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Techno-Economic and Environmental Study of Optimum Hybrid Renewable Systems, including PV/Wind/Gen/Battery, with Various Components to Find the Best Renewable Combination for Ponorogo Regency, East Java, Indonesia

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Abstract: Nowadays, hybrid renewable systems can be the best solution for meeting electricity demand, especially where grid extension and environmental issues are important. This study aimed to find the best combination of the typical components used in East Java, Indonesia. In this regard, four types of photovoltaic (PV) panels, four types of wind turbines, and two types of batteries were selected, and the HOMER software simulated all possible combinations of the systems, including 32 scenarios (Sen). Then, considering the most important 15 parameters, such as pollutant emissions and economic values, the results were analyzed and sorted by the multicriteria decision-making (MCDM) method to find the best scenario for the case-study region. The results showed that SunPower E20-327 as PV, Eocycle EO10 10 kW as wind turbine, and Generic 1 kWh Li-Ion as the battery could be the best selection to design a hybrid renewable system for the case-study region since it can fulfill both economic and environmental needs. The cost of energy (COE) of the best-designed system and net present cost (NPC) are 0.24 ($/kWh) and 1.64 million $, respectively, where the renewable fraction (RF) is 55.1% and the scaled annual average load is 1126 kWh/day. The results of the sensitivity analysis on the best scenario's parameters (where the capital cost of PV, battery, and wind turbine changes from 0.6 to 1.2, from 0.7 to 1.2, and from 0.7 to 1.4 of the current price, and diesel price from 0.5 to 1.1 ($/L)) showed that the RF, COE, and NPC values ranged between 51% to 93%, 0.2 to 0.3 ($/kWh), and 1.4 to 2.1 (million $), respectively.

Keywords: hybrid; renewable; TOPSIS; solar; wind; energy

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1. Introduction

With growing populations and energy consumption worldwide, supplying reliable electricity is crucial for everyone [1]. Most electricity is provided through fossil fuels with high greenhouse gas emissions. One of the best solutions for reducing CO_2 emissions is employing hybrid renewable energies [2–4]. Considering the prediction of CO_2 emission in many types of research and the importance of reducing emissions [5], based on the availability of resources in a location, wind turbines [6], PV panels [7,8] Fuel cells [9], and geothermal energy can be employed to supply clean energy. In this regard, designing an optimum system specific to a location and selecting the best cost components is a critical problem that researchers should solve [10,11]. Fortunately, the share of using and installing renewable energies worldwide has been remarkable in recent years, as shown in Figure 1 [12]. According to Figure 1, Indonesia's share of renewable energies in final energy consumption has been descending due to the increasing electricity demand. It is necessary to increase renewables share to fulfill all the electricity demand and supply within the country.

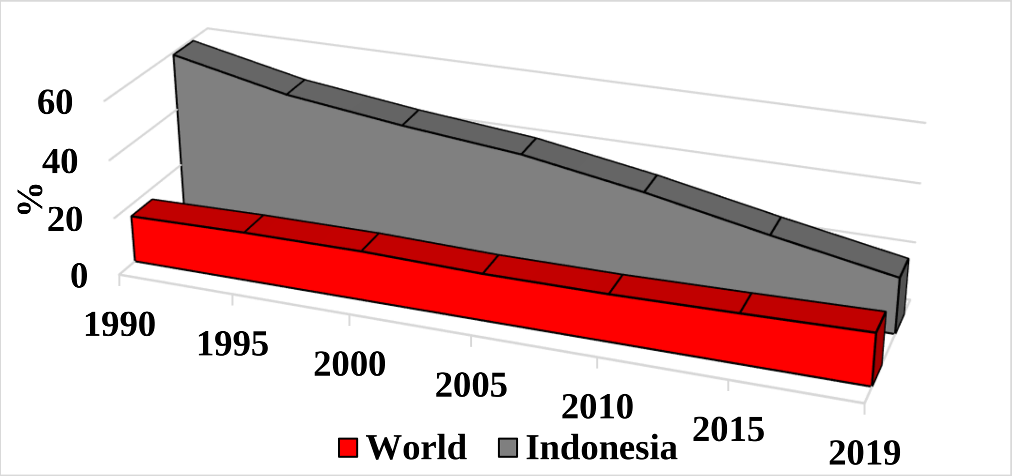

Figure 1. Share of renewable energies in final energy consumption.

In 2014, some targets were set for renewable energies in Indonesia. Although many studies have been conducted on renewables in the country, there are geographical, institutional, and investment limitations that must be considered. The government should revise its politics so that individual and private sectors can cooperate in extending renewables economically [13]. In 2004, Indonesia changed from an oil exporter to an importer due to extreme energy consumption and population growth. In addition, since Indonesia has a shape that has been extended or elongated, extending the national electricity network is difficult and has many problems. Hence, renewables, especially stand-alone hybrid systems, should be significantly considered and developed to compensate for the lack of energy. The country could use diesel generators and coal in the short term; considering that diesel has lower emissions than coal, the government has allocated more subsidies for diesel, which is supplied through imports, but in the long term, renewables should be employed for power generation [14]. At present, PNN and its subsidiaries conduct around 80% of the total power generation in the country [15]; feed-in tariffs are variable from district to district, and a specific budget is allocated for renewables, especially solar, micro-hydro, and biogas [16]. Although about 95% of people have access to the grid, most are outside Jawa-Bali, so, they cannot use reliable and cheap electricity [17]. According to the national planning agency, by 2030 greenhouse gas emissions will increase up to 60% compared to 2020. In 2020, 46% of GHG was from the energy sector, but in 2030 50% of GHG will come from energy consumption. In 2016, the country committed to the United Nations Framework Convention to reduce GHG [18]. Some research has been done on hybrid renewable systems in Indonesia with different goals, mainly towards finding optimum systems for the case studies.

