The Application of PROMETHEE with the recalculated weight method as a more accurate measurement for the selection of the best Hybrid Renewable Energy Technology for a slum building

Donald Ukpanyang

Funding: The author(s) received no specific funding for this work.
Potential competing interests: The author(s) declared that no potential competing interests exist.

Abstract

Criteria weights exert much influence on the final outcome of a decision-making process, and with regards to obtaining accurate measurements of criteria weights, the use of the combined weight method, which integrates the subjective and objective weights into a single component has been investigated in the literature.

The recalculated weight method, which is derived from the application of the Bayes theorem, proposes a more accurate determination of the weights of criteria used in Multi-criteria decision-making. Previous studies on the accuracy of criteria weight determination focus on the combined weight method, where the subjective and objective criteria weights are integrated into a single component, thereby creating a gap in the literature for the exploration of more accurate methods for criteria weight determination.

In this paper, the decision matrix used in the recalculated weight method is obtained from the results of the simulation conducted in a slum settlement in Nigeria, with the use of the HOMER software. The objective weights and subjective weights are obtained initially from the AHP/Fuzzy AHP and Critic/Entropy methods. PROMETHEE method is used to rank the best hybrid renewable energy technology and a comparative analysis between the recalculated weight method and the combined weight method is carried out to determine their level of accuracy. The results obtained are validated with the use of the VIKOR and TOPSIS outranking methods.

Findings from the result reveal that with the recalculated weight method there is 92% accuracy in criteria weight measurement.

Donald Ukpanyang

University of Jaen, Faculty of Engineering, Department of Graphical Design and Projects. Email address: deu00001@red.ujaen.es

Keywords: Hybrid Renewable Energy, PROMETHEE, Criteria Weights, Slums.

1. Introduction

Informal settlements are an integral part of a city with an estimated population of 1 billion inhabitants in 2018, with a future projection of 3 billion in 2030 as the world undergoes an unprecedented rise in the levels of urbanization. The highest number of informal settlers is recorded in the countries of the global south, which include Nigeria[1]. They are characterized by low access to electricity, thereby prompting most of the inhabitants to resort to electricity theft or the use of fossil fuel to provide for their energy needs[2].

The activities of informal settlers in the commercial, transportation, and agricultural sectors of the formal economy and in their respective households contribute immensely to the release of CO_2 emissions, which is of great concern to the environment and is already highlighted in the Paris agreement. It is expected that the available renewable energy sources in slums and informal settlements are sufficient to replace fossil fuel usage thereby providing a cleaner energy option and resilience to the shock in global oil prices[3]. The level of resilience is further reinforced with the use of Hybrid Renewable Energy Systems (HR) which make up for the problem of intermittency and security of supply of renewable energy to slum households in general.

Every settlement is unique in its energy requirement, which informs the design and selection of hybrid renewable energy systems which are tailored to meet those needs[4][5]. In the application of multi-criteria decision-making, there are provisions to consider the energy needs in the social, technical, environmental, and economic dimensions. Outranking models such as VIKOR, TOPSIS, ELECTRE, and PROMETHEE, make use of the weights of criteria to determine the ranking order of renewable energy technologies[4][5][6][7][8].

The MCDM applies the use of criteria with varying levels of importance, to filter out the less preferred alternatives during the selection process. The level of importance of these criteria is a reflection of their respective weights, this signifies that the bigger the size the more influential is the chosen criterion. The criteria weights determine the success of a decision-making process, however there exist the major challenge of determining the accuracy of its measurement.

Normally the weights of the criteria can be subjective and objective. Subjective weights are determined by expert evaluation. These weights express the opinions of experts and are associated with bias and vagueness on the part of the decision maker. i.e stepwise weight assessment ratio analysis (SWARA), simple Multi-attribute Ranking (SMART)[9] analytical hierarchy process (AHP), Delphi and Kemeny Median Indicator Ranks Accordance KEMIRA[10][11][12][13]. On the other hand, objective weights consider the criteria values in the data array provided in the decision matrix. They are represented by mathematical equations, which determine their values without the input of the decision maker[14]. They are not as common as the subjective weights and include: Criteria Importance Through Intercriteria Correlation CRITIC[4][15] and ENTROPY[16]. Others include: Criterion Impact Loss CILOS[17], LINMAP[18] IDOCRIW, and the Correlation coefficient and standard deviation[19].

The subjective weights approach is prone to decision-making bias in the judgment of the decision maker, which can be attributed to lack of experience, and the insubstantial nature of the criteria. Some studies have explored the use of available subjective techniques such as the use of surrogate weights in eliciting methods, to improve the judgement process for decision-makers[20][21][22]. Generally, the objective weights are employed to eliminate bias by carrying out dispersion analysis of the criteria values in the data array and do not benefit from the valuable input from the participation of experts and designers.[20]

In order to overcome the shortcoming and improve the accuracy of criteria weight determination, the integration of subjective and objective weights into one single component is achieved using the combined weight method[14][17][23]. The combined weight method was proposed by Jahan et al.,[24]Literature review shows that, over the years, the combined weight method has been used in MCDM[23][24][25][26][27][28][29].

Over the years several studies involving MCDM have considered the integration of subjective and objective weights in their decision-making analysis, Biswajik[30]applies Pythagorean fuzzy numbers along with TOPSIS MCDM to eliminate uncertainties with the decision maker, by considering AHP and Fuzzy entropy method to determine the objective and subjective weights. Chou & Liang apply the fuzzy set theory where fuzzy linguistic values are assigned to alternatives with respect to the AHP and Entropy weights in a Fuzzy MCDM model used to rank shipping companies[31]. Chung et al[32] perform an assessment of vulnerability characteristics on regional population size, by considering the Delphi technique and the Shannon entropy as subjective and objective weights used to rank the alternatives with the aid of TOPSIS MCDM. Barraghan-Escandon[3], considers entropy and expert opinion to select renewable energy technologies for the intermediate city of Cuenca.

These works claim that the combined weight method is an accurate measure of the criteria weights applicable to the multi-criteria decision-making method. Vinagradov, et al.,(2018), argue that the formal integration of the subjective and objective criteria weights into a single component is inaccurate and proposes the recalculated weight method, which is governed by the Bayes mathematical theorem as a better option.

1.1. Purpose, Scope, and Contribution of the Article

Thus this paper aims to increase the understanding of the application of the recalculated weight method and validate its application with various MCDM methods. This article contributes to the body of knowledge by suggesting a method that improves the way of measuring multicriteria weights for an effective decision-making process. To the best of the author's knowledge, this is the first study to use the PROMETHEE method for the selection of hybrid renewable energy technologies for slum settlements with the use of the most accurate weight.

The remainder of this paper is structured as follows: Section 2 presents the site assessment and the proposed system design carried out with the HOMER software for the optimal selection of the hybrid renewable energy system that is required for the slum household in GKUA.In Section 3, the methodology is described in detail. It includes various steps that depict the objective and subjective weight methods that are applied to the paper. The result of the MCDM process with the use of the combined weight and recalculated weight method are detailed in Section 4 with the use of the PROMETHEE method and validated with other MCDM methods. Section 5 presents the findings and conclusion of this paper.

