 2) were generated on the basis of a similar case study conducted by [40] and adopts Indonesian experts' judgment. It comprises power (P), cost of energy (CoE), operation and maintenance cost (O&M), economic rate of return (ERR), and CO_2 reduction (CR).

The study developed a questionnaire survey in a structured manner by taking into account pairwise comparison and deploy through an online survey system. Nine responses returned to weight the score for each of the available criteria. Respondents have a variety of occupations, such as academics, private contractors, government institutions, and professionals. They have been involved in energy projects in Indonesia for 2 to 16 years.

Each respondent pointed out their preference for the best criterion to other criteria and other criteria over the worst criterion. Each participant has chosen a different preference as the best and the worst criteria. Most of them argued that the cost of energy and CO_2 reduction are the best criteria that should be considered when selecting an alternative. This result shows a different perspective between the participants. Those involved in investment and project planning will select "cost of energy" due to their ability to change the course of the project.

On the contrary, those who work closely with the environmental sector and regulation have preferred "CO_2 reduction" as the best criteria. Clearly, these participants expected the energy project to reduce a significant amount of greenhouse gas emissions rather than address the investment issue. Institutions of the Indonesian government, such as the Ministry of Environment and Forestry, Ministry of Energy and Mineral Resources, and other related ministries, also prefer to support a project with environmental issues and global emissions as the main concern. Table 4 shows the preference for best-to-other criteria.

Most of the respondents suggested that operation and maintenance as the worst criteria in the energy project, followed by CO_2 reduction. Renewable resources such as solar, wind, geothermal, hydro, biomass, bio-fuel, wave, and tidal have been expected to have low operation and maintenance costs. For instance, the PV system, as part of renewable energy, only required 2% of the initial budget for incidental expenditure [52]. Sen and Bhattacharyya [53] suggested PV maintenance cost of approximately US$10/year. Other types of renewable energy projects have similar costs for operation and maintenance. The findings suggest that the respondent preference from other criteria over the worst one is shown in Table 5.

Based on previous evaluation of best-to-others (see Table 4) and others-to-worst (see Table 5), each criterion was processed by taking into account equation (4) to generate the value of ξ^{L*} for each respondent. However, limited literature found to be related to acceptable value in the BWM, therefore this research uses the value often adopted in the comparison matrix realm.

As suggested by Rezaei et al. [54], the consistency ratio adopts the value of pairwise comparison matrix from 0.1. Based on this output shown in Table 6, the value of from three respondents (R1, R2, and R3) was used for further analysis out of nine respondents. These findings confirmed the work of Mi et al. [55], which components argued to be low credibility when found above 0.1, thus excluded from the decision-making process.

Table 3: PV alternatives and attributes for installation in Tomia Island

Code	Alternatives	P	CoE	O&M	ERR	CR
		kW	US$/kWh	US$/year	%	Ton CO_2 /year
A1	Full PV installation	710	0.83	14,520	20.69	491.405
A2	Hybrid Installation (PV+diesel generators)	642	0.67	92,904	31.04	178.175
A3	Full PV Installation (two integrated villages)	740	0.82	19,227	22.7	491.405
A4	Hybrid Installation (PV+diesel generators with two integrated villages)	488	0.68	113,094	33.31	287.738

Table 4: Respondent preference from best criterion to other criterion

Respondent	Best Criterion	C_1	C_2	C_3	C_4	C_5
R1	Power	1	2	3	5	3
R2	Cost of Energy	2	1	5	3	4
R3	Cost of energy	3	1	5	2	4
R4	Cost of energy	1	5	3	4	2
R5	Economic rate of return	1	4	3	5	2
R6	CO_2 reduction	4	2	1	3	5
R7	Economic rate of return	4	3	2	1	5
R8	CO_2 reduction	3	1	2	4	5
R9	CO_2 reduction	4	3	2	1	5