Hidayat et al. [19], considering that not all people in Indonesia have access to electricity and the instability of weather conditions, studied a hybrid system in Malang regency in terms of costs, power output, and pollutant emissions and concluded that a hybrid system is not economically feasible; however, it is more suitable where environmental issues are important. Junus et al. [20] studied different hybrid systems to reach the best cost-effective solution to supply the electricity demand in Malang. Although there is good biosource potential in the region, it is not well used. In this respect, various components such as bio- and diesel generators were investigated in the design steps. They also considered emissions and compared systems' COEs. The results showed that bio-generators cause a 68% and 6% reduction in fuel consumption and NPC, respectively. Compared to a system without a wind turbine, systems with wind turbines have lower NPCs. Aditya et al. [21] designed an economical hybrid system with and without a diesel generator for a remote area on Ur island. The obtained results showed lower COE for the system, including the diesel generator, since it needs more PV and batteries to supply electricity demand. They conducted sensitivity analyses on the amount of GHI, wind speed, diesel price, operation and maintenance (O&M), and capital costs of the components and found that wind speed and battery's initial cost have the highest effect on COE. Azahra et al. [22] pointed out that most of Indonesia's power systems need low capacity, which diesel generators can provide. They studied a hybrid renewable system in which COE is significantly lower than a diesel power plant where the optimization strategy is cycle charging. In addition, when they chose the load-following strategy, the results showed more RF; consequently, the system was more environmentally friendly. The sensitivity analysis results on the price of batteries and diesel price showed that they remarkably affect the system's operation. Syafii et al. [23] studied a hybrid system in Mentawai in which pumped hydro storage was used instead of batteries. They concluded that systems without wind turbines have lower COEs and are more economical. Although the calculated COEs are higher than electrical utility tariffs, this system is applicable for remote areas and leads to reducing the country's emissions. The use of wind turbines was also reported to be nonprofitable for the case-study region. Bukit et al. [24] mentioned that Pemping island is far from the surrounding cities and there are 40 kW diesel generators to supply power, but the transportation of diesel fuel to the power station is expensive and will increase the final energy costs. They could decrease COE with a hybrid system by 31% compared to using diesel generator systems. Javed et al. [25] mentioned that there is not enough research on the loss-of-power-supply probability in Indonesia when they studied a hybrid system in Jiuduansha. They employed a hybrid system and minimized it using a genetic algorithm (GA) to find the optimum combination of the components when economic aspects and the system's reliability were their primary concerns. The results showed that GA is generally superior to HOMER software in terms of run-time optimization. They also disclosed that wind turbines have the lowest effect on the system's sizing. Their sensitivity analyses on the system's reliability showed that remote areas should first consider a small power supply probability loss since it significantly decreases capital cost and COE. Nugroho et al. [26] relied on the fact that the remote areas in Indonesia generally use diesel generators (due to the grid-extension prices, including submarine cables) which have high pollutant emissions, designed a hybrid renewable system for the Eastern region. They compared two systems with and without wind turbines with a system that just uses diesel generators; the results showed 21% and 53% reduction in COE and fuel consumption (emission). In addition, the results showed that wind turbines will not significantly affect the systems' power generation but increases the COE and NPC.

Although there has been much research on finding optimum hybrid systems in Indonesia [27–30], various components have not been investigated to find the appropriate equipment for the case-study regions. Knowledge of the suitable components helps researchers to analyze other combinations and hybrid systems accurately. In this study, a possible combination of the components is discussed using selected scenarios considering the components used in previous studies, and optimum solutions are found using HOMER software. The selected scenarios are then ranked by the MCDM method, and the best components for the case-study region are introduced. In the methodology section, the case-study region is introduced, the technical information of the components is classified, and finally the MCDM method and the selected criteria are described. In the results and discussion section, the results obtained from HOMER software and the MCDM method are reported, and some sensitivity analyses were done for the best-choice scenario. The numerical results of the studies mentioned above are presented in Table 1.

Table 1. Renewable hybrid systems in Indonesia.