2. Site assessment and resource availability

The hybrid renewable energy technologies to undergo selection and evaluation are situated in the Greater Karu Urban Area (GKUA), which is a conurbation of hybrid multi-structural settlements with the existence of both formal and informal housing types, which have low or no access to electricity. The GKUA is very unique, it is approximately 28 km from Abuja which is the capital city of Nigeria, thereby making it a strategic location where informal workers who are unable to afford the expensive house rents in Abuja can live and travel to and from. The informal workers resort to erecting illegal structures in the GKUA to shelter their families. The face me- I- face you (tenement building), represents the prototype of the informal housing structures that are prevalent in GKUA. The average amount of hours of electricity supply in the (GKUA) is 6 hours in a day[33].

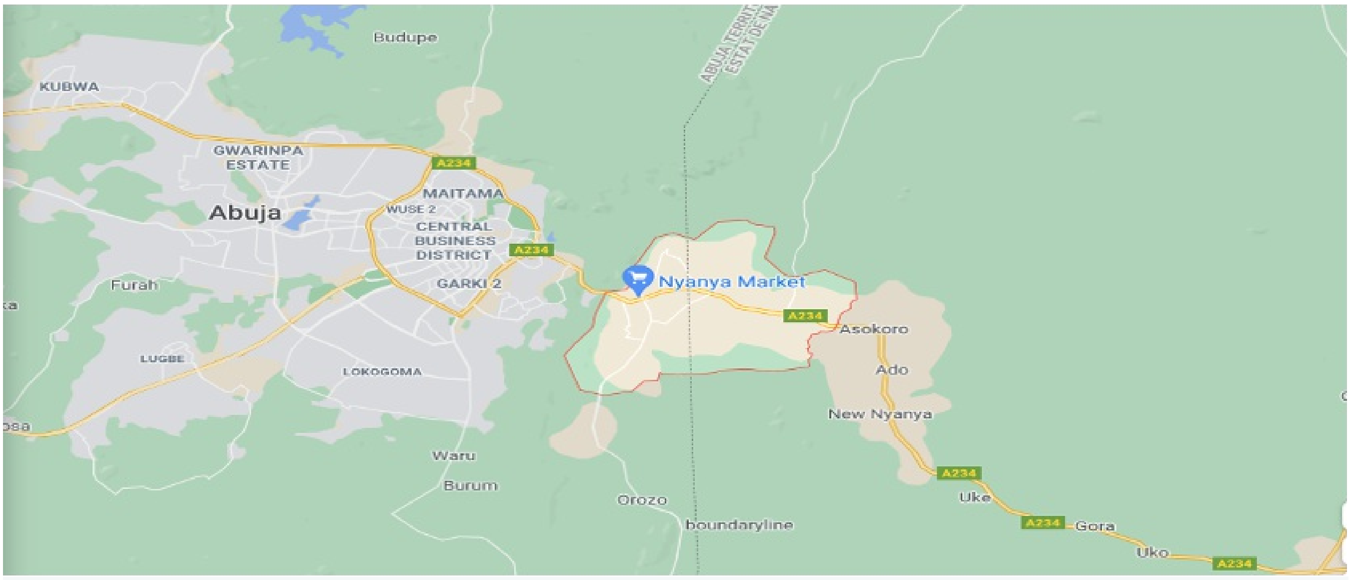

Figure 1. *Study Area*

There is a fair abundance of renewable energy sources, which include wind and solar energy. The values for the average solar radiation and wind speed for (GKUA) were obtained from the NASA website and the National Renewable Energy Laboratory[34]. The average wind speed and solar radiation were taken for 38 years.

