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Multicriteria Decision-Making to Determine the Optimal Energy Management Strategy of Hybrid PV–Diesel Battery-Based Desalination System

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Abstract: This paper identifies the best energy management strategy of hybrid photovoltaic–diesel battery-based water desalination systems in isolated regions using technical, economic and techno–economic criteria. The employed procedures include Criteria Importance Through Intercriteria Correlation (CRITIC) and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) as tools for the solution. Twelve alternatives, containing three–four energy management strategies; four energy management strategies, load following (LF), cycle charging (CC), combined LF–CC, and predictive strategy; and three different sizes of brackish water reverse osmosis (BWRO) water desalination units, BWRO-150, BWRO-250, and BWRO-500, are investigated with capacity of 150, 250, and 500 m^3/day, respectively. Eight attributes comprising different technical and economic metrics are considered during the evaluation procedure. HOMER Pro® software is utilized to perform the simulation and optimization. The main findings confirmed that the best energy management strategies are predictive strategies and the reverse osmosis (RO) unit's optimal size is RO-250. For such an option, the annual operating cost and initial costs are $4590 and $78,435, respectively, whereas the cost of energy is $0.156/kWh. The excess energy and unmet loads are 27,532 kWh and 20.3 kWh, respectively. The breakeven grid extension distance and the amount of CO_2 are 6.02 km and 14,289 kg per year, respectively. Compared with CC–RO-150, the amount of CO_2 has been sharply decreased by 61.2%.

Keywords: decision-making; CRITIC–TOPSIS; optimization; energy management

1. Introduction

The exponential growth in fossil fuels resulted in plenty of health and environmental problems [1,2]. A massive work has been done to raise the efficiency of the current processes [3] and use new devices that are environmentally friendly and have high efficiency.

Due to the sustainability of renewable energies and their low environmental impacts [4,5], they are considered the best candidates to replace fossil fuel, shortly. Currently, securing freshwater resources is one of the main challenges facing human beings [6]. Although more than two-thirds of the earth's surface is water, less than 1% of this water is suitable for industrial and domestic usage [7]. Water desalination is considered the best method for securing freshwater. Water desalination can be classified into two main categories, i.e., thermal desalination and membrane-based desalination. Reverse osmosis is one of the membrane-based desalination methods that demonstrated promising results in the water productivity at lower specific energy consumption, compared to the other desalination methods. Therefore, it is widely used on the commercial state [8,9], although, of the promising features of the reverse osmosis, it is challenged by fouling and scaling that resulted in decreasing the water productivity and increasing the energy consumption. Moreover, the discharge of the brine is one of the main byproducts that has severe environmental impacts, and significant efforts are being done to find a suitable solution for it [10,11]. Several parameters affect the overall performance of the reverse osmosis process [12]. The optimization of the different reverse osmosis (RO) parameters are very critical in deciding the overall performance, in terms of water productivity and specific energy consumption; therefore, several studies have been carried out to optimize the performance of the RO units [13–17].

However, water desalination, "even using RO", is an extensive energy consumption technology with severe environmental impacts [18]. Securing the desalination energy from renewable energy will not only reduce the cost but also save the environment. However, several challenges face the widespread of renewable energy sources (RESs), such as variable atmospheric conditions, intermittency, new technology, cost, etc. The most promising renewable energy source (RES) is solar energy, used effectively in water desalination with low or no environmental impacts [19]. However, solar energy, mostly when used for direct electrical power production using solar photovoltaics, is subject to partial shading, high initial cost, dust accumulation, and low panel efficiency [20]. Therefore, to tap maximum power from Solar Photovoltaic Systems (SPV), maximum power point tracking (MPPT) controllers are practical and efficient solutions for uncertain weather conditions [21,22]. The policy of electricity generation is a strategic one that helps in community development. These policies are analyzed to guarantee reliable and affordable generation to the community. Achieving this aim has a high probability in case of combining the energy policy with the social, technical, economic, and environmental needs of the community [23].

Multicriteria Decision-Making (MCDM) is helpful in sorting out accessible data, reevaluating choices, and investigating their discernments and requirements [24]. Choices and inclinations are communicated as conditions, information sources, and coefficients, which can be watched and imitated. MCDM techniques have just been generally and effectively applied to illuminate the enormous scope of socio-specialized choice issues, identified with vitality strategy, arranging them to allow for deciding the best sustainable power source or feasible vitality framework plan [25]. Aside from that, likewise, a few audits on MCDM are accessible in their entirety in economic and sustainable power source advancements and frameworks [26]. Nonetheless, because of the wandering objectives and degrees and the heterogeneity of approaches these do neither permit the inference of any decision about the reasonableness of various energy storage systems (ESSs) for giving framework administrations nor provide rules about how to lead the MCDM for assessing ESSs in a powerful and far-reaching way [27,28].

The main strategies of selecting the best RESs are divided into main criteria, subcriteria, and subnetwork [29,30]. The main criteria include environmental, economy, technology, security, global effect, and human well-being. At the same time, the subcriteria is divided into benefits, costs, opportunities, and risks. The subnetwork is divided into solar, wind, geothermal, biomass, hydro, and nuclear energies. The decision process framework can be divided into four main steps: step 1: data collection and analysis process; step 2: content validity; step 3: calculation procedure; and step 4: selecting the optimal RES based on using optimal MCDM methods [31].

There are several MCDM methods, such as Weighted Product Method (WPM) [32,33], Weighted Sum Method (WSM) [26,34,35], Elimination and Choice Translating Reality (ELECTRE) [36–38], Analytical Hierarchy Process (AHP) [39], Vlse Kriterijumska Optimizacija I Kompromisno Resenje (VIKOR) [40–42], Technique for Order Preference by Similarity to Ideal Solutions (TOPSIS) [43–46], Preference Ranking Organization Method (PROMETHE) [47–49], and Multi-Attribute Utility Theory (MAUT) [50–52]. Each method has its advantages, disadvantages, and application as being summarized in the literature [53–55].