Ref.	Location	Usage	Hybrid System	Grid	COE ($/kWh)	RF (%)
[19]	Malang	Residential	PV/Wind/Gen/Batt	Off/Grid	0.254	100
[20]	Malang	Public	PV/Wind/Gen/Batt	Off/Grid	1.23	100
[21]	Ur	Residential	PV/Wind/Gen/Batt	Off/Grid	0.276	95
[22]	East	Residential	PV/Gen/Batt	Off/Grid	0.135	34.5
[23]	Mentawai	Residential	PV/Wind/Gen/Batt	Off/Grid	0.17	30.1
[24]	Pemping	Residential	PV/Gen/Batt	Off/Grid	0.22	39.4
[25]	Jiuduansha	Residential	PV/Wind/Batt	Off/Grid	0.11	100
[26]	East	Residential	PV/Wind/Gen/Batt	Off/Grid	0.156	47

2. Methodology

This section presents the case-study region, loads, and renewable sources. Then, the characteristics of the components—wind turbines, PV panels, batteries, and generators—are discussed. The proposed scenarios are presented, and finally the MCDM method and its alternatives and criteria are discussed.

2.1. Case Study Region

The selected case-study region is located in Ponorogo Regency, East Java, Indonesia. The latitude and longitude of the case study are 111.56136 and −7.99872, respectively. East Java and Ponorogo have around 40 million and 1 million people, respectively. Figure 2 [31] shows the clearness index and solar radiation and Figure 3 the wind speed in the region. Figure 2 showed that the location has appropriate radiation for power generation, especially from April to October when the clearness index is high, which means that PV panels can receive more sunrays. Figure 3 [31] and Figure 4 [32] also show the wind speed and mean power density heat map in the selected location that has the highest power generation potential from wind turbines. The yearly average wind speed of the location is 4.28 m/s, and from April to October is more than the rest of the months and can be a good feature for wind turbines. The case study's usage is proposed residential, so the load is assumed on average to be constantly 1126 kWh/day. The location of the selected case-study region is shown in Figure 5.

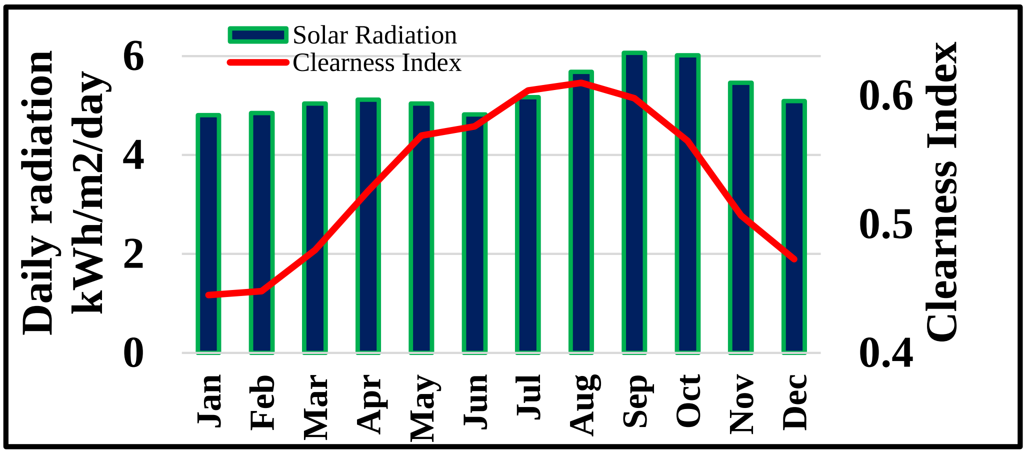

Figure 2. Solar GHI and clearness index for Ponorogo.

In this study, inflation and discount rate are assumed to be 1.5% and 3.5% for all scenarios [20], and the capacity shortage and project's lifetime are considered to be around 1% and 20 years, respectively. Table 2 shows the selected components used in the literature review: four wind turbines, four PV panels, two batteries, and one generator. The selected components are typical in the case-study region and are vastly used in hybrid renewable systems research. For instance, lead acid batteries and lithium ion batteries are challenging choices for researchers. It could be noted that usually, generators do not have a remarkable effect on the system's final costs and sizing, so only one type of generator is considered in this study. In addition, it should be mentioned that the prices of PV panels increased by USD400 compared to the mentioned references due to the use of vertical tracker systems in the simulation steps.

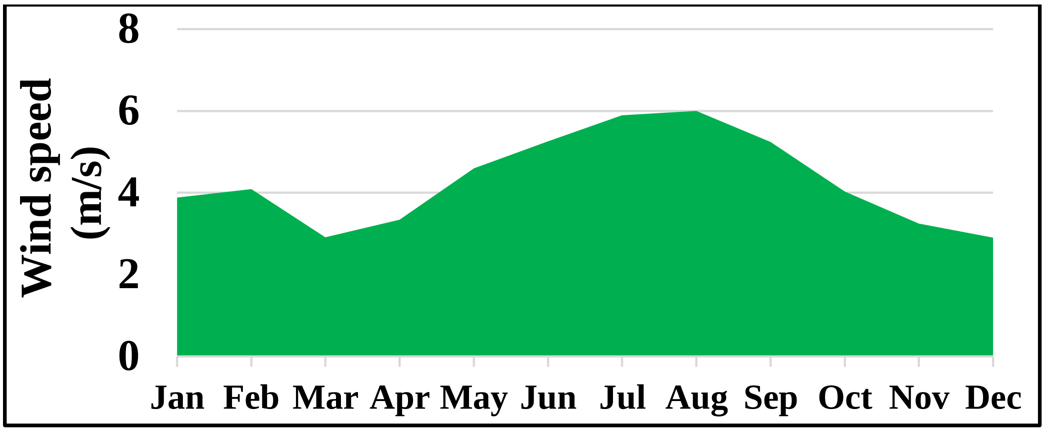

Figure 3. Average wind speed in Ponorogo.