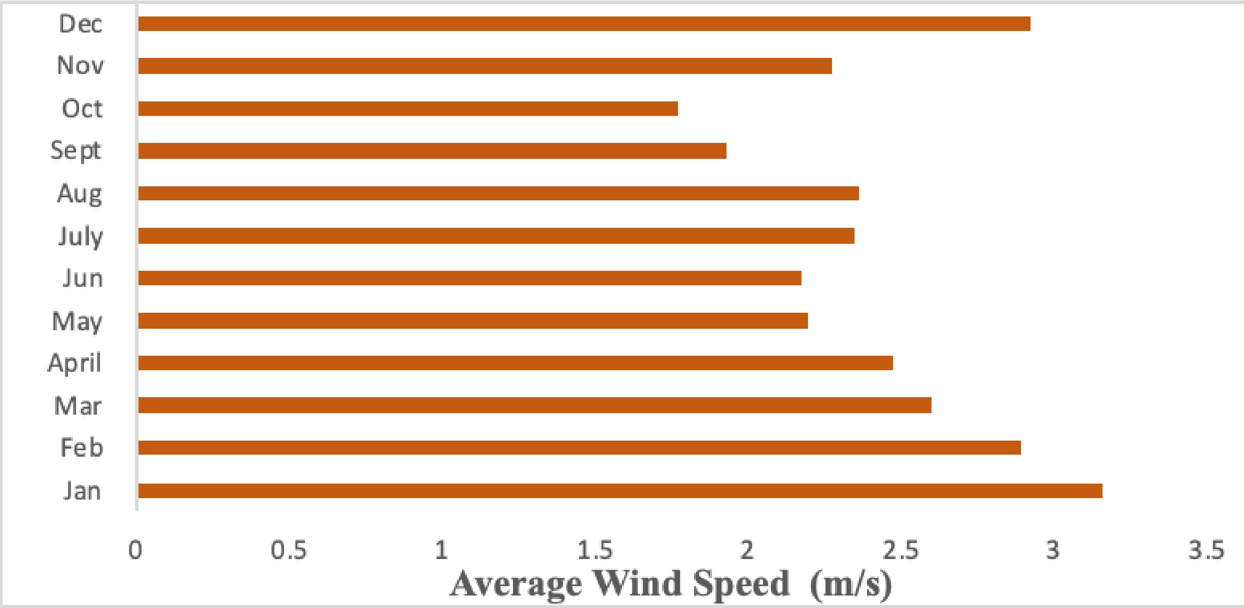

Figure 2. *Average Wind Speed*

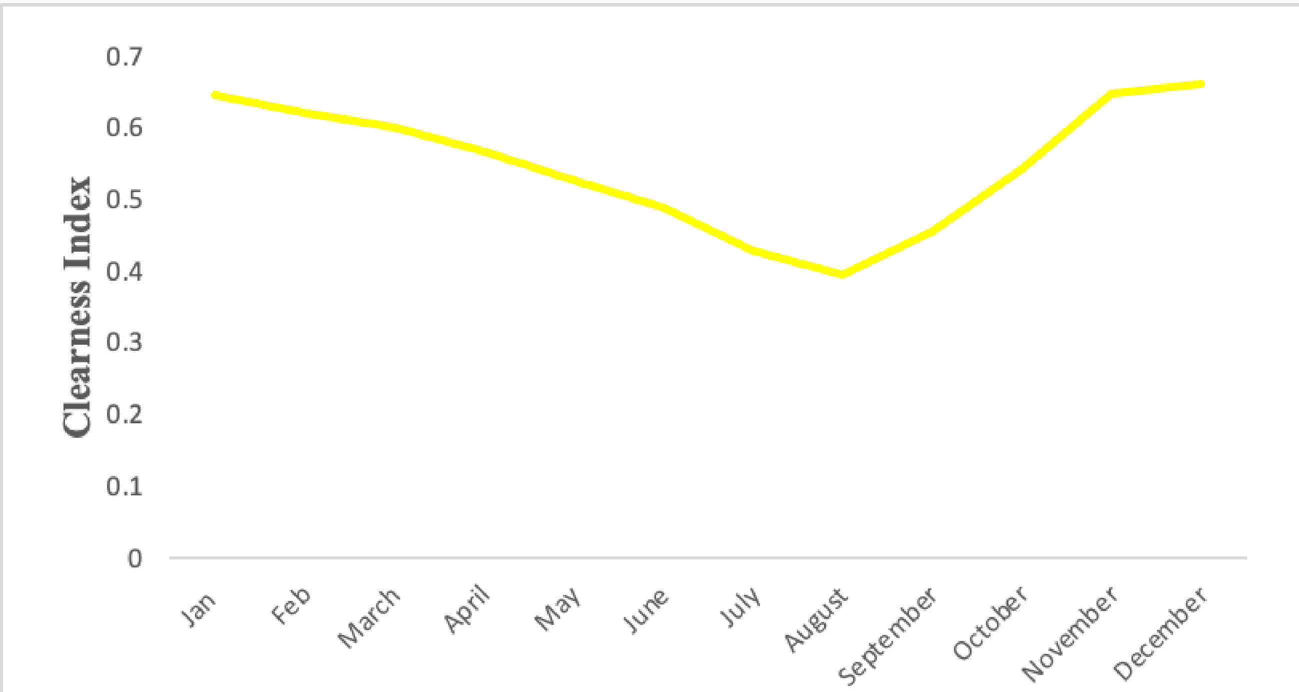

Figure 3. *Clearness Index*

Figure 3 shows that peak solar radiation was obtained in January, while the lowest was obtained in the month of August. According to Figure 2, the highest wind speed was obtained in January (3.5m/s) while the lowest value was recorded in October (2.4m/s).

2.1. HOMER System Design

HOMER software is used to design and optimize Hybrid renewable energy systems in all sectors, from grid-connected homes to rural and island utilities

The simulation carried out by HOMER allows the economically feasible system alternatives to undergo a ranking process that is based on the total net present cost (TNPC). The Hybrid system with the lowest value for TNPC is preferentially selected as the most economically feasible system to meet the energy demand.

Technical input into the HOMER software includes: energy demand on a daily basis, renewable energy sources, and operational constraints such as variable wind speed and the intensity of solar radiation. The economic input includes: Operational and Maintenance cost, Cost of Fuel. The output obtained from the simulation process carried out by the HOMER software include: TNPC and the renewable energy penetration fraction.

2.2. Energy Demand

The determination of the energy demand of an informal household prototype is considered for this study. The “face me I face you” residential building represents the type of building structure that is prevalent in slums and informal communities.

The estimation of the hourly energy consumption is carried out by using equation 1. Table 1 shows the breakdown of the energy demand from a “face me I face you” building.

Table 1 shows the load of the electrical equipment, daily hours of usage, and energy consumption from a single room, a shared bathroom, and a kitchen. The energy demand profile is similar to that of the average Nigerian household, only that there is slightly higher energy consumption during the official working hours of 9.00 am to 5.00 pm. This is a result of some informal residents owning small-scale enterprises, which are operational from their single rooms in the building to provide services to the formal sector during this period.

$$E_{total\ required} = \sum_{i=1}^{load} d_{load} \times t_{load} \times n_{load} \qquad (1)$$

Where D_{load} is the power rating of the electrical appliances, η_{load} is the number of appliances connected to the load and t_{load} is the number of hourly usage of the appliance.

Table 1. Results from the survey on commercial-based productive enterprises

S/N	Building design	Basic appliance	Hourly use (hr)	Power rating (kW)	load (kWh/day)
1	Single room	Television	6 hours	0.1	0.6 kWh
		Ceiling Fan	6 hours	0.08	0.48
		Mobile	8 hours	0.006	0.240
		Phone			
		Lamp	3 hours	0.06	0.36 kWh
		Refrigerator	10 hours	0.120	1.2 kWh
2	Shared Kitchen	Electric Iron	0.5 hours	2	1
		Boiling ring	2 hours	1	4
		Blender Machine	1 hour	0.5	1
3	Walkway	Lamp	10 hours	0.06	2.4
4	Shared toilet	Lamp	4 hours	0.06	0.480
5	Shared Bathroom	Lamp	4 hours	0.06	0.480
Total					12.24kWh

2.3. Proposed Design Specification

The hybrid renewable energy system proposed for this study includes: a gasoline generator, wind turbine, battery storage system, and a solar PV panel. The estimated number of years for the project life is 25 years. The annual interest rate is taken as 5%.

The design specification of the various components of the proposed hybrid renewable energy system is described below.

- Photovoltaic panel: The PV panel is assumed to have a life span of 25 years, the capacity of the Solar Panel is between 0.35kW and 5 kW. The investment cost is $2,500/kW, while the operation and maintenance cost is $2/year. The replacement cost is $2,000/kW. It has a derating factor of 80.0%
- Converter: A 4 kW converter with an investment cost of $ 300 is selected. It also has a replacement cost of $ 300 and an operating cost of $2 /year. Inverter efficiency of 90% and a
- Wind turbine: A 1kW wind turbine connected to the DC terminal is selected, with an investment cost of $2,500 and a replacement cost of $1500 with a life time of 25 years. The hub height is 25 m and the cost of operation and maintenance is 10$/year.
- Diesel Generator: A 10 kW generator is selected, while the capital cost of $ 4,500 and a replacement cost of $4000 is used. The operation and maintenance cost of the generator is $ 0.070 /h. The fuel cost is $ 0.5/L with a life time00 hours. The minimum load ratio is 50%. Other generator sizes which include: 0.5, 0.75.1, and 2.6KW, respectively were considered.
- Battery Storage: A 12 Volts battery storage system with 2 string size is selected, with a capital and replacement cost of

$410 and $400. The battery has a life time of 20 years. The number of batteries is selected within the range of 0 to 40. The minimum and initial state charges are 30 and 100 respectively. The operation cost for the battery in a year is $10 annually.

