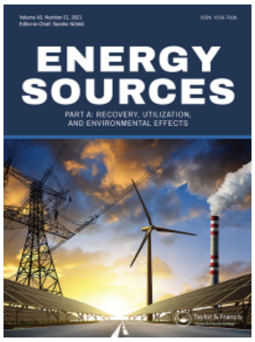

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Optimum Site Selection of Hybrid Solar Photovoltaic (PV) - Hydro Power Plants in off Grid Locations in Cameroon using the Multi-Criteria Decision Analysis (MCDA)

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ABSTRACT

The deployment of renewable power systems is influenced by the geographical, economic, social, and environmental aspects of the location. These factors play a leading role in the project's sustainability and compel developers to carefully analyze them before the decision to install. In Cameroon, there are reported cases of off-grid systems that were deployed arbitrarily such that they could not generate power within the systems' economic life. This necessitates the development of a viable framework of criteria on the sites earmarked for the implementation of these systems. Six potential off-grid sites for the implementation of hybrid solar PV – hydro were examined with the aim of determining the suitable location of the hybrid solar – hydro system in Cameroon. The sites were selected from the North West and South West Regions of Cameroon and were assessed in this paper. In this framework, the computation of the weighted values of the criteria was done through brainstorming with energy experts in Cameroon. The hybrid AHP-TOPSIS method was used in the site selection analysis. The results of this study showed that accessibility of site, resource availability (solar and mini-hydro resources), acute power need, good topography, and distance from the nearest grid-connected locality were the most effective factors influencing the placement of a hybrid solar PV – hydropower system in an off grid location. Munkep was the most suitable site for the installation of the hybrid solar – hydropower system with a performance score of 0.63, hence, it was ranked the first in the analysis. In descending order, Munkep, Zhoa, Esaghem, Kingomen, and Wone were ranked with values of index of proximity to the ideal solution (Rp) of 0.638, 0.491, 0.487, 0.45, and 0.39 respectively.

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Sustainability; Resource availability; AHP- TOPSIS; Weighted values; Economic life

Introduction

Cameroon has been using fossil fuel-based thermal plants to meet her peak demand despite the growing global call on the need for states to decarbonize the power sector. The power generated from these sources poses environmental issues as they can produce substances that damage the ozone layer. Despite enormous renewable energy (RE) sources in the country, they continue to rehabilitate existing thermal plants to support peak demand (Iweh et al. 2023). However, there are policy ambitions to substitute the fossil fuel-based plants with sources that are less polluting. Another challenge is identifying areas in the country where it will be sustainable to deploy RE systems so that polluting power generating systems could be evaded. Site selection of renewables is a significant aspect in system development as it enhances its sustainability. This usually involves analyzing a set of conflicting decisions which if not properly conducted could negatively weigh into the reliability of the installed system; the need for an appropriate decision-making framework.

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Several researchers opine that inadequate methodological support for the optimal siting of renewable energy systems is a major obstacle to the deployment of renewable power systems (SEDDIKI and BENNADJI 2019). Decision making in the deployment of power systems is complex, and requires integrating multiple criteria which can be classified under social, geographical, technological, political, and economic factors. In situations of several criteria in project development, there is a need for a tool which takes into consideration the analysis of all the criteria, with a justification of contradictory ones (Wang et al. 2009). Consequently, to solve for the assorted variables in the problem, expert analysis and a logical framework are needed to consolidate the system data. A Multiple Criteria Decision Making (MCDM) tool offers a logical way of helping developers to combine these inputs with the benefit/cost data as well as the stakeholders' perceptions. The use of qualitative factors in making decisions regarding plant location has extensively used the weighted checklist method with various vital criteria such as nearness to consumers, business environment, regulations, economic incentives, and other weighted scale-related indices. An aggregate score is calculated where the site with the best score is chosen. This approach has been used in a number of industries by (Chase, Aquilano, and Jacobs 1998). However, this method has the potential of offering biased results, tilted toward the perceptions of the decision maker. Furthermore, less effort has been made in previous studies to assess the efficiency of such a weighting method. The impact of qualitative variables in siting a plant was done in Schmenner (1982) through a broad survey of 500 Fortune firms in the United States. The study used factors such as promising labor market, market proximity, the site's quality of life, suppliers' proximity, and cheap labor. The study raised concerns on the fact that the subject of the plant location problem was superficially addressed, with so much emphasis on quantitative criteria such as transportation costs, cost of labor, exchange rate, and tax, ignoring qualitative criteria such as workers' competence, regulations, and accessibility of suppliers.

Following the trends in scholarly attention from previous studies, they have barely given a robust justification of the suitability of the selected MCDM used in the various studies. Predominantly, weak rationales hinged on the authors understanding of the selected MCDM tool have been presented. This limitation has been substantiated by Guarini, Battisti, and Chiovitti (2018) where they showed the scantily available literature on the guidance for choosing suitable MCDM tools for various projects. Although there is an urgent need to increase the RE generation in the power generation mix of Cameroon, like most countries, there is limited information on the use of MCDM tools in prioritizing the localization of RE projects. The method adopted in this study uniquely considers the following aspects:

- The use of the AHP (Analytical Hierarchy Process) method with experts' opinion to identify the relevant criteria for site selection of a hybrid solar PV – Hydro renewable energy systems.
- The application of the AHP method to determine criteria weights considering the uncertainties in experts' judgment.
- Applying the TOPSIS (Technique for Order Preference by Similarity to an Ideal Solution) method to select the optimum site while considering the vagueness in analyzing the alternatives.