Among the different MCDM methods, TOPSIS is an effective method that shows a real solution for several issues [56]. TOPSIS helps decision-makers (DMs) to understand, complete examination and correlations quickly, and rank the other options. According to the needs, the determination of a reasonable alternative(s) will be made. Notwithstanding, numerous dynamic issues inside associations will be a synergistic exertion. Thus, this examination will stretch out TOPSIS to oblige the choice condition to fit honest work. A comprehensive and effective strategy for decision-making will then be obtained. The main idea of TOPSIS is relatively direct. It starts with the concept of a dislodged ideal point from which the tradeoff arrangement has the briefest separation [57,58]. Hwang and Yoon [56] further suggest that the positioning of choices will be founded on the shortest good ways from the positive ideal solution (PIS) and so-far negative ideal solution (NIS) or base. TOPSIS thinks about the separations between the two PIS and NIS, and an inclination request is positioned by their relative closeness and a mix of these two separation measures. As per Kim et al. [59], four TOPSIS preferences are tended to: (i) a sound rationale that speaks to the reason of human decision; (ii) a scalar worth that represents both the best and most noticeably awful options at the same time; (iii) a basic calculation measure that can be handily modified into a spreadsheet; and (iv) the presentation proportions of all choices, based on characteristics, can be pictured on a polyhedron, in any event for any two measurements. These focal points make TOPSIS a significant MCDM strategy as contrasted to other related procedures, for example, hierarchical analytical process (AHP) and ELECTRE [56]. Truth be told, TOPSIS is a utility-based strategy that analyzes every option legitimately, relying upon the information in the assessment frameworks and loads [60]. Moreover, as per the recreation correlation from Zanakis et al. [61], TOPSIS has the least position inversions among the classification's techniques. Hence, TOPSIS is picked as the principal group of advancement. The high adaptability of this idea can oblige further expansion to settle on better decisions in different circumstances. This is the inspiration of our examination.

It is not phenomenal for specific gatherings to continually settle on complex selections inside relatives. Notwithstanding, for using any MCDM approach, e.g., TOPSIS, it is generally approved that the selected data is provided ahead of time by grouping the assignment. Hence, Shih et al. [62] propose to upgrade TOPSIS as a critical thinking apparatus. However, this remuneration needs a cooperative choice emotionally supportive network to satisfy its destinations. To rearrange the dynamic exercises, we will recommend an incorporated gathering TOPSIS strategy for considering the genuine issues to settle on successful choices.

This paper's main objective is to identify the best energy management strategy of hybrid photovoltaic–diesel battery-based water desalination systems in isolated regions considering technical, economic, and techno–economic criteria. The selection procedure combines CRITIC and TOPSIS as a solution method. Twelve alternatives, containing three–four energy management strategies; four energy management strategies, load following (LF), cycle charging (CC), combined LF–CC, and predictive strategy; and three different sizes of brackish water reverse osmosis (BWRO) water desalination units, BWRO-150, BWRO-250, and BWRO-500, are investigated with capacity of 150, 250, and 500 m^3/day, respectively. Different attributes comprising economic and technical metrics are used during the evaluation procedure.

2. Information about the Analyzed Location and Load Demand

A water desalination plant in Wadi-Addwaser (Saudi Arabia) is selected as a case study. It is situated at 20.4493° N, 44.8501° E, as displayed in Figure 1. The location of Wadi-Addwaser City has a high average solar irradiance level. The mean solar radiation and clearance index for one year are shown in Figure 2. The average horizontal solar radiation per day is 6.16 kWh/m^2. The maximum value of irradiance per day is 7.64 kWh/m^2, occurred in June, while the minimum one is 4.31 kWh/m^2 in December. The electrical energy required is 210 kWh/day, and the maximum power needed is 10.5 kW for BWRO-150 unit. The electrical and technical specifications of different sizes of BWRO units are presented in Table 1. It is worth mentioning that the variation of the different operating conditions mentioned in Table 1 would affect the overall performance of the RO. For instance, the temperature of the feed water would affect the performance of the RO process, where the increase in the feed temperature will result in increasing the water permeability, increasing salt permeability, and decreasing the energy consumption [63]; additionally, the water recover rates in the RO units depend on the inorganic contents and its varied from 60 to 85% [64,65]. However, as long as the RO unit is operated within the condition mentioned in Table 1, "that is very close of the commercial conditions," the mentioned energy demand would be accepted.

The proposed hybrid system's techno–economic parameters are listed in Table 2 [66,67]. These parameters are employed to determine the proposed system's optimal sizes using HOMER Pro® software [68,69].

Figure 1. The location of the considered case study.

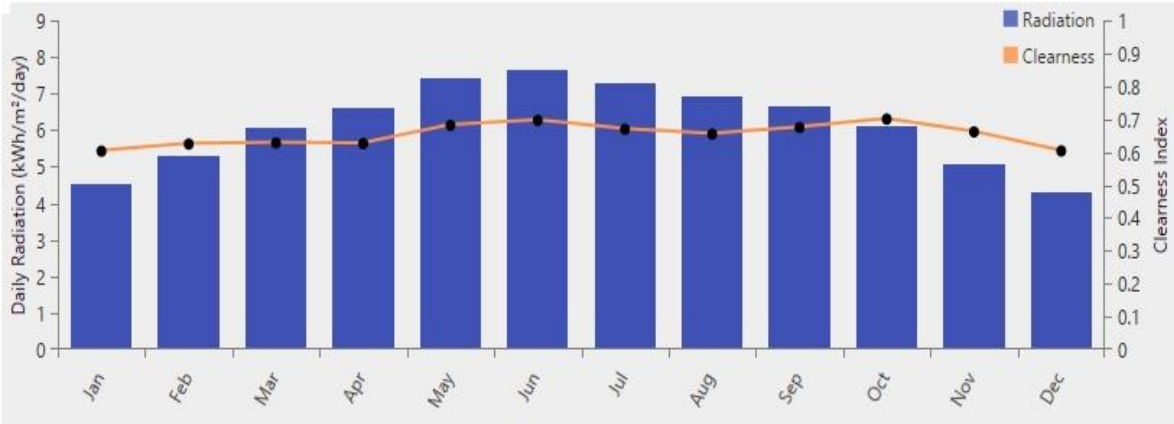

Figure 2. Average solar radiation and clearance index during one year of the studied location.

Table 1. The electrical and technical specification of different sizes of brackish water reverse osmosis (BWRO) units *.