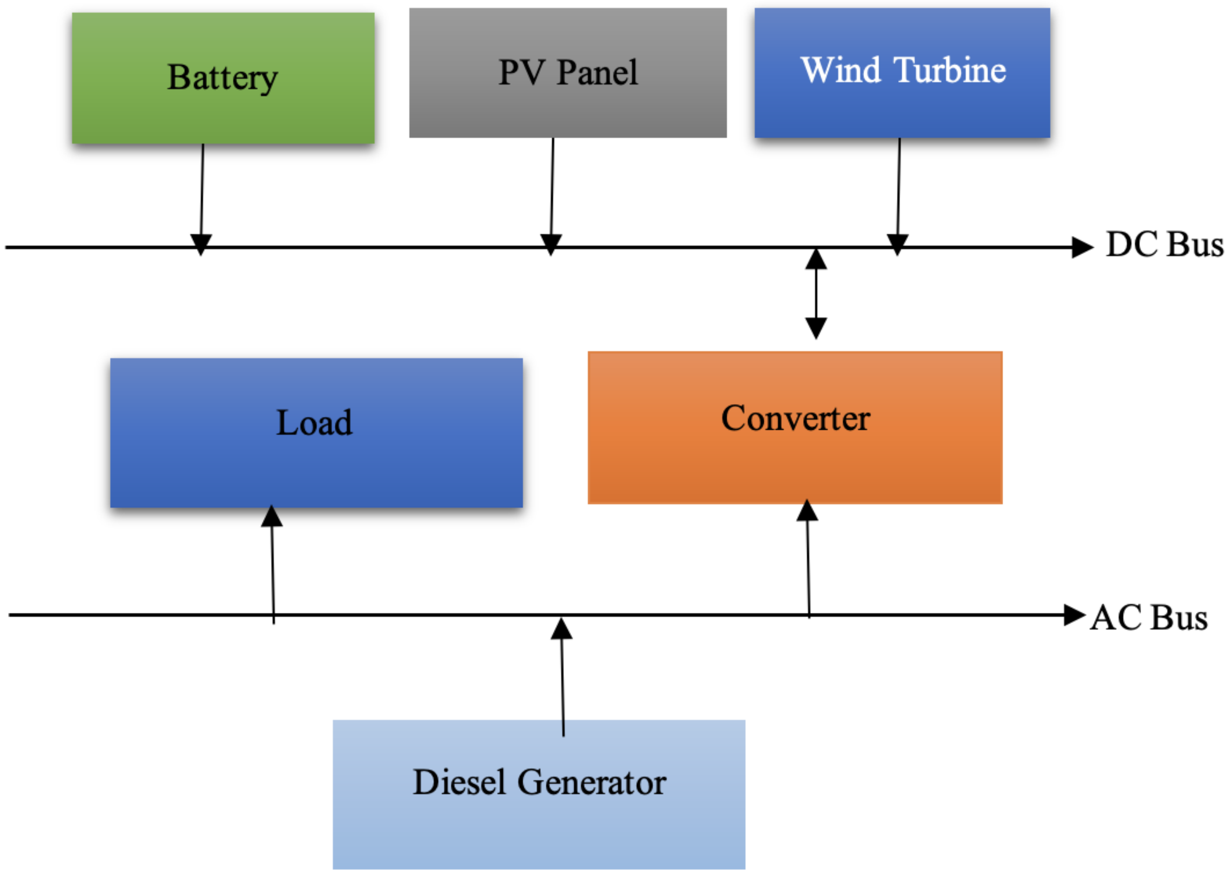

Figure 4. *Design Configuration*

3. Methodology

The recalculated weight method is obtained from the underlying principle of the Bayes theorem, which proposes the determination of the probability of an event occurring alongside another independent event. The Bayes theorem determines the criteria weight to be accurate by considering the evaluations obtained from other expert groups or the use of different weighting methods. The Bayes theorem is represented by the equation:

$$P(A|B) = \frac{P(B|A) * P(A)}{P(B)} \quad (2)$$

The application of the Bayes theorem symbolises the integration of two events A and B, where there is a probability of A occurring given that B is true. In this case, the events are represented as the subjective weights and the objective weights consequently. For the Subjective weights, the two events are represented by the AHP and Fuzzy AHP method and for the Objective weights, the two events are represented by the CRITIC and entropy method.

- In this paper, the combination of the objective and subjective weights are carried out in pairs. Firstly, the objective weights are obtained by applying the CRITIC and Entropy methods.
- Secondly, the subjective weights are obtained by applying the AHP and Fuzzy AHP methods.
- Thirdly, the application of the recalculated weight formula is carried out in order to obtain the first set of criteria weights.
- The application of the combined weight formula is carried out in order to obtain the second set of criteria weights.
- Apply the PROMETHEE method to rank the HRES alternatives with the most accurate.
- Compare the results of the recalculated and the combined weight method with the TOPSIS and VIKOR outranking methods.
- Apply Kendall’s coefficient of concordance.

3.1. CRITIC method

In this paper, the combination of the objective and subjective weights are carried out in pairs. Firstly, the objective weights are obtained by applying the CRITIC and Entropy methods:

3.1.1. Step 1

Obtain the data of array for the decision matrix from the results of the application of HOMER optimization and expert opinion and normalize the decision matrix using equation (3).

$$X_{\tilde{ij}} = \frac{X_{ij} - X_j^{worst}}{X_j^{best} - X_j^{worst}} \qquad (3)$$

3.1.2. Step 2

Calculate the standard deviation for σ_j each criterion

$$\sigma_j = \sqrt{\frac{1}{n}\sum_{i=1}^{n}} (n x_{i,j} - n x_{\tilde{j}})^2 \qquad j = 1, 2, \ldots, m \qquad (4)$$

Where nxj is the symbol for the mean of the j-th criterion.

3.1.3. Step 3

Determine the conflict between the j-th criterion and the other criteria

$$R_j = \sum_{k=1}^{m} (1 - \vartheta_{j,k}) \qquad j = 1, 2.., m \qquad (5)$$

Where nxj is the symbol for the mean of the j-th criteria.

3.1.4. Step 4

Determine the linear correlation coefficient between the vectors i.e the j-th and k-th criteria.

$$\partial_{j,k} = \frac{\sum_{i=1}^{n} (n\, x_{i,j} - n\tilde{x_j}) (x_{i,k} - n\tilde{x_k})}{\sqrt{\sum_{i=1}^{n} (nx_{i,j} - n\, \tilde{x_j})^2 \quad \sum_{i=1}^{n} (nx_{i,k} - n\tilde{x_k})^2}} \qquad j, k = 1, 2.., m \qquad (6)$$

$$-1 \le \partial_{j,k} \le 1 \qquad (7)$$

3.1.5. Step 5

Determine the Objective weight of the criteria

$$\omega_j = \frac{\partial_j \cdot \; R_j}{\sum_{i=1}^{n} \partial_k \cdot \; R_k} \qquad (8)$$

3.2. Entropy Method

3.2.1. Step 1

Obtain the normalized matrix from the data array of the decision matrix selected from the results of the HOMER optimization and Expert opinion conducted using equation (9).