The solar and hydro resources in Cameroon are abundant (Yimen et al. 2018) but the challenge is the suitable selection of the sites where these resources could be harnessed at minimum cost while ensuring their sustainable operation. There have been reports of poor performance of installed pico hydro power systems in rural communities in Cameroon (Mungwe, Mandelli, and Colombo 2016) partly due to inadequate feasibility and no data on sites that can support sustainable systems (Iweh et al. 2022). Consequently, the selection of the best location to deploy a power system, is a major factor that determines the ability of the plant to sustainably deliver electricity to users during the course of its lifecycle. The development of dedicated tools for the enhancement of accurate decision-making, can significantly contribute to solving the sustainability challenge. This study proposes a decision-making approach for the selection of the best site for power plant deployment, from the standpoint of sustainable development. Hence, there is a need for more research on site identification in the country in order to add to the most often scanty data available for RE developers. The main aim of this study is to identify the optimum location for the deployment of a hybrid solar PV – Hydro power system for rural Cameroon. Due to the several criteria and other aspects influencing the choice of the optimal option, the process needs a dedicated tool. This paper presents significant criteria which are used in determining the location of a hybrid solar PV – hydro plant. These criteria are presented in a hybrid approach to categorize the priority of various possible sites. This paper proposes an integrated AHP-TOPSIS decision tool for site selection of renewable power generation. So far, the integrated AHP-TOPSIS decision tool has not been used in the analysis of site selection solar PV – Hydro renewable energy system. The paper's novelty is the application of an integrated AHP – TOPSIS method for optimal site selection of off-grid solar PV – Hydro power systems in Cameroon. Cameroon was used as a case study to validate the effectiveness of the method. The results showed that the AHP – TOPSIS approach helped in formulating the problem and effectively handling conflicting data. This culminated in the optimal selection of Munkep as the ideal location for the deployment of the solar PV – Hydro energy system in a robust, participatory, reliable, and comprehensive way.

The paper starts by reviewing previous studies linked to the use of multi-criteria decision tools in solving the location problem so as to develop a broad context for the decision criteria. The next section presents the contributions of this research after the assessment of the available literature on the subject. The study proceeds by presenting the adopted methodology, where the process of the hybrid AHP-TOPSIS method is discussed. Moreover, the results of the study are presented. This section presents the various alternatives as well as their relative proximity to the ideal solution. Lastly, the study ends with a conclusion.

Literature review

There are several methods of MCDM available in literature, namely: Fuzzy Analytical Hierarchy Process (FAHP), Data Envelopment Analysis (DEA) model, entropy method, TOPSIS, and Weighted Aggregated Sum Product Assessment (WASPA), Analytical Hierarchy Process (AHP) (Almeida 2019; Fatemi and Rezaei-Moghaddam 2019). TOPSIS is an acronym for Technique for Order Preference by Similarity to an Ideal Solution developed in 1989 by the scholars in (Hwang and Yoon 1981). Site selection problems mostly have several objectives; ambiguous and uneven framework that makes modeling quite challenging. Another promising ranking method is the ELECTRE (Election et Choix Traduisant la Realite) (Rey, Soriano, and Stampfli 1995) used to reconcile solutions obtained from several criteria. These methods are used by scholars to address problems of choice of site, idea, equipment, etc. The siting problem is prevalent in gas station siting, fast food outlets placement to landfills and power plants location.

Ohunakin and Saracoglu (2018) used five MCDM methods in the identification of optimum sites for solar PV installation. Their results showed that the MCDM approach gave a reliable solution to the problem of solar PV site selection. In order to recover solid waste from organic products, Masebinu et al. 2016 used the MCDM approach in a model which was able to resolve the problem and enhance the environmental sustainability of the production process. Similar studies were conducted by (Aras, Erdogmus, and Koc 2004) using the AHP method to determine the optimum location for the installation of a wind monitoring unit. The AHP method has also been used to determine the best site to setup a restaurant (Tzeng et al. 2002) in a city. The AHP has been widely used in proffering solutions to site selection problems. In sorting to select the best wind turbine model, Sarja and Halonen 2013 conducted surveys with criteria that focused on product dependability and accessibility, size, cost, and maintenance related factors. The study failed to provide the approach used to model the problem and hence, casted doubts on the strength of selection decisions. Similar studies using genetic algorithm (GA) were conducted by (Perkin, Garrett, and Jensson 2015), focusing on turbine parameters such as size of generator, rotor diameter, range of pitch angle, hub height, and revolutions per minute (RPM). The GA method has issues of computational complications. Another artificial intelligence (AI) based method was used by (Chowdhury et al. 2013) with the capacity of energy production as the lone criterion. They used the particle swarm optimization (PSO) method. Apart from the weakness of using a single turbine type, the PSO algorithm equally requires high computational time. The GA, PSO, and the differential evolution (DE) was used in (Dong et al. 2013) for turbine selection with a focus on matching integrated index and the turbine cost index. The AHP was applied to a number of well over 30 criteria by (Shirgholami, Zangeneh, and Bortolini 2016) for turbine selection with the final utilization of only a subset of these criteria for the turbine selection process according to the features of the potential location. A turbine selection method for offshore wind farms was suggested in (Bagocius, Zavadskas, and Turskis 2014) with the consideration of five criteria. These considered criteria included turbine nominal power, maximum generated power, annual energy generated, costs, and CO_2 emissions. The researchers in (Khan and Rehman 2012) suggested a turbine selection approach using the fuzzy logic with a focus on aspects such as rated output, hub height, and zero output percentage. The scholars in (Shafiqur, Luai, and Alhems 2020) used the TOPSIS tool for site selection of offshore wind turbines. A hybrid AHP – TOPSIS method was proposed by (Dinmohammadi and Shafiee 2017) for turbine selection. Similar studies were conducted by (Beskese et al. 2020) using a hybrid AHP – TOPSIS method for site selection of wind turbines and the data used in the research was qualitative and quantitative data. Another study in (Sedaghat et al. 2019) used the Pareto front approach for turbine selection with the consideration of aspects such as annual energy generated, levelized cost of electricity, and capacity factor. The simple multi-attribute rating technique (SMART) and AHP methods were used in (Kigozi, Aboyade, and Muzenda 2014) in the selection of the best type of bio-digester and plant placement site. The study identified the present and future land use as a significant criterion that influences the location of the biogas plant. A GIS (Geographical Information System) and AHP- based approach was proposed in (Akther et al. 2018) for the site selection of a bio-digester in Bangladesh. They used 11 decision criteria and the AHP results indicated that the three main criteria influencing the site selection were the distance from exclusion zones, agricultural areas, and land use. The DEA method was used in (Azadeh, Ghaderi, and Maghsoudi 2008) for optimum location of solar farms in Iran. Similar studies for solar farms were conducted by (Sánchez-Lozano et al. 2013) using GIS and the hybrid AHP – TOPSIS methods in Spain. The main criteria identified in the study included; nearness to the grid, distance to substation, solar resource potential, and topography.