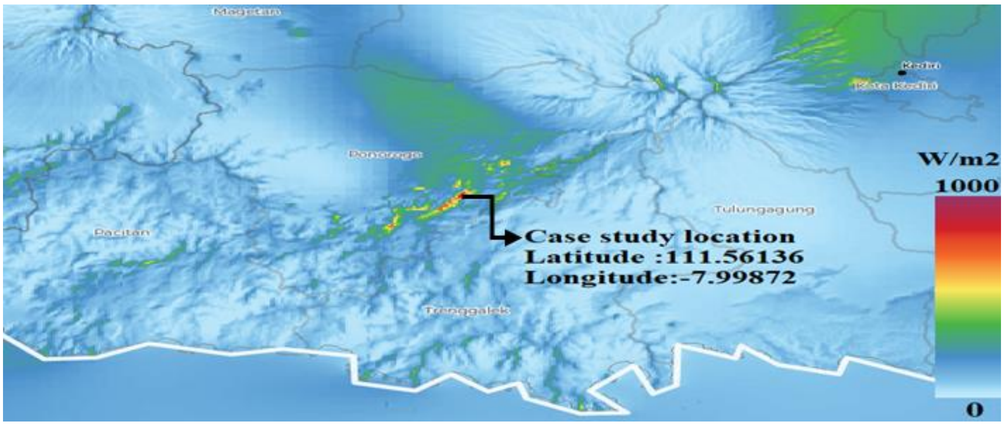

Figure 4. Heat map of mean power density for the case-study region.

Figure 5. The location of the case-study region.

Table 2. Name and prices of the selected components.

PV	Ref.	Model	Capital Cost ($)	Replacement ($)	O&M ($)
P1	[30]	CS6U-330P	1445/kW	1445/kW	7/year
P2	[20]	SunPower E20-327	2400/kW	1600/kW	30/year
P3	[23]	Sharp ND-250CS	1600/kW	1500/kW	34.5/year
P4	[21]	CanadianSolar MaxPower CS6X-325P	950/kW	950/kW	11/year
Wind					
T1	[30]	AWS 5.1 kW	7387/kW	7387/kW	95/kW
T2	[20]	Eocycle EO10 10 kW	29,000/item	25,000/item	50/year
T3	[21]	AWS HC 1.5 kW	3600/item	3600/item	100/year
T4	[33]	Pika T701 1.5 kW	5995/item	5995/item	100/year
Generator	[31]	Generic Small Genset (size-your-own)	500/kW	500/kW	0.03/op.hr
Battery					
B1	[31]	Generic 1 kWh Li-Ion	600/kWh	600/kWh	10/year
B2	[31]	Generic 1 kWh Lead Acid	300/kWh	300/kWh	10/year
Converter					
	[30]	Hoppecke 24 OPzS 3000, 7.15 kW Lead Acid	585/item	585/item	6/year

2.2. Scenarios

The selected scenarios are defined by all 32 possible combinations of the components mentioned in Table 1. The number of each scenario shows which components have been used: the first number shows the type of PV, the second number is the type of turbine, and the third number is for the battery. For instance, 322 (PV type, wind turbine type, battery type) means PV3 (P3-Sharp ND), wind turbine 2 (T2-Eocycle), and battery 2 (B2-lead acid). Table 3 shows all the proposed scenarios.

Table 3. The proposed combination of the components as scenarios.

111	112	121	122	131	132	141	142
211	212	221	222	231	232	241	242
311	312	321	322	331	332	341	342
411	412	421	422	431	432	441	442

According to the general configuration shown in Figure 6 [31], all the mentioned scenarios are optimized by HOMER software, and the results are reported in the Results and Discussion section.

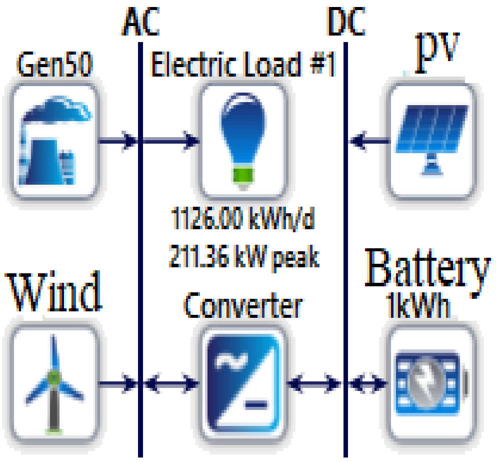

Figure 6. Schematic view of the proposed systems.

After finding the optimum system for each scenario, the most important parameters—the size of the PV (kW), the number of wind turbines, the size of the generators (kW), the size of the batteries (kWh), COE ($/Wh), NPC (million $), operation cost ($/year), initial cost ($), RF (%), fuel consumption (L/year), return on investment (RI/year), excess electricity (%), unmet electricity (%), salvage ($), and total emissions (kg/year)—are reported. Then, the MCDM method was used to select the best scenario.