$$r_{ij} = \frac{X_{IJ}}{\sum_{i=1}^{m} X_{IJ}} \qquad (9)$$

3.2.2. Step 2

Obtain the entropy by applying equations (10), (11), and (12).

$$e_j = -h\sum_{i=1}^{m} r_{i,j} * \ln(r_{i,j}) \qquad (10)$$

$$h = \frac{1}{\ln m} \qquad (11)$$

Where

m is the number of alternatives

dj is the degree of diversification, the weight vector Wj is presented as the ratio of dj and ej.

$$d_j = 1 - e_j \qquad (12)$$

$$r_{i,j} = \frac{X_{i,j}}{\sum_{i=1}^{m} X_{i,j}} \qquad (13)$$

3.3. AHP method

The AHP is the subjective weight obtained from expert knowledge about hybrid renewable energy systems. It is the subjective weight of the normalized pair-wise comparison matrix

3.3.1. Step 1

Normalize the pairwise matrix that is obtained from the use of the scale of relative importance by using equations (13) and (14).

$$Wc = \frac{\sum normalized\ principal\ eigen\ vector}{n} \qquad (14)$$

Where W_c is the criteria weight obtained from the pair-wise comparison matrix by taking the average of the summation of criteria values when n is the number of the criteria.

3.3.2. Step 2

There is a need to check for the consistency of the pair-wise matrix with the use of a consistency ratio C.R. The consistency ratio is determined by using equation (15).

$$C.R = \frac{C.I}{R.I} \qquad (15)$$

Where C.I and R.I are the consistency index and random index. The consistency index is obtained from equation (16).

$$C.I = \frac{\lambda_{max} - n}{n - 1} \qquad (16)$$

Where λ_{max} is the ratio o the weighted sum value of the criteria and the criteria weight W_c.

$$C.I\ must\ be\ < 0.1 \qquad (17)$$

3.4. Fuzzy AHP with the geometric mean

3.4.1. Step 1

Convert the crisp numeric values from the scale of relative importance are converted into fuzzy numbers. Fuzzification involves converting the linguistic terms to membership function, which in most cases assumes a triangular and trapezoidal function. In this case, we obtain a triangular function denoted as

$$\mu_A(x) = A^{\sim} = (l, m, u) \qquad (18)$$

Where l,m,u represent the lower, middle and upper values.

3.4.2. Step 2

Convert the fuzzy numbers to a reciprocal value.

$$A^{-1} = (l, m, u)^{-1} = \left(\frac{1}{u}, \frac{1}{m}, \frac{1}{l}\right) \qquad (19)$$

3.4.3. Step 3

Determine the fuzzy geometric mean

$$A_1 \Theta A_2 = (l_1 * l_2, m_1 * m_2, u_1 * u_2) \qquad (20)$$

$$\tilde{r_i} = (l_1 * l_2)^{\frac{1}{n}}, (m_1 * m_2)^{\frac{1}{n}}, (u_1 * u_2)^{\frac{1}{n}} \qquad (21)$$

Where n represents the number of criteria

$$\tilde{\omega_i} = \tilde{r_i} \varnothing (\tilde{r_1} \varnothing \tilde{r_2} \ldots. \varnothing \tilde{r_n})^{-1} \qquad (22)$$

The equation for adding two fuzzy numbers is given as

$$\tilde{A_1} \varnothing \tilde{A_2} = (l_1 + l_2, m_1 + m_2, u_1 + u_2) \qquad (23)$$

3.4.4. Step 4

Defuzzify the weights to crisp numerical values using the centre of area.

$$w_i = \frac{(l + m + u)}{3} \qquad (24)$$

Where wi represents the centre of area (COA).

3.5. Step 1

The recalculated weight method.

The Bayes theorem from equation (2). is used in the work of Vinagrod[17], and it is represented as:

$$\omega (R_J/X) = \frac{\omega (R_j) * \omega (X/R_J)}{\sum_{j=1}^{m} \omega \left(R_J\right) * \omega(X/R_j)'} \qquad (25)$$

Where $\omega (R_j)$ represents the weight of the first event of the j-th criterion R_j.

$\omega (X/R_j)$ represents the weight of the new event, which is determined from a different evaluation method or by a new group of experts. In this research paper, different evaluation methods are considered. The application of the Bayes theorem symbolises the integration of two events i.e evaluation method to determine the subjective weights and the objective weights consequently. For the Subjective weights, the two events are represented by the AHP and Fuzzy AHP method and for the Objective weights, the two events are represented by the CRITIC and entropy method.

3.6. Ranking of the hybrid renewable systems with the use of PROMETHEE MCDM.

3.6.1. Step 1.

Formation of a decision matrix: The decision matrix is obtained from the optimization result from the application of the HOMER software and the evaluation of the qualitative criteria weight by experts.

3.6.2. Step 2.

Normalization of matrix (C_{ij}) to obtain R(ij) using equations (26) and (27).

$$R_{ij} = \frac{[x_{ij} - min(x_{ij})]}{[max(x_{ij}) - min(x_{ij})]} \qquad (26)$$

$$R'_{ij} = \frac{[max(x_{ij}) - x_{ij})]}{[max(x_{ij}) - min(x_{ij})]} \qquad (27)$$

Where R_{ij} and R'_{ij} stand for the matrix values for the minimum and maximum criteria.

3.6.3. Step 3.

Determination of Criterion Weight: The determination of weights is done through subjective and objective methods. The varying criteria weights are used to determine the deviation during the selection process using equation (25).

3.6.4. Step 4.

Determine the aggregate preference function. The preference index Π (a,b) evaluates the difference in preference for alternative *a* over alternative *b*. When Π (a,b) = 0, then there is no preference between both alternatives. If Π (a,b) =1 there is a preference for *a* over *b*. The aggregate preference function is presented in equation (28).

$$\Pi(a, b) = \frac{[\sum_{j=1}^{n} w_j H_j(a, b)]}{\sum_{j=1}^{n} w_j} \qquad (28)$$

Where w_j is the subjective or objective weight from the AHP, Equal, and Entropy method.

3.6.5. Step 5.

Determine the net outranking flow. The preference index is used to quantify the entering and leaving the flow of each alternative.

$$\phi_a^+ = \frac{1}{m-1}\sum_{i=1}^{m}\Pi\,(a, i) \qquad (28)$$

$$\phi_a^- = \frac{1}{m-1}\sum_{i=1}^{m}\Pi\,(i, a) \qquad (29)$$

3.6.6. Step 6.

Determine the net outranking flow. The leaving flow ϕ+ determines to what extent alternative a performs better than alternative b.The entering flow ϕ- determines to what extent other alternatives perform better than alternative a. For a complete ranking the net outranking flow is presented as

$$\phi_a = \phi_a^+ - \phi_a^- \qquad (30)$$

The partial ranking of two alternatives a and b, is presented as follows:

Alternative a is preferred to alternative b if $(\phi_a^+ > \phi_b^+)$ and $(\phi_a^- < \phi_b^-)$; or $\left(\phi_a^+ > \phi_b^+\right)$ and $(\phi_a^- = \phi_b^-)$ or $\phi_a^+ = \phi_b^+$ and $(\phi_a^- < \phi_b^-)$. If $(\phi_a^+ = \phi_b^+)$ or $(\phi_a^- = \phi_b^-)$, then the alternatives a and b are in different. The alternatives are incomparable if$\phi_a^+ > \phi_b^+$ and $\phi_a^- > \phi_b^-$; or $\phi_a^+ < \phi_b^+$ and $(\phi_a^- < \phi_b^-)$.