Contribution of the study

The presented literature has shown some gaps which we intend complementing in this study. Literature on site selection of hydropower systems as well as hybrid solar-hydro systems using MCDM is scarce, especially in developing countries like Cameroon. Therefore, there is a need to conduct more site selection studies on solar and hydro development in Cameroon to minimize the failure rate of these systems as well as encourage sustainable growth of the RE sector in Cameroon. This will increase the installed power capacity and the electrification rate of the country. Also, the country’s vision 2035 (Ministry of Economy, Planning and Regional Development MINEPAT 2009), which is based on the industrialization of the country certainly needs electricity to strive and this research will support this vision. Moreover, most of the reviewed literature have used models whose input data acquisition was rigorous and often costly in terms of time and finance. For instance, the approach used in studies such as (Helgason 2012) were models with a single selection criterion that were shady, ambitious, and impractical. Other studies such as (Bagocius, Zavadskas, and Turskis 2014; Beskese et al. 2020) using several criteria presented models that were complex with data acquisition for the study based on indices which are difficult to measure. They used criteria such as product reliability, the integrated matching index, product availability, system reliability index, turbine cost index, matching index, CO_2 emissions. Most of these criteria are based on approximations with no accurate means of acquiring the indices. Another wave of studies used AI-based approaches such as DE (Dong et al. 2013; Perkin, Garrett, and Jensson 2015), GA (Dong et al. 2013), Pareto frontier (Sedaghat et al. 2019) and PSO (Chowdhury et al. 2013) which are complex algorithms. These computational approaches require a lot of computer resources such as memory and time when compared to deterministic methods like TOPSIS. The weighted sum method, AHP and fuzzy logic have equally been used in studies such as (Khan and Rehman 2012; Shirgholami, Zangeneh, and Bortolini 2016).

The AHP method has been extensively used in solving decision problems and it is famous in weight allocation. However, the common criticism on the Saaty's AHP is the "rank reversal" highlighted by (Belton and Gear 1983; Dyer 1990), claiming that arbitrary ranking is generated with the comparison of alternatives using several criteria. However, the strength of the AHP method is its ability to verify the consistency of entries in the pairwise matrix. It helps in calibrating the numeric scales used in measuring quantitative and qualitative performances. The AHP obtains an optimal alternative through four stages: decomposing the problem, comparing the pair-wise matrix, generating the priority vector and synthesis

The TOPSIS method is simple, yet computationally efficient with the ability to consider an infinite amount of alternatives (a drawback of the AHP) (Junior, Osiro, and Carpinetti 2014). Researchers have used this method to solve several decision-related problems. One important advantage of the TOPSIS method is that it does not need a survey of decision maker's opinion in the definition of limits of criteria as it is a requirement in fuzzy logic, and other weighted sum-based methods. Besides, the TOPSIS method offers a modest yet efficient framework in solving multi-criteria problems as well as being computationally efficient. The paper presents the use of a hybrid AHP-TOPSIS method with data sets from Cameroon. It is worthy to note that the approach can be applied to data from anywhere since the method is not site-specific, but only used to provide solutions to local problems. Hence, the main contribution is using the hybrid AHP – TOPSIS method to determine the site selection of hybrid solar PV/Hydro system which is the first attempt, to the best of our knowledge. Single traditional MCDA methods fairly do not satisfactorily assess the site selection challenge of hybrid RE systems since the collection of accurate data, especially during prefeasibility, is challenging. Moreover, some decision criteria have an extensive range of values which many existing methods cannot manage. A hybrid method, combining at least two MCDA approaches, could possibly help in reducing the complexity of decision-making problems and exploit the strengths of the selected methods (AHP and TOPSIS in this case). Nevertheless, limited literature on the use of hybrid methods in locating hybrid solar – hydro RE system exist especially in developing countries like Cameroon. The study aims at using a hybrid MCDA method to determine the optimum location of a hybrid solar – hydro RE system from six selected rural communities in Cameroon.

Relevant criteria relating to the site and the system are considered such as accessibility of site, availability of the renewable energy resources, demand for energy, topography of location, distance from the nearest grid connected location. The study has used this approach due to its robustness and scalability as well as its ability to accommodate more criteria. Six rural communities in Cameroon with differences in climate and topography were selected for the hybrid AHP-TOPSIS method so that comparative analysis of the options could be conducted.

Materials and Methods

The study starts by categorizing the criteria into technical, economic, geographical, and social elements which were subsequently used for the selection of the optimum site for the deployment of a hybrid solar PV – hydro plant. The AHP-TOPSIS method was used in the determination of the suitable site for the hybrid solar PV/Hydro system in six rural communities in Cameroon. This approach necessitates the definition of the site concept in the deployment of the hybrid solar PV – Hydro plants. A number of stated local indicators represent the inputs and outputs of the model. The AHP method is famous for finding criteria weights and will be used in the initial part of study to find criteria weights. Ranking is done using the TOPSIS approach where alternatives are ranked based on criteria weights obtained from the AHP method. Nine decision criteria were considered in the model.