Table 5: Respondent preference from other criterion to worst criterion

Respondent	Worst Criterion	C_1	C_2	C_3	C_4	C_5
R1	CO_2 reduction	5	5	2	1	3
R2	Operation and maintenance	4	5	1	2	3
R3	Operation and maintenance	4	5	1	2	3
R4	Operation and maintenance	4	5	1	3	2
R5	Power	1	4	2	3	5
R6	Operation and maintenance	4	2	1	3	5
R7	CO_2 reduction	3	1	5	4	2
R8	Cost of energy	1	2	3	4	5
R9	Economic rate of return	3	4	2	1	5

Table 6: Criteria weights from participant responses

Respondent	C_1	C_2	C_3	C_4	C_5	
R1*	0.4000	0.2276	0.1517	0.0690	0.1517	0.0551
R2*	0.2426	0.4081	0.0661	0.1618	0.1213	0.0772
R3*	0.1693	0.4169	0.0652	0.2215	0.1270	0.0912
R4	0.3848	0.1163	0.0626	0.1454	0.2908	0.1969
R5	0.1630	0.1630	0.2174	0.1304	0.3260	0.4891
R6	0.1685	0.3371	0.1348	0.2247	0.1348	0.5393
R7	0.1362	0.0839	0.2725	0.3983	0.1090	0.1468
R8	0.0693	0.3663	0.2970	0.1485	0.1188	0.2277
R9	0.1685	0.2247	0.3371	0.1348	0.1348	0.5393
Mean weights	0.2707	0.3509	0.0943	0.1507	0.1334	

Notes: Value of criterion from * is used to generate mean weights

Although inconsistency may appear in the initial judgment matrix provided by decision-makers when using comparative methods, this research will not perform another round of evaluation to re-assign the weighting and ranking scenario due to time constraints and decision-makers' availability. As a result, the weighting value for power, cost of energy, operation and maintenance, economic rate of return, and CO_2 reduction (see Table 5) were generated based on the mean score of three respondents which denotes by 0.2707, 0.3509, 0.0943, 0.1507, and 0.1334, respectively.

5.3. Alternative ranking based on VIKOR method

Ranking of PV for the case study consider alternatives (See Table 7), benefits and cost attributes, and weighting score (See Table 5). The analysis firstly adopted a normalized decision matrix before producing utility measure (S_j), regret measure (R_j), and rank measure (Q_i). A balanced weighting value expressed in $v = 0.5$ was used to calculate the ranking of available scenarios.

The result (See Table 7) shows three rankings of S, R, and Q. The best alternative should meet "acceptable advantage" and "acceptable stability in decision making" conditions. An "acceptable advantage" takes into account the second-lowest score of Q minus the lowest one, and the result should be greater than $DQ = 1/(4-1) = 0.33$. Although A_3 ranked first by S and R, the first condition is not met as 0.191 is less than 0.33 of DQ. Therefore, a compromise solution is proposed where $Q(A_2) - Q(A_3) < DQ$. This sequence suggests A_3 or full PV installation (two integrated villages) as the best solution for PV installation in the case study.

Table 7: Ranking by VIKOR method

	A_1	A_2	A_3	A_4
S_j	0.278	0.340	0.220	0.488
Rank by S	2	3	1	4
R_j	0.151	0.133	0.127	0.271
Rank by R	3	2	1	4
Q_i	0.191	0.249	0.000	1.000
Rank by Q	2	3	1	4

Table 8: Sensitivity analysis

	v										
	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
A_1	0.17	0.17	0.18	0.18	0.19	0.19	0.20	0.20	0.21	0.21	0.22
A_2	0.05	0.09	0.13	0.17	0.21	0.25	0.29	0.33	0.37	0.41	0.45
A_3	–	–	–	–	–	–	–	–	–	–	–
A_4	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

5.4. Sensitivity analysis

In each decision-making process, decision-makers may have different opinions and lead to different orders of alternative priority. Therefore, it is crucial to examine the findings by taking into account the sensitivity analysis to present the validity of the results. In the VIKOR method, parameter *v* can be used to provide research validity. Normally, a 0.5 value is used to produce a significant result, but it can range from 0 to 1. This value may generate different results depending on the parameters of each research and the data used in the research evaluation.