3.7. Compare the results from using the different sets criteria weights

This is obtained using the recalculated and the combined weight method and validated with TOPSIS and VIKOR.

3.8. Rank the hybrid renewable energy sytems with the application of the combined weights

This is obtained by using equation (31) presented below:

$$w_k^c = \propto w_k^s + (1 - \propto)w_k^o, \quad \propto \in [0, 1] \qquad (31)$$

3.9. Compare the results of the different outranking methods by checking for concordance

This is carried out with the use of kendall's coefficient of concordance presented below:

$$W = \frac{12 \sum d^2}{(n)(n^2 - 1)} \quad (32)$$

4. Results

4.1. Step 1: HOMER Optimization and Expert Evaluation

The first set of objective weight is obtained from applying the critic method. The normalized decision matrix is obtained from using the equation (3) and the data array of the decision matrix from the contribution of expert opinion and the HOMER optimization. The simulation conducted by the HOMER software returns seven hybrid renewable energy technologies which include:

- HR1: Solar PV/Diesel/Battery.
- HR2: Solar PV/Wind/ Diesel/Battery.
- HR3 : Solar PV/ Wind energy/Battery.
- HR4: Solar PV/Battery.
- HR5: Wind energy/ Diesel/ Battery.
- HR6: Wind energy/Battery.
- HR7: Solar PV/Wind energy/Diesel.

Table 2. Decision Matrix

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
HR1	1	1	79	20472	0.385	452.15	863	1	2	1
HR2	1	1	76.8	20569	0.387	453.41	953	3	1	4
HR3	2	1	100	21243	0.4	267.97	0	1	3	5
HR4	3	5	100	23187	0.436	284.48	0	4	3	1
HR5	1	1	33.5	24534	0.461	882.65	2729	1	1	4
HR6	1	1	100	54880	1.03	901.7	0	1	2	2
HR7	3	1	0	113,331	2.13	6224	23976	1	1	1
Best	3	5	100	20472	0.385	267.97	0	4	3	5
Worst	1	1	0	13,331	2.13	6224	23976	1	1	1

4.2. Step II. CRITIC Method

The normalized decision matrix is obtained from using the equation (3) and the data array of the decision matrix from the contribution of expert opinion and the HOMER optimization.

Table 3. Normalized Decision Matrix

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
HR1	4	0	0.79	1	1	0.969077	0.964006	0	0.5	0
HR2	3	0	0.768	0.998955	0.998854	0.968865	0.968865	0.667	0	0.75
HR3	1	0	1	0.991697	0.991404	1	1	0	1	1
HR4	4	1	1	0.970762	0.970774	0.997228	0.997228	1	1	0
HR5	1	0	0.335	0.956256	0.956997	0.896797	0.896797	0	0	0.75
HR6	1	0	1	0.62946	0.630372	0.89359	0.893599	0	0.5	0.25
HR7	3	0	0	0	0	0	0	0	1	0

Table 4. Objective weights from CRITIC Method

Criteria	Value of Weight
C1	0.401471
C2	0.069641
C3	0.0550459
C4	0.04909956
C5	0.04908774
C6	0.0467505
C7	0.049216
C8	0.080038
C9	0.0822414
C10	0.1174064

The objective weights are obtained from the application of equations (4), (5), (6), (7), and (8). The values of the objective weights are shown in Table 5.

4.3. Step III : Entropy Method

The normalised decision matrix is obtained from the equation (9).

Table 1. Normalized decision matrix

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
HR1	0.083	0.09	0.16	0.073	0.073	0.047	0.03	0.083	0.153	0.055
HR2	0.083	0.09	0.15	0.073	0.074	0.047	0.033	0.25	0.076	0.222
HR3	0.166	0.455	0.203	0.076	0.764	0.028	0	0.083	0.230	0.277
HR4	0.25	0.09	0.203	0.083	0.833	0.030	0	0.333	0.230	0.055
HR5	0.083	0.091	0.068	0.088	0.083	0.093	0.095	0.083	0.076	0.222
HR6	0.083	0.091	0.204	0.197	0.196	0.095	0	0.083	0.153	0.111
HR7	0.25	0.091	0	0.407	0.407	0.657	0.840	0.083	0.076	0.055

The second sets of objective weight is obtained from the values of Wj in the Table, (6). by applying equations (10), (11) and (12).

Table 6. Objective Weights from the Entropy Method

Criteria	Values of Wj
C1	0.0340
C2	0.7552
C3	0.0550
C4	0.0696
C5	0.0695
C6	0.0196
C7	0.3659
C8	0.0534
C9	0.0274
C10	0.0529

4.4. Step IV

The first set of subjective weight is obtained from the fuzzy AHP method.

Table 7. Pairwise comparison matrix

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
C1	1	2	2	2	2	3	3	2	5	9
C2	1/2	1	2	1/2	2	2	3	1	4	7
C3	1/2	1/2	1	1/2	1/2	2	2	1/2	3	5
C4	1/2	2	2	1	2	2	3	2	4	8
C5	1/2	1/2	2	1/2	1	2	2	1/2	3	6
C6	1/3	1/2	0.5	1/2	1/2	1	2	1/2	2	4
C7	1/2	1/3	0.5	1/3	1/2	1/2	1	1/3	2	3
C8	1/2	1	2	1/2	2	2	3	1	4	7
C9	1/5	1/4	1/3	1/4	1/3	1/2	1/2	1/4	1	2
C10	1/9	1/7	1/5	1/8	1/6	1/4	1/3	1/7	1/2	1

Table 8. Subjective weights AHP method

Criteria	AHP Weight
C1	0.206983
C2	0.133423
C3	0.087249
C4	0.167719
C5	0.101696
C6	0.067539
C7	0.050512
C8	0.133423
C9	0.033413
C10	0.018042