Structure of the decision framework

Initially, the AHP is used to determine the main criteria weights (economic, social, technical, and environmental) while the TOPSIS is used in the ranking of the sites. The technical and economic criteria were developed from information obtained from literature. The geographic and social criteria were established by the authors especially criteria such as degree of traffic convenience and social acceptability. There was no relationship between the adopted criteria as each criterion was independent. The comparison matrix is tested for consistency and the matrix is acceptable when consistency ratio $CR \leq 0.1$. In case the consistency test fails, the pairwise matrix must be reconstructed until the consistency test is fulfilled. Figure 1 shows the decision framework.

The analysis was executed using Microsoft Excel through setting up the algorithm and inputting the collected data into the program to obtain the various solutions. The optimal option was sorted by the algorithm based on the relative closeness of the alternative to the ideal solution.

The steps involved in the AHP process were according to Saaty (1980) and are presented below:

(a) Arrange the decision variables into a hierarchical structure with the most important goal at the top and the least important at the bottom.
(b) Create a pair-wise comparison matrix.
(c) Calculate the weight of the elements using Eq. 1

$$\omega_j = \frac{\sum_{i=1}^{n} b_{ji}}{n} for\ all\ j = 1, 2, 3, \ldots, n. \ldots \tag{1}$$

Where:

ω_j is the equivalent normalized Eigen vector and;
n is the number of decision criteria.

d) Calculate the consistency index (CI) and the consistency ratio (CR) by using Eqs. 2 and 3 respectively.

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{2}$$

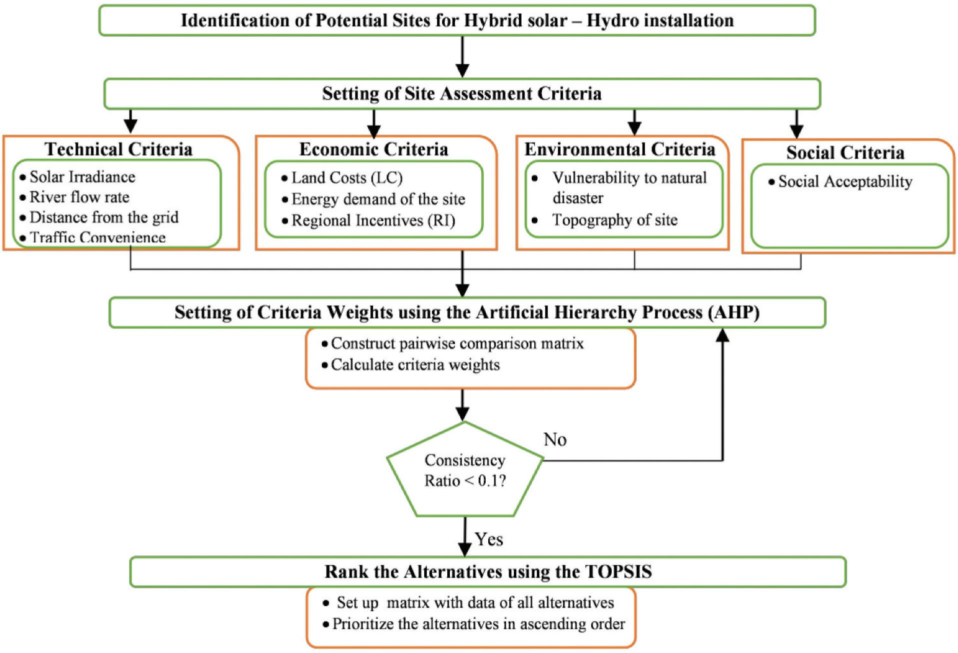
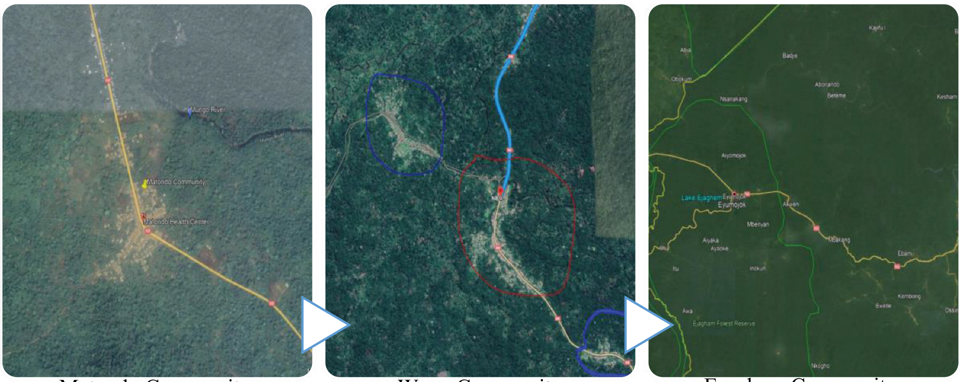


Figure 1. Methodology of the decision framework.



Matondo Community Wone Community Esaghem Community

Munkep Community Kingomen Community Zhoa Community

Figure 2. Google Earth Image of Candidate sites.

$$CR = \frac{CI}{R_i} \tag{3}$$

Where:

λ_{max} is the largest real Eigen value of the pair-wise comparison matrix,

n is the matrix size,

R_i is the random index, obtained from the R_i scale.

A CR value less than 0.1 implies that the pair-wise comparison matrix is consistent, otherwise, the pair-wise matrix has to be re-generated until consistency is achieved.