Based on the *v* value assessment (see Table 8), the result showed that the ranking remains the same from *v* value between 0.4-1.0. In the range of 0 and 0.3, this research found that there were slight changes between the second and third spots, while the best and the worst alternatives have not been altered. These findings show that A_2 will be superior than A_1 when decision-makers vote by veto, but not with consensus or majority rule scenario.

From this analysis, A3 becomes the most potential alternative, followed by A1, A2, and A4 respectively. Despite the high economic returns that could be achieved from hybrid installation, the findings have shown that the installation of PV without taking into account non-renewable energy is still the best alternative for development. Sensitivity analysis supported this argument, where A3 and A1 (through consensus or majority rule scenario) became the top priority for implementation.

Table 9: Result comparison with other methods

	A1	A2	A3	A4	Ranking
VIKOR	Q_i				A3>A1>A2>A4
	0.191	0.249	0.000	1.000	
TOPSIS	P_i				A3>A1>A2>A4
	0.884	0.528	0.986	0.020	
Promethee II	Φ				A3>A2>A1>A4
	0.015	0.051	0.071	–0.137	
Electre III	C_i				A3>A1>A4>A2
	0.855	–1.478	1.184	–0.561	

5.5. Comparison with other methods

This research combines BWM and VIKOR methods to select the best alternative for PV installations in developing countries located in equatorial area. Despite the alternative proposed by this combination, comparisons with other outranking methods, such as TOPSIS, PROMETHEE II, and ELECTRE III, are required to indicate the validity and reliability of the research findings. The comparison of each method is summarized in Table 9.

Based on a comparison of the other three outranking methods, the result showed that alternative A3 is the closest to the ideal solution, produces the maximum flow, and generates the highest net superior, which is similar to the findings of the VIKOR method. TOPSIS method indicates the same sequence as the VIKOR method. While Promethee II and Electre III offer different rankings. The first swaps alternative in between the best and the worst alternatives, while the latter changes the third and the last alternative.

The difference between the two methods is that Promethee II involves maximum group utility, but excludes individual regret. While Electre III considers individual regret but does not take into account group utility. Therefore, it is understandable that these methods provide a slightly different recommendation of alternatives compared to VIKOR and TOPSIS.

Based on these findings, the result of VIKOR method is valid and feasible for the decision making process. The results of this research also confirmed previous literature suggesting the benefit of VIKOR method and its ability to calculate close to ideal solution, taking into account thebalance between maximum group utility and minimum individual regret [38,40,51].

6. Conclusion

Decision-making in an energy project, particularly a renewable one, requires complex decision-making due to different interests of stakeholders, social-economic impact on the community, and environmental issues. Several researchers attempt to adopt MCDM in the energy sector in order to have accurate options for decision-makers. To the best of the authors' knowledge, there is limited research that takes into account the BWM and VIKOR methods for the selection of PV projects in developing countries. As a result, this research output is expected to fill the gap of knowledge both in the energy sector and decision-making model.

The BWM combined with the VIKOR method, argued as one solution to integrate quantitative data between alternatives and expert judgment concurrently. This method also significantly reduces the exhaustive questionnaires and complex computational models. However, some limitations of this research should be addressed for future work. First, this research only involved Indonesian experts to gain a similar understanding and knowledge about the case study. This study suggests involving international participants to produce alternative perspectives and more insight into the broader research context. Second, national experts are still not familiar with this questionnaire, which affects low reliability of the returned questionnaire. An in-depth interview or focus group discussion was suggested as one of the data collections to increase the context of the study and offer adequate time for socialization.

As this research focuses on technical, economic, and environmental aspects as the main consideration to determine PV selection, future research development encourages to involve other aspects, such as social, political, and policy and regulatory issues. Subsequently, there are other methods in both multi-attribute and multi-objective decision making such as grey rational analysis (GRA), DEMATEL, ANP, stepwise weight assessment ratio analysis (SWARA), and entropy-based approach. Fuzzy programming can also be used when decision-making is under some uncertainty, and the subjectivity of decision-makers should be articulated into a quantitative manner to generate objective output. This research encourages integrating those methods into a similar context of study that includes additional aspects for considerations, generates comparisons, and proposes a comprehensive decision-making model.

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