4.5. Step V

Table 9. Fuzzy AHP matrix

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
C1	1,1,1	1,2,3	1,2,3	1,2,3	1,2,3	1,2,3	1,2,3	1,2,3	4,5,6	9,9,9
C2	1/3,1/2,1	1,1,1	1/3,1/2,1	1/3,1/2,1	1,2,3	1,2,3	2,3,4	1	3,4,5	6,7,8
C3	1/3,1/2,1	1/31/2,1	1,1,1	1/3,1/2,1	1/3,1/2,1	1,2,3	1,2,3	1/2	2,3,4	4,5,6
C4	1/3,1/2,1	1,2,3	1/3,1/2,1	1,1,1	1,2,3	1,2,3	2,3,4	1,2,3	3,4,5	7,8,9
C5	1/3,1/2,1	1/3,1/2,1	1/3.1/2,1	1/3,1/2,1	1,1,1	1,2,3	1,2,3	1/3,1/2,1	2,3,4	5,6,7
C6	1/3,1/2,1	1/3,1/2,1	01/3,1/2,1	1/3.1/2,1	1/3,1/2,1	1,1,1	1,2,3	1/3,,1/2,1	2,3,4	3,4,5
C7	1/3,1/2,1	1/3,1/2,1	1/3,1/2,1	¼,1/3,1/2	1/3,1/2,1	1/3,1/2,1	1,1,1	1/3,1/2,1	2,3,4	3,4,5
C8	1/3,1/2,1	1,1,1	1,2,3	1/3,1/2,1	1,2,3	1,2,3	2,3,4	1,1,1	3,4,5	6,7,8
C9	1/6,1/5,1/4	1/5,1/4,1/3	¼,1/3,1/2	1/5,1/4,1/3	¼,1/3.1/2	1/3,1/2,1	1/3,1/2,1	1/5,1/4,1/3	1,1,1	1,2.3
C10	1/9,1/9,1/9	1/8,1/7,1/6	1/6,1/5,1/4	1/9,1/8,1/7	1/7,1/6,1/5	1/5,1/4,1/3	1/51/4,1/3	1/8,1/7,1/6	1/3,1/2,1	1,1,1

Table 10. Geometric mean values of Fuzzy numbers.

Criteria	Lower point	Middle Point	Upper Point
C1	1.644	2.578	3.405
C2	1.148	1.669	2.309
C3	0.711	1.064	1.712
C4	1.302	2.082	2.911
C5	0.740	1.162	1.835
C6	0.561	0.835	1.311
C7	0.443	0.626	0.933
C8	1.149	1.669	2.309
C9	0.314	0.421	0.608
C10	0.197	0.233	0.292

Table 11. Deffuzified subjective weights.

Criteria	Deffuziffied Weight
C1	0.19844
C2	0.13338
C3	0.09275
C4	0.16530
C5	0.09954
C6	0.07176
C7	0.05245
C8	0.13334
C9	0.03487
C10	0.01818

4.6. Step VI : Results from the application of the recalculated weight method

The overall objective weight is obtained from integrating the criteria weight values of the CRITIC and ENTROPY method with the use of equation (25) The criteria weight values are obtained from Table 4 and Table 6. Secondly the overall subjective weight are obtained from integrating the criteria weight values of the AHP and Fuzzy AHP method with the use of equation (25). The criteria weights are obtained from Table 8 and Table 11.The overall integrated subjective and objective weights are shown in Table 12.

Table 12. Overall integrated subjective and objective weights.

Criteria	Overall integrated subjective weights using Bayes equation	Overall integrated objective weights using Bayes equation
C1	0.31215	0.1989
C2	0.13519	0.0765
C3	0.06150	0.0441
C4	0.21069	0.0497
C5	0.07693	0.0497
C6	0.03683	0.1336
C7	0.02013	0.2620
C8	0.13520	0.0622
C9	0.00885	0.0328
C10	0.00249	0.0904

Finally, the recalculated weight is determined by integrating the overall objective weight and subjective weight with the use of equation (25). The recalculated weight values are shown in the table below:

Table 13. Recalculated weight values

Criteria Weights	Final Recalculated Weights
C1	0.5718
C2	0.0953
C3	0.0250
C4	0.0966
C5	0.0352
C6	0.0453
C7	0.0486
C8	0.0775
C9	0.0027
C10	0.0021

4.7. Step VII: PROMETHEE

The recalculated weights are used as the criteria weights in the selection and subsequent ranking of the available hybrid renewable energy systems.

The Table 14 shows the normalized matrix, with the consideration of the maximum and minimum criteria, which are represented by equation (26) and equation (27).

Table 14. Normalized PROMETHEE Matrix

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
HR1	0	0	0.790	1	1	0.969	0.964	0	0.5	0
HR2	0	0	0.768	0.998	0.968	0.968	0.960	0.667	0	0.75
HR3	0.5	0	1	0.991	1	1	1	0	1	1
HR4	1	1	1	0.971	0.997	0.997	1	1	1	0
HR5	0	0	0.335	0.956	0.896	0.896	0.886	0	0	0.75
HR6	0	0	1	0.630	0.893	0.893	1	0	0.5	0.25
HR7	1	0	0	0	0	0	0	0.333	0	0

The aggregate preference functions of the seven hyybrid renewable energy technologies are obtained from the application of equation to the normalized matrix.

The overall ranking of the seven hybrid renewable technology available is carried out using the equations (28), (29) and (30) respectively. The results of the PROMETHEE ranking is shown in the table below:

Table 15. PROMETHEE ranking using the recalculated weight.

Alternatives	Entering Flow	Leaving flow	Net flow	Ranking
HR1	0.285	0.055	-0.230	4
HR2	0.361	0.093	-0.268	6
HR3	0.137	0.253	0.115	3
HR4	0.003	0.745	0.742	1
HR5	0.303	0.045	-0.258	5
HR6	0.322	0.040	-0.283	7
HR7	0.263	0.45	-0.183	2

4.8. Step VIII. Results from the Combined weight method

The values for the subjective and objective weight which are obtained by applying the combined weight method using equation (31) are presented below in Table 16.

Table 16. Results for the application of the combined weight method.

Criteria	AHP/Entropy method	Fuzzy AHP/ Critic method
C1	0.1205	0.5718
C2	0.1015	0.0953
C3	0.0739	0.0250
C4	0.1072	0.0965
C5	0.0743	0.0352
C6	0.0592	0.0453
C7	0.0508	0.0486
C8	0.1067	0.0775
C9	0.0586	0.0027
C10	0.0678	0.0021

4.9. Step IX

The weight obtained from using the recalculated weight method and the combined weight method are validated with the use of other outranking models, which include the TOPSIS and the VIKOR methods.

Table 17. Ranking of alternatives with weight recalculated method.

Alternatives	PROMETHEE	TOPSIS	VIKOR
HR1	4	4	5
HR2	6	7	4
HR3	3	3	3
HR4	1	1	1
HR5	5	5	6
HR6	7	6	7
HR7	2	2	2

Table 18. Ranking of alternatives with the AHP/entropy combined weight method.

Alternatives	PROMETHEE	TOPSIS	VIKOR
HR1	4	4	3
HR2	6	3	6
HR3	2	2	2
HR4	1	1	1
HR5	3	5	5
HR6	5	6	4
HR7	7	7	7

Table 19. Ranking of the alternatives with the Fuzzy AHP/Critic combined weight method.