Candidate sites under consideration

The candidate sites are primarily only off grid communities in Cameroon, i.e., Wone, Matondo, Munkep, Esaghem, Kingomen, and Zhoa. Subsequently, the suitability of these communities is evaluated for the development of a hybrid solar – hydro RE system. The communities with a grid connection or plans of grid connection in the nearest future were not selected. Hence, Wone, Matondo, Munkep, Esaghem, Kingomen, and Zhoa communities were assessed to select where it would be optimum to install a hybrid power plant. The best community will be that which has an exploitable potential of both solar and hydro at minimum cost. The solar radiation data of the communities were obtained from NASA and other qualitative data was collected from experts through questionnaires. Seven experts with knowledge in Cameroonian renewable energy landscape responded to the questionnaire. Figure 2 shows the google image of candidate sites

The challenge is that no site meets all the criteria (technical, economic, social, and environmental) at the same time. Thus, selecting a particular site becomes a complicated task for energy engineers. These types of problems are solved through methods that can handle many criteria at the same time.

The identification of decision criteria

The study was based on nine criteria, grouped into technical, environmental, economic, and social factors. While other scholars opine that more criteria are advantageous when making decisions on clean energy, this is absolutely not ideal. On the contrary, setting a few criteria is suitable for energy system analysis because it minimizes the likelihood of criteria repetition (Wang et al. 2009). The criteria were classified into social, technical, economic, and environmental indicators. The determination of the best site from the criteria was generally based on the local social, economic, environmental, and technical structure. These criteria include:

The acute demand for electricity

Generally, the location of businesses is based on the acute need of the users who will patronize the services of the business. This is equally true for the siting of the hybrid solar – hydropower system, as this will help in the sustainability of the system. Thus, the site should have a reasonable population that will be able to use the power generated. This explains why the power demand of the site is a decision criterion. Sites with more people willing to use electricity are more favored than those with a less power demand.

Distance from the nearest grid connected locality

The distance of the site from the nearest grid connected community was used as a decision criterion, because the systems were off grid systems whose design is meant to operate without a direct grid connection. Also, the installation of off grid hybrid solar – hydro power plants in remote locations is a better option especially in sites where the resources are abundant. The distance from the nearest electrified location has to be far enough such that the cost of grid extension is uneconomical. This is also to make sure the grid does not arrive the locality within the project lifetime.

Land acquisition cost

The cost of land in the selected communities is an important criterion since the installation of the solar PV – hydro system requires space for construction. This criterion is even more significant for large solar and hydro power plants that need a considerably large area of land with a reasonable distance from residential environments. Therefore, an estimated land cost for all the sites considered in the study will be used in the model as inputs.

Geographical indicators

Average river flow rate: A significant aspect of the feasibility of a hydropower system is the availability of a constant flow from a river on the site. Every hydro turbine has an operational range of optimal water flow rates within which it operates and therefore, its continuous operation depends on the flow rate at the level of the turbine. Sites with high average river flow rate has a high probability of being chosen for the deployment of the hydropower station.

Vulnerability to natural disasters: A location's vulnerability to natural disasters could greatly affect its selection for the installation of a power plant as this can be dangerous in the event of the occurrence of the disaster. Hence, power station should be placed in safe locations with a negligible history and potential for harmful natural phenomena. Natural phenomena that can most likely occur with damaging consequences are volcanic eruptions, earthquakes and flooding. The probability of occurrence of these events is determined and their impact considered in the analysis.

Topographical of the site

The deployment of a solar – hydro plant could be viable when the site's topography is not extremely hilly. The construction of solar plants in highly hilly sites is not only challenging but also causes shading effects on the solar panels which reduces system performance. This makes the topography of the site an important aspect. Hydroelectric systems will equally need a fairly sloppy zone in order to have a reasonable net head for power generation.

The assessment of criteria through scale allocation

The acquisition of accurate data from the selected sites is usually a challenge because of the uncertainties that accompany the development of RE projects. Criteria such as vulnerability to natural disaster, power demand of site, degree of traffic convenience, distance from the grid, topography of site, land acquisition cost, and social acceptability are adapted to a scale ranging from 0 to 5 as presented in Table 1. This approach differentiates the traditional TOPSIS method from the improved TOPSIS algorithm used in this study. The data used in the analysis is collected from power system engineers who are familiar with electricity project development. Table 1 presents the scale used in transforming the decision criteria.

The TOPSIS ranking procedure

The TOPSIS method (Hwang and Yoon 1981) picks out the optimum solution from a pool of options and its fundamental concept is that the selected option ought to be nearest to the positive ideal option and furthest from the negative ideal solution (Jahanshahloo, Lotfi, and Izadikhah 2006). It has a good computational efficiency and yet, still not complex. The application of the TOPSIS method in multi-criteria solar PV – hydro site selection requires several conditions that must be met. The TOPSIS method is scalable with the capability of extending the criteria without losing the simplicity. Secondly, weights must be assigned to each criteria so that the weighted normalized matrix can be determined. Thirdly, there is a need for meeting the incommensurability factor, which is an integral part of the TOPSIS method. Incommensurability is a situation in which various criteria have different magnitudes and unit of measurement. The TOPSIS procedure is (Jahanshahloo, Lotfi, and Izadikhah 2006) presented below:

1. Compute the normalized matrix. The normalized matrix, n_{ij}, is given by;

Table 1. Scale allocation of decision criteria.