Item	Unit	BWRO-150	BWRO-250	BWRO-500
Permeate flow rate	m^3/day	150	250	500
Permeate recovery rate	%	60–85		
Permeate TDS	mg/L	<500		
Raw water (RW) TDS	mg/L	<5000		
RW TSS	mg/L	<30		
RW temperature	°C	15–35		
Nominal power consumption	kW	10.5	15	29.5
Water demand in winter	m^3/day	100		
Water demand in summer	m^3/day	150		
Hourly flow rate	m^3	6.25	10.417	20.83
Operation period in winter	hours	16	10	5
Operation period in summer	hours	24	15	8
Average energy demand	kWh/day	210	187.5	191.75

* Data presented in Table 1 is provided by mak water Company (https://www.makwater.com.au/) (Accessed on 7 January 2021).

Table 2. Specification of different elements of the hybrid system.

Properties	Specification
Photovoltaic panel	
Name	Canadian solar-CS6K-290MS
Rated peak power	290 W_p
Temperature coefficient	−0.39%/°C
Operating temperature	45 degree
Efficiency	17.72%
Initial cost	$1200/kW
Replacement cost	$1000/kW
O&M cost	$5/year
Lifespan	25 years
Derating rate	88%

Table 2. *Cont.*

Properties	Specification
Battery Storage	
Name	Generic 1 kWh Li-Ion
Nominal capacity	276 Ah, 1.02 kWh
Nominal voltage	3.7 V
Capital cost	700 $/one unit
Replacement cost	700 $/one unit
Initial SOC	100%
Minimum SOC	20%
Limit of degradation	30%
O&M cost	5 $/year
Converter	
Type	Bi-directional
Capacity	1 kW
Initial cost	300 $/kW
Replacement cost	300 $/kW
O&M cost	$5/year
Lifespan	15 years
Efficiency	90%
Diesel Generator	
Name	Generic 10 kW fixed capacity genset
Capacity	10 kW
Initial cost	50000 $
Replacement cost	50000 $
O&M cost	0.3 $/hour
Lifespan of diesel generator	15000 h
Curve intercept of fuel	0.48 L/hr
Curve slope of fuel	0.286 L/hr/kW
Price of fuel	0.5 $/L
Emissions: CO_2	19.76 g/L fuel

3. Methods and Analysis

3.1. HOMER Software

In this work, HOMER software is applied to identify the best size for different alternatives. The photovoltaic/diesel generator/batter (PV/DG/B) optimal size is determined such that the cost of energy (COE) and total net present cost (NPC) are minimized. The formula of the NPC can be written as follows [66,67]:

$$NPC = \frac{C_{ann,tot}}{CRF_{(i,N)}} \tag{1}$$

$C_{ann,tot}$ is the total cost per year, i is the real interest rate per year, N is the project's lifetime, and CRF is the capital recovery factor. The formula of CRF can be written as follows:

$$CRF(i,N) = \frac{i(1+i)^N}{(1+i)-1} \tag{2}$$

The total cost $C_{ann,tot}$ comprises capital cost, operational and maintenance (O&M) cost, and replacement cost. The value salvage can be computed as follows:

$$Salvage = C_{rep}\frac{R_{rem}}{R_{comp}} \tag{3}$$

C_{rep} is the replacement cost, R_{rem} is the remaining life; R_{comp} is the project's life span. The *COE* can be determined as follows:

$$COE = \frac{C_{ann,tot}}{Total\ energy\ demand} \tag{4}$$

3.2. TOPSIS Method

To incorporate the numerous inclinations of more than one DM, which will consider the detachment measures by taking the mathematical mean or number juggling mean of the people for TOPSIS. The standardization strategies and separation measures are also mulled over. Contrasted with the original TOPSIS technique, the proposed model offers an overall perspective on TOPSIS with a bunch of inclination collections. The nitty-gritty system, with a couple of choices inside each progression, is shown in the accompanying [43–46].

Stage 1. Create the decision matrix for every DM as following:

$$D^k = \begin{bmatrix} x_{11}^k & x_{12}^k & \ldots & x_{1j}^k & \ldots & x_{1n}^k \\ x_{21}^k & x_{22}^k & \ldots & x_{2j}^k & \ldots & x_{2n}^k \\ \vdots & \vdots & \ldots & \vdots & \ldots & \vdots \\ x_{i1}^k & x_{i2}^k & \ldots & x_{ij}^k & \ldots & x_{in}^k \\ \vdots & \vdots & \ldots & \vdots & \ldots & \vdots \\ x_{m1}^k & x_{m2}^k & \ldots & x_{mj}^k & \ldots & x_{mn}^k \end{bmatrix} \tag{5}$$

where x_{ij}^k denotes the alternative performance rating; x_{ij}^k denotes the element of D^k.

Stage 2. Create the normalized decision matrix (R^k, $k = 1, \ldots, K$) for every DM as following.

$$r_{ij}^k = x_{ij}^k \odot \left\{ x_{i1}^k \circledcirc x_{i2}^k \circledcirc \ldots \circledcirc x_{in}^k \right\} \bigotimes x_j^{k*} \tag{6}$$

$$r_{ij}^k = x_{ij}^k \odot \left\{ x_{i1}^k \circledcirc x_{i2}^k \circledcirc \ldots \circledcirc x_{in}^k \right\} \bigotimes x_j^{k\sim} \tag{7}$$

where $x_j^{k*} = max_i \left\{ x_{ij}^k \right\}$ and $x_j^{k\sim} = min_i \left\{ x_{ij}^k \right\}$ for $i = 1, \ldots, m$; $j = 1, \ldots, n$; and $k = 1, \ldots, K$.

For normalization, Equation (6) for benefit criterion j will be as follows:

$$r_{ij}^k = \frac{x_{ij}^k}{x_j^{k*}} \tag{8}$$

Equation (7) for cost criterion j will be as follows:

$$r_{ij}^k = \frac{x_j^{k\sim}}{x_{ij}^k} \tag{9}$$

Moreover, the standardized value of r_{ij}^k is considered as the value of the corresponding element x_{ij}^k divided by the operation of its column elements, i.e., vector standardized; then:

$$r_{ij}^k = \frac{x_{ij}^k}{\sqrt{\sum_{j=1}^n \left(x_{ij}^k \right)^2}} \tag{10}$$

where $i = 1, \ldots, m$; $j = 1, \ldots, n$; and $k = 1, \ldots, K$.

Note that while utilizing Equation (10) for standardization, a distinction will be made as one of the cost criteria for further manipulation.