2.3. MCDM Method

This method includes five general steps. This study has 32 scenario options (rows in Table 4) and 15 criteria as mentioned above (columns in Table 4).

Table 4. The obtained results of the simulated scenarios in HOMER Pro 3.14.2 software.

Sen.	PV (kW)	Wind Quantity	Gen (kW)	Battery (kWh)	COE ($/Wh)	NPC (M$)	OP ($/year)	Cost ($)	RF (%)	Fuel (L/year)	RI (year)	Excess Elect (%)	Unmet (%)	Salvage ($)	Emission (kg/year)
111	241		80	717	$0.26	$1.73	$53,630	$845,712	74.3	34,283	4.88	14	0.656	207,391	91,084.06
112	181		80	501	$0.29	$1.93	$87,296	$481,978	53	62,691	3.08	13.2	0.622	122,802	166,557.24
121	148	8	80	411	$0.23	$1.52	$46,288	$756,378	74.7	34,448	4.03	23.7	0.402	148,515	91,520.18
122	134	10	60	440	$0.24	$1.64	$57,939	$676,523	69.3	40,418	3.71	30.1	0.615	63,206	107,382.06
131	220	13	80	659	$0.26	$1.73	$54,600	$826,249	72.9	36,155	4.8	13.6	0.608	221,165	96,055.54
132	158	24	80	468	$0.28	$1.92	$84,385	$525,509	55.5	59,679	3.37	11.5	0.598	131,105	158,553.85
141	236		80	721	$0.26	$1.73	$53,901	$841,523	74	34,822	4.87	13.7	0.655	211,090	92,514.51
142	178		80	509	$0.29	$1.93	$87,451	$480,757	52.9	62,879	3.08	12.5	0.627	128,237	167,056.46
211	126		80	149	$0.29	$1.95	$90,025	$463,630	34.8	82,692	3.19	10.5	0.564	101,316	219,695.6
212	163		80	513	$0.31	$2.11	$90,484	$616,707	51.7	64,654	4.16	9.36	0.673	130,396	171,771.94
221	80.6	9	60	207	$0.24	$1.64	$60,928	$633,450	55.1	56,791	3.67	23.2	0.482	47,563	150,881.47
222	91.1	10	80	336	$0.26	$1.77	$66,455	$673,643	64	49,014	3.84	24.2	0.57	27,109	130,221.1
231	108	32	80	140	$0.29	$1.94	$85,244	$527,943	40.8	75,302	3.45	9.58	0.511	23,669	200,062.58
232	140	33	80	468	$0.31	$2.09	$85,887	$667,738	55.6	59,685	4.59	8.85	0.613	43,326	158,570.85
241	118		80	152	$0.29	$1.95	$91,202	$443,246	33.8	84,028	3.05	8.51	0.582	99,573	223,245.73
242	163		80	513	$0.31	$2.11	$90,484	$616,707	51.7	64,654	4.16	9.36	0.673	130,396	171,771.94
311	247		80	694	$0.26	$1.79	$54,918	$878,854	73.8	34,989	5.2	15.1	0.652	245,753	92,958.63
312	182		80	501	$0.29	$1.97	$88,021	$510,389	52.9	62,934	3.35	12.2	0.64	159,336	167,202.47
321	136	8	80	399	$0.23	$1.56	$48,501	$753,335	73.3	36,414	4.12	20.8	0.478	166,906	96,744.77
322	137	10	60	434	$0.25	$1.67	$58,397	$700,106	69.3	40,475	3.87	29.9	0.614	88,421	10,7534.07
331	216	21	80	608	$0.26	$1.78	$55,898	$851,536	72.5	36,789	5.1	13.4	0.595	244,172	97,741.11
332	162	25	80	460	$0.29	$1.96	$84,654	$556,051	55.7	59,413	3.64	11.4	0.617	159,420	157,849.62
341	247		80	694	$0.26	$1.79	$54,918	$878,854	73.8	34,989	5.2	15.1	0.652	245,753	92,958.63
342	183		80	498	$0.29	$1.97	$87,974	$511,412	52.9	62,862	3.36	12.4	0.633	157,717	167,010.46
411	265		80	704	$0.23	$1.57	$50,128	$740,190	74.7	33,424	3.96	20.8	0.628	207,680	88,799.38
412	253		60	629	$0.27	$1.80	$78,687	$493,840	59.6	52,570	2.97	26.6	0.637	162,738	139,667.05
421	187	7	80	457	$0.21	$1.42	$42,079	$718,750	77	30,957	3.77	27.3	0.297	147,261	82,244.33
422	157	8	60	417	$0.23	$1.54	$58,940	$566,503	68.4	41,715	3.17	29	0.589	35,865	110,827.09
431	265		80	704	$0.23	$1.57	$50,128	$740,190	74.7	33,424	3.96	20.8	0.627	207,680	88,799.38
432	238	12	60	604	$0.27	$1.79	$77,165	$514,371	60.6	51,313	3.09	25.4	0.642	18,686	136,326.93
441	265		80	704	$0.23	$1.57	$50,128	$740,190	74.7	33,424	3.96	20.8	0.627	207,680	88,799.38
442	253		60	629	$0.27	$1.80	$78,687	$493,840	59.6	52,570	2.97	26.6	0.637	162,738	139,667.05