Assigned Scale Criteria	1	2	3	4	5
Vulnerability to natural disaster	Very low	Low	Medium	High	Very High
Power demand of site	Very low	Low	Medium	High	Very high
Degree of traffic convenience	Not convenient	Less convenient	Convenient	More convenient	Extremely convenient
Distance from the grid	<10 km	10–2 km	20–30 km	30–40 km	>40 km
Topography of site	Very tough	Tough	Normal	Suitable	Extremely suitable
Land Acquisition cost	Very cheap	Cheap	Moderate	High	Very high
Social acceptability	Very negative	Negative	Neutral	Positive	Extremely positive
Average River flow rate (Litres per second)	≤ 10	$10 < I \leq 25$	$25 < I \leq 40$	$40 < I \leq 75$	≥ 75
Average Solar Irradiance (kWh/m^2/day)	≤ 1	$1 < I \leq 3$	$1 < I \leq 3$	$3 < I \leq 5.5$	≥ 5.5

$$n_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^{2}}} i = 1, 2, 3, \ldots, m \quad j = 1, 2, 3, \ldots, n \tag{4}$$

2. Compute the weighted normalized matrix. The weighted normalized, v_{ij}, is given by;

$$v_{ij} = w_j n_{ij} i = 1, 2, 3, \ldots, m \quad j = 1, 2, 3, \ldots, n \tag{5}$$

Where:

w_j is the weight of the i_{th} criterion, and

$$\sum_{m}^{i=1} w_j = 1 \tag{6}$$

3. Compute the positive and negative ideal solutions using the equations:

$$S^{+} = \left\{v_i^{+}, \ldots, v_n^{+}\right\} = \left\{\left(\max v_{ij} | i \in I\right)\left(\min v_{ij} | i \in J\right)\right\} \tag{7}$$

$$S^{-} = \left\{v_i^{-}, \ldots, v_n^{-}\right\} = \left\{\left(\min v_{ij} | i \in I\right)\left(\max v_{ij} | i \in J\right)\right\} \tag{8}$$

Where:

i is related to the benefit criteria, and j is related to the non-benefit criteria.

4. Compute the n-dimensional Euclidean distance. Each solution is separated from the positive ideal solution by the equation;

$$d_i^{+} = \left\{\sum_{j=1}^{n} \left(v_{ij} - v_j\right)^{+}\right\}^{0.5} i = 1, 2, 3, \ldots, m \tag{9}$$

Also, each solution is separated from the negative ideal solution by the equation;

$$d_i^{-} = \left\{\sum_{j=1}^{n} \left(v_{ij} - v_j\right)^{-}\right\}^{0.5} i = 1, 2, 3, \ldots, m \tag{10}$$

5. Compute the relative proximity of the ideal solution. The relative proximity of the solution, R_p, from S^{+} is given by;

$$R_p = \frac{d_i^{-}}{d_i^{+} + d_i^{-}}, i = 1, 2, 3, \ldots, m \tag{11}$$

It should be noted that $R_p \in [0, 1]$, since $d_i^{-} \geq 0$ and $d_i^{+} \geq 0$.

When the level of proximity of an alternative is close to 1, it implies that the alternative is closer to the positive ideal solution and is further from the negative ideal solution for the specific alternative.

6. Rank the results order. The solution having the highest R_p becomes the best option.

Results and discussion

The study followed an empirical approach using real data from six potential sites in rural Cameroon. These six sites were Munkep, Kingomen, Zhoa, Matondo, Wone, and Esaghem. They were taken from the North West and South West Regions of Cameroon. As stated above, the criteria weights were determined using the AHP method while the ranking of alternatives was done using the TOPSIS method. The data for all sites were analyzed using TOPSIS method to determine the optimum solution. The compared 36 options including; - solar resource potential (CT1), hydro resource potential (CT2), vulnerability to natural disaster (CT3), power demand of site (CT4), degree of traffic convenience (CT5), distance from the nearest grid

Table 2. The pairwise comparison matrix of the decision criteria.

Decision Criteria		CT1	CT2	CT3	CT4	CT5	CT6	CT7	CT8	CT9
Availability of solar Resources	CT1	1	1	2	1	1	3	2	1	2
Availability of hydro Resources	CT2	1	1	2	1	1	3	2	1	2
Vulnerability to natural disaster	CT3	0.5	0.5	1	2	2	3	1	2	2
Power demand of site	CT4	1	1	0.5	1	2	1	1	3	2
Degree of traffic convenience	CT5	1	1	0.5	0.5	1	2	1	3	2
Distance from the grid	CT6	0.33	0.33	0.33	1	0.5	1	1	1	1
Topography of site	CT7	0.5	0.5	1	1	1	1	1	1	1
Land Acquisition cost	CT8	1	0.5	0.5	0.33	0.33	1	1	1	1
Social acceptability	CT9	0.5	0.5	0.5	0.5	0.5	1	1	1	1

connected community (CT6), topography of site (CT7), land acquisition cost (CT8), and social acceptability (CT9). The scale used in the study ranged from 1 to 3 with 1 implying equal importance, 2 meaning moderate importance, and 3 signifying strong importance. The comparison matrix was generated from power system engineers in Cameroon through an online survey. The normalized pairwise matrix as well as the weights are presented in Table 2. The weights were calculated using the principal eigenvector matrix in Table 2. Table 2 shows the pairwise comparison matrix and the criteria weights. This comparison was conducted based on the authors' experience and familiarity with the sites under consideration. The matrix was checked for consistency and the consistency ratio obtained was 0.041, implying that the pairwise matrix in Table 2 is suitable. In assigning criteria weights, the Satty's equation of weights (Saaty and Thomas 1987) must be satisfied.

The equation is given by;

$$w_j = \frac{1}{n} \tag{12}$$

Table 2 shows the pairwise comparison matrix of the decision criteria.

The entries in Table 2 were further analyzed by normalizing the pairwise matrix as well as determining the weights of the decision criteria. The consistency of the decision matrix was verified in order to validate the weights obtained. Table 3 shows the normalized pairwise comparison matrix as well as the criteria weights.