Stage 3. Evaluate the ideal solution (V^{k+}) and negative ideal solution (V^{k-}) for each DM, $k = 1, \ldots, K$ based on the following formula:

$$V^{k+} = \left\{r_1^{k+}, \ldots, r_n^{k+}\right\} = \left\{\left(max_i\ r_{ij}^k \,\middle|\, j \in j'\right), \left(min_i\ r_{ij}^k \,\middle|\, j \in j'\right)\right\} \tag{11}$$

$$V^{k-} = \left\{r_1^{k-}, \ldots, r_n^{k-}\right\} = \left\{\left(min_i\ r_{ij}^k \,\middle|\, j \in j'\right), \left(max_i\ r_{ij}^k \,\middle|\, j \in j'\right)\right\} \tag{12}$$

where j is the benefit criteria component; j' is the cost criteria component; $i = 1, \ldots, m$; $j = 1, \ldots, n$; and $k = 1, \ldots, K$.

Stage 4. Determine the weight vector (W) to the attribute set for the group.

Each DM will provoke weights for attributes as w_j^k, where $j = 1, \ldots, n$, and $\sum_{j=1}^{n} w_j^k = 1$, and for each DM, $k = 1, \ldots, K$. Each element of the weight vector (W) represents the operation of the attributes' weights per DM elements.

Stage 5. Estimate the distance between the best solution ($\overline{S_i^+}$) and a negative one ($\overline{S_i^-}$) for the group as following:

Stage 5a. Calculate the measures from PIS and NIS and for DM k. In this phase, Minkowski's L_p metric is applied to estimate the distance between PIS and NIS, as following:

$$S_i^{k+} = \left\{\sum_{j=1}^{n} w_j^k \left(v_{ij}^k - v_j^{k+}\right)^p\right\}^{1/p} \text{ for alternative } i,\ i = 1, \ldots., m. \tag{13}$$

$$S_i^{k-} = \left\{\sum_{j=1}^{n} w_j^k \left(v_{ij}^k - v_j^{k-}\right)^p\right\}^{1/p} \text{ for alternative } i,\ i = 1, \ldots., m. \tag{14}$$

where $p \geq 1$ and integer, w_j^k is the attribute weight for j and DM k, and $\sum_{j=1}^{n} w_j^k = 1$ and $k = 1, \ldots., k$. If $p = 2$, the metric is a Euclidean distance. Equations (13) and (14) will be:

$$S_i^{k+} = \sqrt{\sum_{j=1}^{n} w_j^k \left(v_{ij}^k - v_j^{k+}\right)^2} \text{ for alternative } i,\ i = 1, \ldots., m. \tag{15}$$

$$S_i^{k-} = \sqrt{\sum_{j=0}^{n} w_j^k \left(v_{ij}^k - v_j^{k-}\right)^2} \quad \text{ for alternative } i,\ i = 1, \ldots., m. \tag{16}$$

Stage 5b. Estimate the PIS and NIS for the group. Additionally, the measure of the group separation for every option will be joint via an operation $\otimes$ for all DMs, as following.

$$\overline{S_i^+} = S_i^{1+} \bigotimes \cdots \bigotimes S_i^{k+}, \text{ for alternative } i \tag{17}$$

$$\overline{S_i^-} = S_i^{1-} \bigotimes \cdots \bigotimes S_i^{k-}, \text{ for alternative } i \tag{18}$$

Several selections are presented in operation, like geometric mean, arithmetic mean, or their modifications. Therefore, the above equation will be:

$$\overline{S_i^+} = \left(\prod_{k=1}^{k} S_i^{k+}\right)^{1/k}, \text{ for alternative } i \tag{19}$$

$$\overline{S_i^-} = \left(\prod_{k=1}^{k} S_i^{k-}\right)^{1/k}, \text{ for alternative } i \tag{20}$$

where $i = 1, \ldots$, m and $k = 1, \ldots, K$.

Stage 6. Calculate the group relative closeness ($\overline{C_i^*}$) to the ideal solution, as following:

$$\overline{C_i^*} = \frac{\overline{S_i^-}}{\overline{\overline{S_i^+} + \overline{S_i^-}}},\ i = 1, \ldots.., m \tag{21}$$

where $0 \leq \overline{S_i^*} \leq 1$

Stage 7. Ranking.

The final step is ranking the alternatives based on the descending order of $\overline{S_i^*}$.

3.3. CRITIC-Technique

CRITIC-technique for weight estimation is as follows [70]:

Stage 1: Estimate "best" (B) and "worst" (T) solution ([1x*n*]-vector) for all attributes.
Stage 2: Estimate relative deviation matrix *V* [*m*x*n*].

$$v_{ij} = \frac{(a_{ij} - b_j)}{(b_j - t_j)}. \tag{22}$$

Stage 3: Estimate standard deviation (*StD*) ([1x*n*]-vector) for colls of *V*.

$$StD = \mathrm{std}(V) \tag{23}$$

Stage 4: Estimate correlation matrix (*Cr*) ([*n*x*n*]-matrix) for *colls* of *V*.

$$Cr = \mathrm{corr}(V) \tag{24}$$

Stage 5: Estimate vector (*c*) and calculate the weight of criteria *wk*.

$$\begin{aligned} c_k &= St_k \cdot \sum_{j=1}^{n} (1 - Cr_{kj}), \ \ k = 1, \ldots, n \\ w_k &= c_k / \sum_{k=1}^{n} c_k \end{aligned} \tag{25}$$

4. Results and Discussion

4.1. Results of HOMER

This section introduces the details of the feasibility and techno–economic evaluation for the PV/DG/B system to power the BWRO desalination plant. To identify the most cost-effective and best size of this system, three different sizes of BWRO plants, BWRO-150, BWRO-250, and BWRO-500; and four energy management control strategies, LF, CC, combined, and predictive, were considered in the current research work. Eight main criteria, the COE, operating cost, renewable fraction (RF), initial cost (IC), excess energy, unmet load, environmental impact (size of CO_2), and breakeven grid extension distance (BED), are used to determine the best alternatives for the case study. Using Homer software, the values of the eight parameters for all options are shown in Table 3.