In the first step, the objective matrix's values are normalized through Equation (1), where X_{ij} means the present matrix values, R is the normalized values, and m is the number of alternatives [34]:

$$R_{ij} = \frac{X_{ij}}{\sqrt{\sum_{i=1}^{m} X_{ij}^2}} \tag{1}$$

Then, the required weights must be multiplied by the normalized matrix. The weights for each criterion can be obtained through the entropy method using the following steps: where m is the number of alternatives (here, 32) and W_i is the weight of each scenario.

$$k = \frac{1}{Ln(m)} \tag{2}$$

$$E_j = -k \times \sum_{i=1}^{m} R_{ij} Ln\, R_{ij} \tag{3}$$

$$D_j = 1 - E_j \tag{4}$$

$$W_i = \frac{D_j}{\sum D_j} \tag{5}$$

After the weights have been multiplied by the normalized matrix, the V matrix is obtained, and the positive (V+) and negative (V−) ideal solutions must be determined. In this regard, the criteria should be separated into negative and positive values.

In this study, the size of the PV (kW) is considered a negative criterion, since the higher the PV, the more it needs land for installation, and it increases the expenses (there is also the issue of limited land availability). The number of wind turbines is also considered a negative criterion for the same reasons mentioned for PV panels. The size of the generators (kW) is considered negative for their emissions. The size of the batteries (kWh) is considered negative for the same reasons mentioned for PV panels. COE ($/Wh), NPC (million $), return on investment (year), operation cost ($/year), and initial cost ($) are considered such that the lower they are, the more economic the system is, so they are considered negative. In addition, fuel consumption (L/year) and total emissions (kg/year) are considered negative criteria, since the lower they are, the more environmentally friendly the system is. Excess electricity (%) is considered negative since it shows the system is overdesigned. Unmet electricity (%) is also considered negative since the system could not have been provided electricity. Salvage ($) is considered negative since the study's goal is designing optimum systems, while higher salvage values show that the remaining components will be sold after the project's lifetime. RF (%) is considered a positive criterion since it shows the share of renewables used in the system.

In the next step, the relative distance of each solution from positive and negative solutions must be calculated through Equations (2) and (3), respectively, where n is the number of criteria and V_{ij} are values of the V matrix [34].

$$S_i^+ = \sqrt{\sum_{j=1}^{n} \left(V_{ij} - V_j^+\right)^2} \tag{6}$$

$$S_i^- = \sqrt{\sum_{j=1}^{n} \left(V_{ij} - V_j^-\right)^2} \tag{7}$$

In the next step, the closeness coefficient of each option to the best solution can be obtained as in Equations (4) [34].

$$P_i = \frac{S_i^-}{S_i^- + S_i^+} \tag{8}$$

The final step is the sorting of the obtained P_i values from largest to smallest to determine the best possible solution. The more the P_i value for a scenario, the more it is suitable for selection.

3. Results and Discussion

This section presents the results obtained from the simulated systems in the HOMER software [31] in Table 3. Then, the MCDM method results are presented in Figure 7. Other important results are also presented in Table 4, including the results of all the 15 parameters selected as criteria for the MCDM method. Based on the reported results in this table, the general analyses of the designed systems are presented in Sections 3.1–3.3.

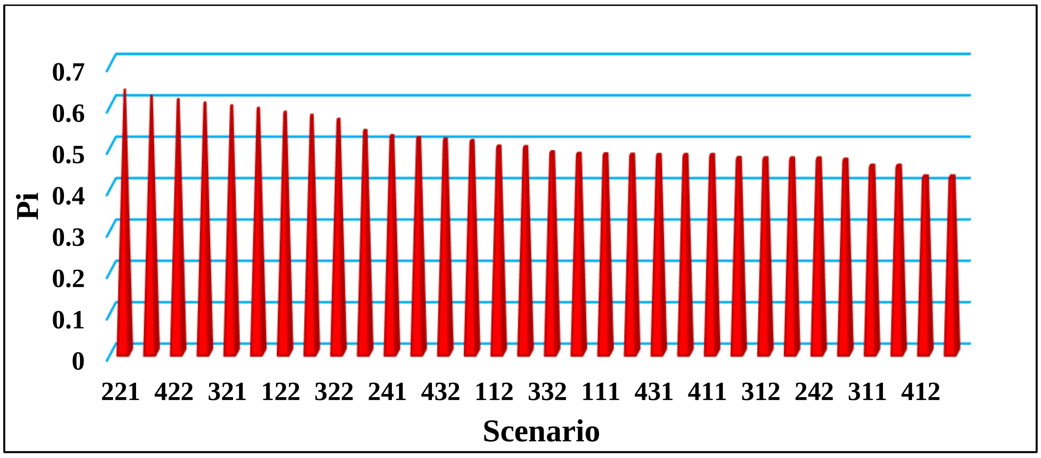

Figure 7. The obtained Pi values through the MCDM method for 32 scenarios.