Alternatives	PROMETHEE	TOPSIS	VIKOR
HR1	3	4	5
HR2	5	3	4
HR3	2	2	2
HR4	1	1	1
HR5	4	5	6
HR6	6	6	7
HR7	7	7	3

4.10. Step X. Check for concordance

The concordance in the ranking obtained by the recalculated weight method is measured and compared to the results from the ranking conducted by the combined weight methods in Table 18 and Table 19 by the application of equation (32).

5. Discussion

The accuracy of the criteria weight method is determined from the measure of the level of closeness in the rank orders carried out with the different outranking models. The Kendall's co-efficient of concordance is used to measure the closeness in the agreement between variables (m) used to measure (n) sets of objects [35][36]. In this research paper the variables are the outranking models which include: PROMETHEE, TOPSIS and VIKOR and the objects to be assessed are the available hybrid renewable energy technologies. The ranks of the hybrid renewable energy technologies are shown in Tables 17, 18 and 19.

The comparative analysis is carried out between the measures of the concordance value (W), for the ranking conducted with the use of recalculated weight method and the combined weight method as weights used in the outranking models.

The results of the value of W are obtained by applying equation (32) and it is shown in the table below:

Table 20. Showing Kendall's co-efficient of concordance.

Method	Recalculated method	AHP/ENTROPY method	Fuzzy AHP/CRITIC method
Concordance value (W)	0.9206	0.8651	0.7937

The values for (m), which represents the number of variables i.e PROMETHEE, TOPSIS and VIKOR is obtained as 3, while the value for (n), which represents the number of hybrid renewable energy technology is obtained as 7 respectively. In the three scenarios of weight ranking method, it can be observed that the value of concordance (W) is the highest for the recalculated weight method, followed by the AHP/Entropy and FuzzyAHP/CRITIC method with values 0.9206, 0.8651 and 0.7937 respectively.

Generally, the values of concordance (W) ranges from 0 to 1, and it can be interpreted to mean that 1 denotes the highest agreement and 0 the lowest respectively. With a concordance value of 0.9206, the recalculated method shows a higher level of agreement between the variables in comparison to the combined weight methods. Therefore it provides the most accurate measure of accuracy. The significance is that even though the ranking is conducted by different outranking methods, they all require the application of a common criteria weights as a prerequisite for the determination of the outcome of the ranking process. The use of the recalculated method creates a close to perfect uniformity in the individual ranking models. It is expected that a value of 1 which represents the highest level of agreement is far from reachable and the reason is because the outranking models are different in their ranking methodologies leading to a shortcoming in achieving a perfect rank order, regardless of the use a common criterion weighting method that is employed for each ranking model. For example, TOPSIS applies the principle of determining the Euclidean distance from the ideal best and worst solution, PROMETHEE applies the aggregate preference function of the alternatives. The VIKOR method is based on the concept of determining a compromise solution for conflicting criteria, by introducing a ranking index that measures the closeness to the ideal solution.[6].

The highest level of concordance, obtained from the use of the recalculated weight method in comparison to the combined weight method can be attributed to the different approach to the measurement of criteria values between these methods.

The application of the recalculated weight method is guided by the underlying principle of Bayes theorem, which considers the inclusion of the re-evaluated values of a criterion weight either by an additional expert opinion or a different weighting method. It obtains and interprets information provided in the data array of the decision matrix. On the other hand, the combined weight method works on the basis of integrating components of weight into a single value.

The principle of the Bayes theorem makes the provision for obtaining the average values of two events, when the probability of one event occurring given that the second event is true. In the case of multi-criteria decision making, the posterior probability of the subjective weight occurring given that the objective weights is true or the posterior probability of the first weighting method occurring given that the second weighting method is true are the conditions that need to be fulfilled. As long as the first and second weighting methods are different events. In the application of the Bayes equation, the relative mean of the weighing methods are obtained through the process of normalisation, which improves on the accuracy in the weight measurement.

On the other hand, the combined weight method considers the inclusion of components of both subjective and objective weights at intervals that is determined from the values of $\propto \in [0, 1]$.

At $\propto$ 0.5, there is a 50% integration of both subjective and objective weights to, the percentage combination of subjective and objective weights vary from 0 to 1. However the limitation of this approach to criteria weight determination is evident in the inability to account for the relative mean of criteria values, and the consideration of other weighting methods, which is accounted for in the recalculated weight method.

The results from Table 17, 18, and 19, show that the criteria weight scenarios agree that the best hybrid renewable energy technology is HR4 which is a representation for Solar PV/Battery storage. The AHP/Entropy and AHP Fuzzy/CRITIC combined weight methods, agree that the Solar PV/Wind energy/Diesel/ Battery Storage, which is represented as HR3 occupies the second position, this is in aberration with the ranking of the second position by the recalculated method. The recalculated weight method ranks HR7, the Solar PV/Wind Energy/Diesel in second position. It is evident that the weights of the criteria determined by these methods have a direct influence on the ranking measured by the out-ranking models. The results from Table 13 and Table 16, show some discrepancies in the measurement of weights obtained. It can be observed that the ranking of criteria values according to their respective sizes are consistent for criteria C1,C2,C3,C4,C5,C8,C9 and C10. For criteria C6 and C7, which represent operating cost and CO_2 emissions, there are large differences in the size rank for the AHP/Entropy method and AHP Fuzzy/ CRITIC combined weight methods. C7 has the lowest size of 0.050833 for the AHP Fuzzy/CRITIC method, while it is the largest size criterion for the AHP/Entropy method with a value of 0.2082. The same trend can be observed in the value of criterion C6, which is the 2nd lowest in size with a value of 0.0592 for the AHP Fuzzy/CRITIC method, while it is the 2nd largest criterion in size with the use of the AHP/Entropy combined weight method. These discrepancies is corrected with the recalculated weight method, which has the values of criterion C6 and C7 as the 6th and 5th position on the scale of size ranking. The recalculated weight method is closer to the average values from the ideal solution in both instances, further strengthening the argument of the importance of this method over the combined weight method. The influence of the weight size on the final outcome of the ranking process is evident from the data array of the decision matrix in Table 2.

The statistical significance of the Kendall's coefficient value (W) is tested based on two conditions of the alternative and null hypothesis:

H_a= There is an agreement between the variables.

H_O= There is no agreement or concordance between variables.

The level of significance at a 95% confidence interval is 0.05 and the degree of freedom is 3.

Kendall's coefficient of concordance at 95% confidence interval from critical x2 values is given by the equation

$$x^2 = m(n-1)W \qquad (33)$$

Where

m = 3; the number of outranking models.

n= 7; number of hybrid renewable energy technologies.

W = Kendall's coefficient of concordance at 0.9206.

The value for x^2 obtained is 16.571, from the application of equation (33) and the Chi square table value at 95 % confidence interval and 3 degrees of freedom is given as 7.81.

The conclusion is to reject the null hypothesis and accept the alternate hypothesis because there is indeed an agreement between the edecision-making outranking models with the use of the recalculated weight method.

The recalculated weight method provides a more accurate measurement of criteria weights to be used in decision making process.

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