Considering the above table, the following remarks can be outlined: The annual operating cost varies from \$3010/kWh to \$10,139/kWh. The minimum operating cost can be achieved using BWRO-500 unit and the predictive control strategy. The renewable fraction valued varies from 46.1% to 96.8%. The maximum RF values are also achieved using the BWRO-500 unit and the predictive control strategy. The minimum initial cost of \$50,223 is assigned to the BWRO-150 unit and the combined control strategy. Simultaneously, the energy cost values are changed from \$0.156/kWh to \$0.203/kWh. The minimum and maximum COE are achieved by the BWRO-250 unit and the predictive control strategy and BWRO-500 unit and the combined control strategy, respectively. The minimum excess energy and unmet load are 14,654 kWh and 0.1 kWh, respectively, for BWRO-150 unit with the load following (LF) strategy and BWRO-150 unit with the cycle charging (CC) control strategy. Compared to the grid extension, the break-even distance values are varied from 6.02 km to 9.63 km. The minimum BED is achieved by BWRO-250 unit with the predictive control strategy.

Regarding the annual amount of CO_2 emissions, the values are changed from 2076 kg to 36,873 kg, respectively, for BWRO-500 unit with the predictive strategy and BWRO-150 unit with CC strategy. Based on this discussion, it can be concluded that it is very difficult to identify the optimal alternative, directly. To solve this dilemma, multicriteria decision-making must be applied to identify the most suitable size of the hybrid system for the case study. The results of MCDM analysis will present in the next section.

Table 3. The output eight parameters for all alternatives.

Alternatives	Operating Cost ($/Year)	RF (%)	IC ($)	COE ($/kWh)	Excess Energy (kWh)	Unmet Load (kWh)	BED (km)	CO_2 (kg/Year)
LF-150	9516	51.1	61,586	0.186	14,654	1.74	9.15	33,188
CC-150	10,139	45.6	51,598	0.184	15,523	0.1	9.08	36,873
Comined-150	9680	46.1	50,223	0.177	14,817	9.41	8.42	36,090
Predictive-150	10,214	49.5	57,120	0.191	20,758	0.1	9.52	35,158
LF-250	3521	84	103,572	0.168	47,016	4.95	6.92	9686
CC-250	4678	74.5	78,154	0.157	28,142	6.52	6.16	15,477
Comined-250	3619	82.4	96,190	0.162	38,390	20.3	6.44	10,523
Predictive-250	4590	77.5	78,435	0.156	27,532	6.84	6.02	14,289
LF-500	3024	94.7	143,221	0.201	53,987	3.81	9.45	3248
CC-500	3669	91.3	136,212	0.203	40,206	6.89	9.63	5298
Comined-500	3357	93	139,009	0.203	45,939	3.09	9.46	4258
Predictive-500	3010	96.8	132,466	0.189	26,242	9.43	8.58	2076

The optimal size and related costs of various elements of hybrid system with varying the rating of BWRO unit and control strategy are presented in Tables 4–6. The photovoltaic (PV) array size varies from 27.5 kW to 65.7 kW, respectively, for BWRO-150 unit with combined approach and BWRO-500 unit with LF strategy. The required number of batteries storage is varied from 13 units to 98 units. The minimum number of batteries storage (BS) is achieved by BWRO-150 unit with combined strategy, whereas the largest number is assigned to BWRO-500 unit with predictive strategy.

Table 4. Optimal size and related costs of various elements of hybrid system using BWRO-150 plant.

	Size	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
				LF–EMS			
PV	29.8 kW	35,805.25	0.00	0.00	0.00	0.00	35,805.25
DG	10 kW	5000	15,464.35	16,067.61	82,112.86	−113.97	118,531.04
BS	29 unit	17,300	7339.94	2326.95	0.00	−1381.45	25,585.44
Converter	11.6 kW	3480.45	1476.66	0.00	0.00	−277.92	4679.19
Total		61,585.7	24,280.95	18,394.56	82,112.86	−1773.16	184,600.92
				CC–EMS			
PV	27.8 kW	33,399.42	0.00	0.00	0.00	0.00	33,399.42
DG	10 kW	5000	17,626.99	17,584.01	91,229.83	−531.02	130,909.81
BS	15 unit	9710.53	4119.92	612.36	0.00	−775.41	13,667.39
Converter	11.6 kW	3488.16	1479.94	0.00	0.00	−278.54	4689.56
Total		51,598.11	23,226.85	18,196.36	91,229.83	−1584.97	182,666.18
				CS–EMS			
PV	27.5 kW	33,265.92	0.00	0.00	0.00	0.00	33,265.92
DG	10 kW	5000	15,448.59	16,040.46	89,291.91	−127.76	125,653.20
Battery	13 unit	8626.32	3660.28	367.41	0.00	−688.44	11,965.57
Converter	11.1	3330.97	1413.24	0.00	0.00	−265.99	4478.23
Total		50,223.20	20,522.11	16,407.88	89,291.91	−1082.19	175,362.91
				P–EMS			
PV	32.4 kW	38,834.85	0.00	0.00	0.00	0.00	38,834.8
DG	10 kW	5000	19,862.84	19,255.54	86,986.66	−868.40	130,236.64
BS	15 unit	9710.53	7199.05	612.36	0.00	−2242.43	15,279.51
Converter	11.9	3574.19	1516.43	0.00	0.00	−285.41	4805.21
Total		57,119.56	28,578.33	19,867.89	86,986.66	−3396.23	189,156.22

Table 5. The optimal size and the corresponding costs of various elements of the hybrid system using BWRO-250 plant.

		Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
				LF–EMS			
PV	57.2 kW	68,647.88	0.00	0.00	0.00	0.00	68,647.88
DG	10 kW	5000	3679.46	4700.45	23,964.28	−1173.83	36,170.36
BS	43 unit	24,889.47	10,559.95	4041.55	0.00	−1987.49	37,503.49
Converter	16.8 kW	5035.12	2136.27	0.00	0.00	−402.07	6769.33
Total		103,572.48	16,375.69	8741.99	23,964.28	3563.39	149,091.05
				CC–EMS			
PV	43.7 kW	52,397.53	0.00	0.00	0.00	0.00	52,397.53
DG	10 kW	5000	6602.51	7516.06	38,291.55	−922.3	56,487.82
BS	25 unit	15,131.58	6419.93	1837.07	0.00	−1208.3	22,180.82
Converter	18.8 kW	5625.28	2386.66	0.00	0.00	−449.19	7562.75
Total		78,154.39	15,409.10	9353.13	38,291.55	−2579.79	138,628.38
				CS–EMS			
PV	52. kW	62,407.08	0.00	0.00	0.00	0.00	62,407.08
DG	10 kW	5000	3662.28	4677.18	26,036.28	−1185.81	38,189.92
Battery	40 unit	23,263.16	9870.92	3674.14	0.00	−1856.56	34,951.65
Converter	18.4 kW	5520	2341.99	0.00	0.00	−440.79	7421.21
Total		96,190.24	15,875.19	8351.31	26,036.28	−3483.16	142,969.85
				P–EMS			
PV	44.6 kW	53,505.76	0.00	0.00	0.00	0.00	53,505.76
DG	10 kW	5000	7243.9	8551.55	35,353.29	−389.28	55,759.46
BS	24 unit	14,589.47	6189.93	1714.6	0.00	−1165.01	21,328.99
Converter	17.8 kW	5339.31	2265.33	0.00	0.00	−426.36	7178.28
Total		78,434.54	15,699.16	10,266.15	35,353.29	−1980.65	137,772.5