3.1. Components

3.1.1. PV Panels

PV panels range between 80.6 and 265 kW, where PV1, PV2, PV3, and PV4 are used on average at 187, 124, 189, and 235 kW, respectively, which means that in the case of using PV2 (SunPower E20-327), the lower capacity PV will be used (this will reduce the needed land space for installation). Minimum and maximum PV panels are used in scenarios 221 and 441, respectively.

3.1.2. Wind Turbines

Wind turbines are not used in some of the optimized scenarios. Turbines T1 and T4 are not used in any scenario. Maximum wind power is used in scenarios 122, 222, and 322, where T2 is in the proposed system. In the mentioned scenarios, 10 T2 (Eocycle EO10 10 kW) turbines are optimized, meaning that 100 kW of wind power should be installed. In 17 scenarios, wind turbines are not used, which means that the optimization and hybrid systems are sensitive to wind turbines due to their high price, power curve, and wind sources. Hence, this component must be carefully selected since it can significantly change the optimization results.

3.1.3. Batteries

All the scenarios use battery banks to store excess electricity when the demand load is lower than the power produced by the wind turbines and PV panels. Minimum and maximum battery usage are 140 and 721 kWh for 231 and 141 scenarios, respectively. The results show that on average, B1 (generic 1 kWh Li ion) and B2 (generic 1 kWh lead acid) were used at 507 and 497 kWh in all scenarios.

3.2. Economic Parameters

The maximum and minimum COE ranges are 0.21 to 0.31 ($/kWh), belonging to the 212–232–242 and 421 scenarios, respectively. The NPC ranges are 1.42 to 2.11 (million $); the former belonging to scenario 421 and the latter belonging to 212 and 242 scenarios. The operation and maintenance costs (OP) that the system owner must pay every year ranged between 42,079 and 91,202 ($), respectively, where the minimum and maximum refer to scenarios 421 and 241. The initial capital for creating and installing a hybrid system is another important economic factor that affects the decision to select a scenario since the primary finance sources are always limited. The lowest and highest initial capital values are 443,246 and 878,854 ($), which belong to scenarios 241 and 311, respectively. The return on investment (RI) rates are 2.97 to 5.2 (years) compared to the base case scenario when only generators produce all the system's electricity. The lowest and the highest RIs refer to 442–412 and 341 scenarios, respectively. Last but not least, salvage shows the system's revenues. In this study, since there is no proposed electricity sell-back, the values of salvages mean that some of the components can be reused after the project's lifetime. Since this is not the purpose of the study, the higher the salvage values, the less suited the scenario. The minimum and maximum salvage values are 18,686 and 245,753 ($), belonging to scenarios 432 and 341, respectively. Considering the obtained COE values of all scenarios and comparing them with Table 1 values, the accuracy of the simulated values is confirmed.

3.3. Environmental Parameters

Renewable fraction as a general factor that shows how much electricity is produced by renewable components, such as wind turbines and PV panels, can generally show how much a system is environmentally friendly. Environmental factors are mostly interconnected, e.g., the higher the RF, the lower the fuel consumption and pollutant emission. These factors are also affected by the amount of excess electricity, e.g., when a system has a high renewable fraction, its excess electricity is also high: it is overdesigned and maybe uses more generators, consequently producing more pollutants. The RF values are between 33.8% and 77%, and the former and the latter are for scenarios 241 and 421, respectively. Fuel consumption ranges from 30,957 to 84,028 (L/year) for scenarios 421 and 241, respectively. The summation of pollutant emission ranges, including carbon dioxide, carbon monoxide, unburned hydrocarbons, particulate matter, sulfur dioxide, and nitrogen oxides are 82,244 to 223,245 (kg/year), where the lower and the higher values belong to scenarios 421 and 241, respectively.

3.4. MCDM

The identified scenarios are ranked using the MCDM method in consideration of all technical, economic, and environmental factors. In this regard, considering 32 scenarios as alternatives and 15 techno-economic and environmental factors reported in Table 4 as criteria, the MCDM method's results are shown in Figure 6. As seen, scenario 221, due to its highest Pi value, is the best choice, where the type of PV is SunPower E20-327, the type of wind turbine is Eocycle EO10 10 kW, and the type of battery is generic 1 kWh Li ion. In addition, the results showed that the lowest value of Pi belongs to scenario 442 considering all the factors mentioned together.

3.5. Analysis of Scenario 221

The obtained results showed that PV panels, wind turbines, and diesel generators produce 25%, 42%, and 33% of total electricity, respectively. The initial capital for the PV, turbine, generator, converter, and batteries are 193,502, 261,000, 30,000, 24,747, and 124,200 ($), respectively. The capacity shortage in this scenario is 1.1%, which means that this scenario cannot supply 1.1% of the total demand load. Generators on average consume 156 L/day of diesel fuel, mostly from November to March. Figure 8 shows the monthly average electricity production by each component. As seen, from May to September, wind turbines provide most of the electricity, while PV panels produce an almost constant amount of electricity during the year. It is evident that PV panels can only produce electricity when there is sunlight.