The consistency ratio obtained during the analysis was 0.041 which is less than 0.1. Therefore, the weights determined from the pairwise matrix are trustworthy. It is observed that the weights of the solar and hydro resources are given more significance with a similar value of 0.151. Since these systems are standalone systems, the highest weight obtained for the resources is justified because these are some of the most important factors to look out for when conducting the feasibility of an off grid renewable energy project. This is followed by the sites' vulnerability to natural disaster and the power demand with criteria weights of 0.143 and 0.134 respectively. Figure 3 shows the weights of the decision criteria.

The best location must be such that there exist both hydro and solar resources as well as a favorable social environment for the deployment of the hybrid system. Hence, the site should have an acceptable solar irradiance (above 3 kWh/m^2/day) and steady river flow (above 500 l/s) all year round. The site

Table 3. Normalized Pairwise comparison matrix and the criteria weights.

Criteria	CT1	CT2	CT3	CT4	CT5	CT6	CT7	CT8	CT9	Weights
CT1	0.146	0.158	0.240	0.120	0.107	0.188	0.182	0.071	0.143	**0.151**
CT2	0.146	0.158	0.240	0.120	0.107	0.188	0.182	0.071	0.143	**0.151**
CT3	0.073	0.079	0.120	0.240	0.214	0.188	0.091	0.143	0.143	**0.143**
CT4	0.146	0.158	0.060	0.120	0.214	0.063	0.091	0.214	0.143	**0.134**
CT5	0.146	0.158	0.060	0.060	0.107	0.125	0.091	0.214	0.143	**0.123**
CT6	0.049	0.053	0.040	0.120	0.054	0.063	0.091	0.071	0.071	**0.068**
CT7	0.073	0.079	0.120	0.120	0.107	0.063	0.091	0.071	0.071	**0.088**
CT8	0.146	0.079	0.060	0.040	0.036	0.063	0.091	0.071	0.071	**0.073**
CT9	0.073	0.079	0.060	0.060	0.054	0.063	0.091	0.071	0.071	**0.069**

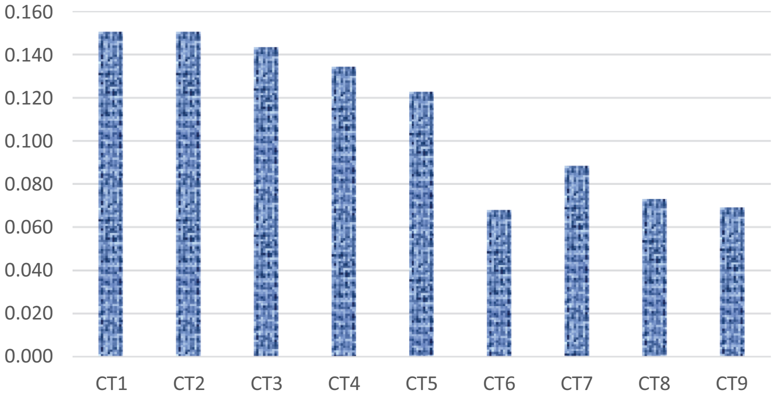


Figure 3. Distribution of criteria weights.

should equally be distant from the nearest grid connected community with a long-term plan of grid extension.

Ranking of sites for hybrid solar hydro

The ranking of alternatives was conducted using the TOPSIS method, after determining the criteria weights from the AHP method. The final weights assigned to the nine criteria are presented in Table 3 after being validated with an acceptable consistency ratio. Data for all the six sites were inserted in the model to form a matrix with the corresponding criteria weights for the analysis using the TOPSIS method. Table 4 shows the initial entries used for the TOPSIS analysis.

The TOPSIS procedure was used to calculate the relative proximity of the ideal solution, after which the ranking of the best location for the hybrid solar PV – hydropower was conducted. Table 5 shows the results containing the weighted normalized matrix, the positive and negative ideal solutions (S^+

Table 4. Matrix used for the TOPSIS Analysis.

Criteria Alternatives	CT1	CT2	CT3	CT4	CT5	CT6	CT7	CT8	CT9
Weights	0.033	0.025	0.032	0.027	0.025	0.023	0.029	0.036	0.023
Wone (A1)	4.5	3	2	4	5	3	2	3	4
Kingomen (A2)	4.9	4	1	2	2	2	3	2	5
Munkep (A3)	4.3	5	1	4	2	3	3	1	4
Esaghem (A4)	4	4	1	2	2	2	4	2	5
Zhoa (A5)	3.9	3	1	3	3	4	2	2	4
Matondo (A6)	4.2	4	2	2	5	2	2	3	5

Table 5. Ranked alternatives of the analysis.

Criteria Alternative	CT1	CT2	CT3	CT4	CT5	CT6	CT7	CT8	CT9	d+	d-	R_p	Rank
Wone (A1)	0.014	0.008	0.018	0.015	0.015	0.010	0.009	0.019	0.008	0.019	0.012	0.390	5
Kingomen (A2)	0.016	0.011	0.009	0.008	0.006	0.007	0.013	0.013	0.010	0.016	0.013	0.450	4
Munkep (A3)	0.014	0.013	0.009	0.015	0.006	0.010	0.013	0.006	0.008	0.011	0.019	0.638	1
Esaghem (A4)	0.013	0.011	0.009	0.008	0.006	0.007	0.017	0.013	0.010	0.015	0.015	0.487	3
Zhoa (A5)	0.012	0.008	0.009	0.011	0.009	0.013	0.009	0.013	0.008	0.014	0.014	0.491	2
Matondo (A6)	0.013	0.011	0.018	0.008	0.015	0.007	0.009	0.019	0.010	0.021	0.010	0.314	6
S+	0.016	0.013	0.009	0.015	0.015	0.013	0.017	0.006	0.010				
S-	0.012	0.008	0.018	0.008	0.006	0.007	0.009	0.019	0.008				

and S^{-}), n-dimensional Euclidean distances (d^{+} and d^{-}), and the relative proximity of the ideal solution (R_p).