Table 6. Optimal size and related costs of various elements of a hybrid system using BWRO-500 plant.

		Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
				LF–EMS			
PV	65.7 kW	78,839.98	0.00	0.00	0.00	0.00	78,839.98
DG	10 kW	5000	0.00	1485.37	8037.28	−433.2	14,089.45
BS	88 unit	49,284.21	20910	9552.75	0.00	−3935.47	75,811.49
Converter	33.7 kW	10,096.64	4283.74	0.00	0.00	−806.24	13,574.13
Total		143,220.83	25,193.74	11,038.13	8037.28	−5174.92	182,315.03
				CC–EMS			
PV	57.1 kW	68,578.24	0.00	0.00	0.00	0.00	68,578.24
DG	10 kW	5000	1240.27	2385.13	13,108.98	−1167.84	20,566.54
BS	94 unit	52,536.84	22,290.01	10,287.58	0.00	−4195.2	80,919.23
Converter	33.7 kW	10,096.83	4283.82	0.00	0.00	−806.26	13,574.39
Total		136,211.9	27,814.1	12,672.71	13,108.98	−6169.31	183,638.39
				CS–EMS			
PV	60.8 kW	72,952.45	0.00	0.00	0.00	0.00	72,952.45
DG	10 kW	5000	0.00	1892.59	10,535.41	−223.59	17,204.41
Battery	93 unit	51,994.74	22,062.17	10,165.11	0.00	−4149.55	80,072.47
Converter	30.2 kW	9062.03	3844.78	0.00	0.00	−723.63	12,183.18
Total		139,009.22	25,906.95	12,057.70	10,535.41	−5096.76	182,412.51
				P–EMS			
PV	52.1 kW	62,552.72	0.00	0.00	0.00	0.00	62,552.72
DG	10 kW	5000	0.00	1210.02	5137.43	−574.94	10,772.51
BS	98 unit	54,705.26	23,210.01	10,777.47	0.00	−4368.36	84,324.38
Converter	34 kW	10,207.9	4330.94	0.00	0.00	−815.13	13,723.71
Total		132,465.88	27,540.96	11,987.48	5137.43	−5758.42	171,373.32

For BWRO-150 plant, the minimum total NPC of $175,362.91 is achieved using a combined strategy. In this case, the fuel cost is $89,291.91 (50.92%), which represents the largest part of the total NPC flowed by the initial cost of 50,223.20$ (28.65%). The full replacement cost is $20,522.11, which represents around 11.7% of the total NPC. The replacement cost of diesel generator (DG) is $15,448.59, which represents 75.3% of the total replacement cost.

For BWRO-250 plant, the minimum total NPC of $137,772.51 is achieved using a predictive control strategy. For this case, the capital cost of $78,434.54 (56.93%) represents the largest part of the total NPC flowed by the fuel cost of $35,353.29 (25.66%). The PV array cost is $53,505.76, which represents around 68.17% of the total system capital cost.

For BWRO-500 plant, the minimum total NPC of $171,373.32 is achieved using a predictive control strategy. In this case, the capital cost of $132,465.88 (77.3%) represents the largest part of the total NPC flowed by the replacement cost of $27,540.96 (16.07%). The replacement cost of batteries is $23,210.01, which represents 84.3% of the total replacement cost. The replacement cost is high, as that the batteries need to be changed many times during the project lifetime.

Table 7 shows the details of the annual produced energy, annually consumed energy, annual excess energy, annual unmet load, annual capacity shortage, and the renewable fraction under different sizes of the BWRO-plant and various control strategies. Increasing the size of the BWRO-plant increases the renewable fraction. This is because increasing the size of the BWRO-plant decreases the required number of operating hours. However, this also increases the size of the PV array and, accordingly, the generated PV energy. The maximum annual generated PV energy of 127,037 kWh is achieved by BWRO-500 unit with the LF control strategy, whereas the yearly minimum generated PV energy of 52,336 kWh is achieved by BWRO-150 unit with the combined control strategy. On the contrary, increasing the size of the BWRO-plant decreases the dependency on the diesel generation system. The minimum annual generated DG energy of 2255 kWh is achieved by BWRO-500 unit with a predictive control strategy, whereas the maximum annual generated DG energy of 41,740 kWh is achieved by BWRO-150 unit with the CC control strategy.

Table 7. The details of the produced and consumed energy.

Item	**Component**	**BWRO-150**			
		LF–EMS	**CC–EMS**	**CS–EMS**	**P–EMS**
Yearly produced energy (kWh)	PV	56,331 (60.1%)	52,546 (55.7%)	52,336 (55.9%)	61,098 (61.2 %)
	DG	37,465 (39.9%)	41,740 (44.3%)	41,360 (44.1%)	38,722 (38.8%)
	Total	93,793 (%)	94,287 (100%)	93,696 (100%)	99,819 (100%)
Yearly consumed energy (kWh)	BWRO-150	76,692 (100%)	76,694 (100%)	76,684 (100%)	76,694 (100%)
Yearly excess energy	kWh	14,654 (15%)	15,523 (16.5%)	14,817 (15.8%)	20,758 (20.8%)
Yearly unmet load	kWh	1.74 (0.0023%)	0.00	9.41 (0.012%)	0.00
Yearly capacity shortage	kWh	13.0 (0.017%)	0.00	69.4 (0.091%)	0.00
Renewable fraction	%	51.1	45.6	46.1	49.5
Item	**Component**	**BWRO-250**			
		LF–EMS	**CC–EMS**	**CS–EMS**	**P–EMS**
Yearly produced energy (kWh)	PV	108,002 (90.8%)	82,435 (82.5%)	98,183 (89.1%)	84,179 (84.5%)
	DG	10,929 (9.19%)	17,461 (17.5%)	12,060 (10.9%)	15,423 (15.5%)
	Total	118,931 (100%)	99,896 (100%)	110,243 (100%)	99,602 (100%)
Yearly consumed energy (kWh)	BWRO-250	68,469 (100%)	68,467 (100%)	68,454 (100%)	68,467 (100%)
Yearly excess energy	kWh	47,016 (39.5 %)	28,142 (28.2%)	38,390 (34.8%)	27,532 (27.6%)
Yearly unmet load	kWh	4.95 (0.0072%)	6.52 (0.0095%)	20.3 (0.0297%)	6.84 (0.01%)
Yearly capacity shortage	kWh	63.6 (0.093%)	64.0 (0.0935%)	66.8 (0.0976%)	56.3 (0.0822)
Renewable fraction	%	84.0	74.5	82.4	77.5

Table 7. *Cont.*

Item	Component	BWRO-500			
		LF–EMS	**CC–EMS**	**CS–EMS**	**P–EMS**
Yearly produced energy (kWh)	PV	127,037 (97.1%)	107,892 (94.7%)	114,774 (95.9%)	97,412 (97.8%)
	DG	3705 (2.90%)	6059 (5.32%)	4880 (4.08%)	2255 (2.24%)
	Total	127,741 (100%)	113,951 (100%)	119,654 (100%)	100,668 (100%)
Yearly consumed energy (kWh)	BWRO-500	70,029 (100%)	70,026 (100%)	70,029 (100%)	70,023 (100%)
Yearly excess energy	kWh	53,978 (42.3%)	40,206 (35.3%)	45,939 (38.4%)	26,242 (26.1%)
Yearly unmet load	kWh	3.81 (0.0054%)	6.89 (0.0098)	3.09 (0.0044)	9.43 (0.0135%)
Yearly capacity shortage	kWh	69.3 (0.0989%)	69.7 (0.0996)	68.6 (0.098%)	69.5 (0.0993%)
Renewable fraction	%	94.7	91.3	93.0	96.8

From the environmental impact, using BRWO-150 plant increases the annual production of produced CO_2. The maximum amount of CO_2 is 36,873 kg, which is produced using BWRO-150 unit with the CC control strategy. This result is compatible with most dependency on the DG under this condition. On the contrary, the amount of CO_2 can be significantly reduced, thanks to increasing the size of BWRO-plant. The lowest annual amount of CO_2 is 2076 kg. It is achieved by BWRO-500 plant with a predictive control strategy. Moreover, the other pollutants are reduced, compared to BWRO-150 plant. Table 8 shows the detailed amount of different pollutant emissions by different sizes of BWRO-plant and various control strategies.

Table 8. Pollutants emission for various considered alternatives of the hybrid system.

Pollutant (kg/Year)	BWRO-150			
	LF–EMS	**CC–EMS**	**CS–EMS**	**P–EMS**
Carbon dioxide (CO_2)	33,188	36,873	36,090	35,158
Carbon monoxide (CO)	251	297	273	266
Unburned hydrocarbons	9.15	10.2	9.95	9.69
Particulate matter (PM)	15.2	16.9	16.5	16.1
Sulfur dioxide (SO2)	81.4	90.5	88.5	86.3
Nitrogen oxides (NOx)	285	317	310	302
	BWRO-250			
	LF–EMS	**CC–EMS**	**CS–EMS**	**P–EMS**
CO_2	9686	15,477	10,523	14,289
CO	73.3	117	79.6	108
Unburned hydrocarbons	2.67	4.27	2.90	3.94
PM	4.44	7.10	4.83	6.55
SO2	23.8	38.0	25.8	35.1
NOx	83.3	133	90.5	123
	BWRO-500			
	LF–EMS	**CC–EMS**	**CS–EMS**	**P–EMS**
CO_2	3248	5298	4258	2076
CO	24.6	40.1	32.2	15.7
Unburned hydrocarbons	0.895	1.46	1.17	0.572
PM	1.49	2.43	1.95	0.952
SO2	7.79	13.0	10.4	5.09
NOx	27.9	45.6	36.6	17.9

4.2. Results of MCDM

As discussed in Section 4.1, it is challenging to determine the optimal alternative directly, because no option has the best parameters. To solve this problem, multicriteria decision-making must be applied to identify the hybrid system's most suitable size for the case study. Based on Table 3, the normalized technical criteria values for the case study are presented in Table 9.

Table 9. The case study normalized the decision matrix for the technical criteria.

Criteria Alternative	C1	C2	C3	C4	C5	C6	C7	C8
A1	0.4244	0.19315	0.17748	0.29474	0.12533	0.06238	0.31639	0.43924
A2	0.45218	0.17236	0.14869	0.29157	0.13276	0.00359	0.31397	0.48801
A3	0.43171	0.17425	0.14473	0.28047	0.12673	0.33738	0.29114	0.47765
A4	0.45553	0.1871	0.16461	0.30266	0.17754	0.00359	0.32918	0.46531
A5	0.15703	0.31751	0.29847	0.26621	0.40212	0.17747	0.23928	0.12819
A6	0.20863	0.2816	0.22522	0.24878	0.24069	0.23376	0.213	0.20484
A7	0.1614	0.31146	0.2772	0.25671	0.32834	0.72782	0.22268	0.13927
A8	0.20471	0.29294	0.22603	0.2472	0.23547	0.24523	0.20816	0.18911
A9	0.13487	0.35795	0.41273	0.3185	0.46174	0.1366	0.32676	0.04299
A10	0.16363	0.3451	0.39253	0.32167	0.34387	0.24703	0.33298	0.07012
A11	0.14972	0.35153	0.40059	0.32167	0.39291	0.11079	0.3271	0.05635
A12	0.13424	0.36589	0.38173	0.29949	0.22444	0.33809	0.29668	0.02748

The CRITIC method is employed to determine the importance of technical criteria. The results confirmed that the most and least important technical criteria were C3 (initial cost) and C7 (BED), respectively, as presented in Table 10. The weighted normalized decision matrix for the technical criteria presented in Table 11 was constructed using Tables 9 and 10.