This shows the precision of the modified TOPSIS algorithm in choosing Munkep as the optimum site for deploying the hybrid solar – hydro RE system. The proximity to the ideal solution index (R_p) for Munkep is about 0.64, which is relatively the closest value to 1. This could be due to the abundance of solar – hydro in the site as well the distance from the grid, non-exposure to natural disasters, acute demand for electricity and a fair degree of traffic convenience.

From Table 5, it is observed that there are slight differences in the relative proximities to the ideal solution (R_p) for Esaghem, Zhoa and Kingomen. This is an indication that these alternatives have similar characteristics, but for slight changes. For example, Esaghem and Zhoa both have good solar – hydro resources, but accessibility to Esaghem is less convenient than that of Zhoa. This is a significant criterion in the deployment of off grid systems since components needs to be easily transported to the site. Besides, after system commissioning, the systems will need maintenance where some of the spare parts will need to be sourced from nearby cities and any accessibility issues could greatly increase system downtimes from days to weeks. This slight variation in some decision criteria showed a tough competition in the choice of location for the hybrid solar – hydro energy system. The low relative proximity of 0.39 for Wone community is mostly due to its relatively short distance from the nearest grid connected community. The idea is that alternatives that are closer to a grid connected community could soon be connected to the grid, thereby rendering the off-grid system less useful. The research considers the challenges usually encountered by off grid systems when the central grid finally arrives, by placing these at locations having a long distance from the nearest grid connected community.

The weights in Table 3 were determined through AHP and the decision criteria (CT1, CT2, CT3, CT4, CT5, CT6, CT7, CT8, and CT9) had an acceptable consistency ratio. These results obtained in this study corroborate with those described in (Bishnoi and Chaturvedi 2022; Çoban 2020), demonstrating the efficiency of the AHP method in weight determination for optimum location of power plants. The low relative proximity of alternative A1 can be interpreted as the location steadily lacking the qualities required for installing an optimum off grid hybrid solar – hydro renewable energy system.

The solar/hydro resource availability, vulnerability to natural disaster, power demand of site and the degree of traffic convenience were given more significance. The drawback of this research is the modification of the existing algorithms to suit the needs of the hybrid solar – hydro renewable energy system in off grid locations. Nonetheless, sophisticated algorithms could be explored to conduct a similar study and compared with the findings in this study. Sitting an optimum location for deploying a hybrid RE system is a decisive step in the project as it safeguards the full coverage of every perceptible risk to the project. Once a location is wrongly chosen, the sustainability of the hybrid system becomes compromised and the system risk failing before its economic life. Therefore, this research will help in enhancing the power generation as well as the overall system performance. The study supports Cameroon's commitment in meeting her energy ambitions through the optimum location of hybrid solar – hydro RE system in the country.

Conclusion

The study has used the MCDA approach in solving the location problem often encountered in siting hybrid power systems in rural Cameroon. The location problem is critical in the installation of RE system especially off grid because it could greatly affect the sustainability of the project. The hybrid system uses locally available solar and hydropower resources to generate electricity for the community. The decision criteria were grouped into technical, social, environmental, and economic factors, which were collectively used to determine the best site. The multi criteria decision-making method used was the hybrid AHP – TOPSIS method. The major findings of the study can be summarized below;

- Munkep was the most suitable site for the installation of the hybrid solar – hydropower system with a performance score of 0.63, hence, it was ranked the first in the analysis.

- The hybrid AHP-TOPSIS have proven to be efficient in site selection of off grid hybrid PV-hydropower energy system when compared to exclusively using the TOPSIS method where weights are assigned arbitrarily without any means to check consistency.
- The placement of hydro-PV power plants need strict siting procedures among which are technical, environmental, social, and economic, which should be considered to improve the sustainability of the system.
- Factors such as accessibility of site, resource availability (solar and mini hydro resources), acute power need of the community, good topography, and distance from the nearest grid-connected locality were the most effective factors influencing the placement of a hybrid PV – hydropower system in an off grid location.
- From the pairwise comparison analysis, the factors with the highest influence in siting a hybrid PV-hydro power plant are the availability of hydro resources (weight of 0.151) and the availability of solar resources (weight of 0.151). This is true for the construction of the power plant.

The study offers a dependable method and information to Non-Governmental Organization as well as policy makers involved in the planning of rural electrification in Cameroon and beyond. This is crucial as some installed rural power projects in Cameroon have failed a few years after commissioning due to inadequate feasibility studies. The application of this study in other regions could require modifications such as the addition of more criteria and constraints. Site selection of RE systems is multi-objective in nature and has mostly been addressed using quantitative decision-making models. The use of tools that address qualitative criteria (such as social acceptability, degree of traffic convenience, vulnerability to natural disaster) for site selection of hybrid RE systems is scarce. More studies need to be done on developing decision support models that consider both qualitative and quantitative criteria with smart evaluation procedure so that the site selection problem for renewables is rendered less complex.

Perspectives on the application of these tools are much needed with the increasing variation in weather patterns due to climate change. It is even more useful in supporting national commitments such as the Nationally Determined Contributions (NDCs) aimed at adapting and mitigating the effects of climate change. With the growing initiatives of climate action, coupled with their intricacies and inadequate resources, this MCDM tool can help stakeholders in making informed developmental decisions. Moreover, Cameroon like other countries has abundant RE resources to meet its NDCs but the main challenge is prioritizing these resources to solve the country’s climate change mitigation goals. Despite the availability of MCDM tools in literature, their practical application in prioritizing climate action initiatives is still scarce. Further research should focus on using these tools to prioritize climate action initiatives in countries.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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