Table 10. Technical Criteria Importance Through Intercriteria Correlation (CRITIC) results.

Criteria	Segma	C-Value	Weights
C1	0.43054	2.9481	0.14145
C2	0.39509	2.84349	0.13643
C3	0.38939	3.13208	0.15028
C4	0.36913	2.24161	0.10755
C5	0.34823	2.88644	0.13849
C6	0.27183	2.38749	0.11455
C7	0.27183	1.58448	0.07602
C8	0.39566	2.81841	0.13523

Table 11. The case study technical criteria weighted normalized decision matrix.

Criteria Alternative	C1	C2	C3	C4	C5	C6	C7	C8
A1	0.06003	0.02635	0.02667	0.0317	0.01736	0.00715	0.02405	0.0594
A2	0.06396	0.02352	0.02235	0.03136	0.01839	0.00041	0.02387	0.06599
A3	0.06107	0.02377	0.02175	0.03017	0.01755	0.03865	0.02213	0.06459
A4	0.06443	0.02553	0.02474	0.03255	0.02459	0.00041	0.02503	0.06292
A5	0.02221	0.04332	0.04485	0.02863	0.05569	0.02033	0.01819	0.01734
A6	0.02951	0.03842	0.03385	0.02676	0.03333	0.02678	0.01619	0.0277
A7	0.02283	0.04249	0.04166	0.02761	0.04547	0.08337	0.01693	0.01883
A8	0.02896	0.03997	0.03397	0.02659	0.03261	0.02809	0.01582	0.02557
A9	0.01908	0.04884	0.06202	0.03426	0.06395	0.01565	0.02484	0.00581
A10	0.02315	0.04708	0.05899	0.0346	0.04762	0.0283	0.02531	0.00948
A11	0.02118	0.04796	0.0602	0.0346	0.05441	0.01269	0.02487	0.00762
A12	0.01899	0.04992	0.05737	0.03221	0.03108	0.03873	0.02255	0.00372

Regarding to Table 11, the technical criteria for ideal and nonideal solutions for the alternatives are determined and presented in Table 12. These results were used to evaluate the alternatives for ideal and nonideal distances for the case study, as illustrated in Table 13.

Table 12. Technical criteria ideal and nonideal solutions.

Criteria	V+	V-
C1	0.01899	0.06443
C2	0.04992	0.02352
C3	0.02175	0.06202
C4	0.02659	0.0346
C5	0.01736	0.06395
C6	0.00041	0.08337
C7	0.01582	0.02531
C8	0.00372	0.06599

Table 13. Economic criteria ideal and nonideal distances.

Alternative	S_i+	S_i-	P_i	Rank
A1	0.07419	0.0965	0.56535	8
A2	0.08177	0.10269	0.5567	9
A3	0.0876	0.07628	0.46544	11
A4	0.07967	0.0992	0.55458	10
A5	0.05147	0.09469	0.64785	4
A6	0.04376	0.08937	0.67129	2
A7	0.09149	0.07204	0.44055	12
A8	0.04271	0.09023	0.67872	1
A9	0.06458	0.10444	0.61791	7
A10	0.05739	0.09361	0.61994	6
A11	0.05632	0.10472	0.65026	3
A12	0.05479	0.09874	0.64312	5

As illustrated in Table 13, the final rank for all alternatives has been determined. Alternative A8, which represents BWRO-250 plant with a predictive control strategy, is the best option for the case study, followed by A6 (BWRO-250 plant with CC strategy) and A11 (BWRO-500 plant with combined strategy), whereas the worst option is alternative A7, which represents BWRO-250 plant with a combined control strategy. The optimal components' sizes corresponding to the best alternative are 44.6 kW PV array, 10 kW DG, 24 units of batteries storge, and a 17.8 kW converter. Under this situation, the technical, economic, and environmental parameters are the annual operating cost ($4590), a renewable fraction (77.5%), initial cost ($78,435), the cost of energy ($0.156/kWh), the excess energy (27,532 kWh), unmet load (6.84 kWh), BED (6.02 km), and the annual amount of CO_2 (14,289 kg). The total present cost is $137,772.5. The capital cost of $78,434.54 (56.93%) represents the largest part of the total NPC flowed by the fuel cost of $35,353.29 (25.66%). The cost of PV array cost is $53,505.76, which represents around 68.17% of the total system capital cost. The total annual produced energy is 99,602 kWh. A total of 84.5 % (84,179 kWh) of the produced energy is generated by the PV array, whereas the remainder amount (15.5%) is generated by DG.

5. Conclusions

Determination of the best energy management strategy and the optimal size of the water desalination unit was the main objective of this research work. Three–four energy management strategies; four energy management strategies, load following (LF), cycle charging (CC), combined LF–CC, and predictive strategy; and three different sizes of BWRO desalination units, BWRO-150, BWRO-250, and BWRO-500 were considered. Various parameters, such as operating cost, renewable fraction, initial cost, the cost of energy, excess energy, unmet load, breakeven grid extension distance, and the amount of CO_2, were considered during the identification process. Based on HOMER software, by combining Criteria Importance Through Intercriteria Correlation (CRITIC) and Technique for Order

Preference by Similarity to Ideal Solution (TOPSIS), the best alternative for the case study has been determined. The main finding can be outlined as follows:

- Increasing the size of the BWRO-plant increases the renewable fraction and decreases the dependency on the diesel generation system.
- Using the BRWO-150 plant increases the annual production of CO_2. The maximum amount of CO_2 is 36,873 kg, which was produced using BWRO-150 unit with the CC control strategy.
- The lowest annual amount of CO_2 is 2076 kg. It is achieved by BWRO-500 plant with a predictive control strategy.
- BWRO-250 plant with the predictive control strategy is the best option for the case study, followed by A6 (BWRO-250 plant with CC strategy) and A11 (BWRO-500 plant with combined strategy).
- The worst alternative is the BWRO-250 plant with the combined control strategy.
- The optimal components' sizes corresponding to the best alternative are 44.6 kW PV array, 10 kW DG, 24 units of batteries storge, and 17.8 kW converter. Under this situation, the technical, economic, and environmental parameters are annual operating cost ($4590), the renewable fraction (77.5%), initial cost ($78,435), the cost of energy ($0.156/kWh), the excess energy (27,532 kWh), unmet load (6.84 kWh), BED (6.02 km) and the annual amount of CO_2 (14,289 kg).

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