The typical components for power production for three days of a year are shown in Figure 9. For instance, on July 29 at noon, only wind turbines and PV panels are working and providing electricity. Considering the power curves in Figure 9, at this time, power production is more than the demand load, meaning that the batteries are being charged if they were not filled previously. On July 28 at 18:00, generators and batteries provide electricity along with wind turbines since the demand load is so much compared to other times and days. In addition, at this time, due to the lack of sunlight, PV panels do not work. According to the figures, most of the power production by the generators is at night and when the demand load is very high. Another conclusion from this figure is that peak times significantly affect the size of the components; hence, controlling the demand load during peak hours can reduce the size of the components and consequently, the COE and NPC values.

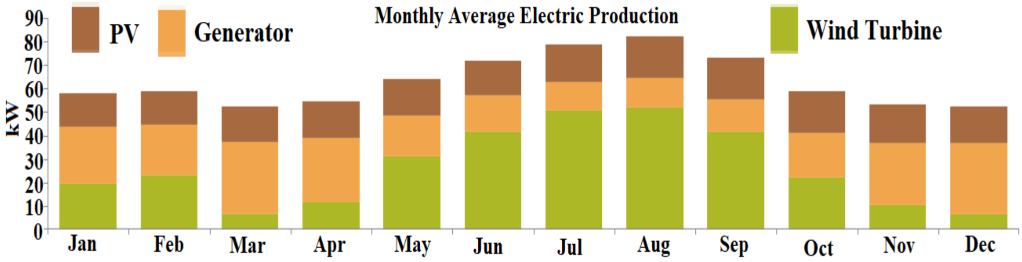

Figure 8. Monthly average electricity production by components.

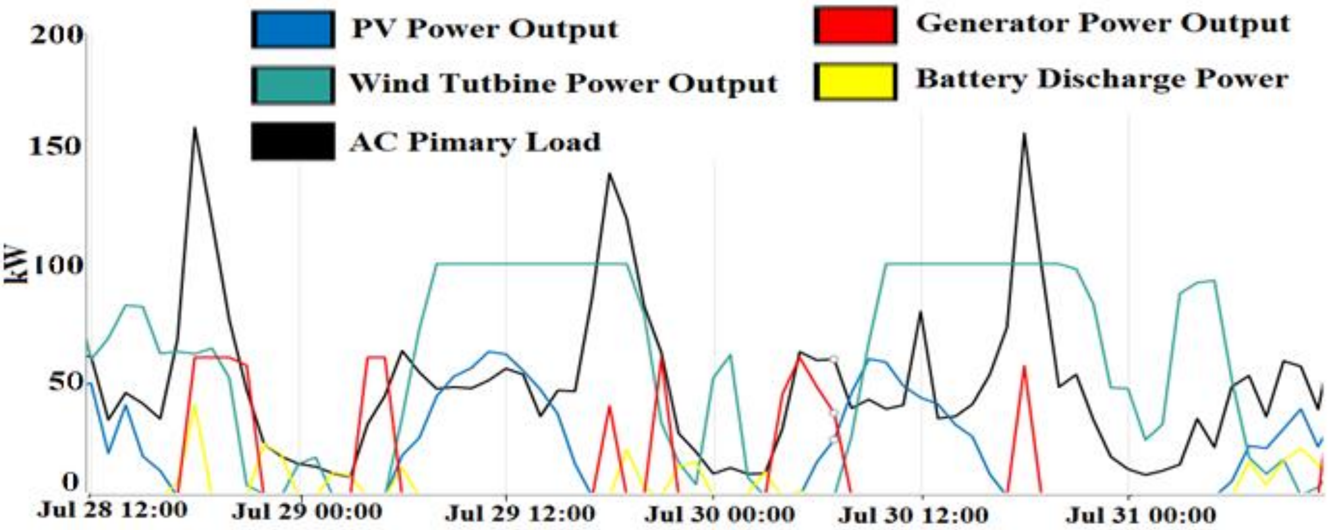

Figure 9. Typical power output curves for 3 days of the year by the components.

3.6. Sensitivity Analysis

The results of the MCDM method showed that scenario 221 is the best choice, and sensitivity analysis was done on some of the important changeable parameters, such as the capital cost of PV, wind turbines, batteries, and diesel fuel price. These sensitivity analyses help us to assess alterations in prices over time and changes in location with similar load demands and renewable resources. They also help in determining the economic and environmental results that would be obtained by simulating the same hybrid systems in a new case-study region.

Figure 10 shows that increasing the capital cost of PV panels from 0.6 to 1.2 of the current price decreases RF from 73% to 58% and increases the system's COE from 0.210 to 0.230 ($/kWh). In addition, the NPC values would be increased from 1.45 to 1.60 (million $). In this scenario, CO_2 emissions increase from 93,409 to 139,909 (kg/year). On the other hand, increasing the capital cost of the wind turbine by 0.7 to 1.4 of the current price changes the COE and NPC values from 0.210 to 0.240 ($/kWh) and from 1.45 to 1.80 (million $), respectively, but the value of Rf will be constant at 73%. Consequently, the CO_2 emissions will not significantly change.

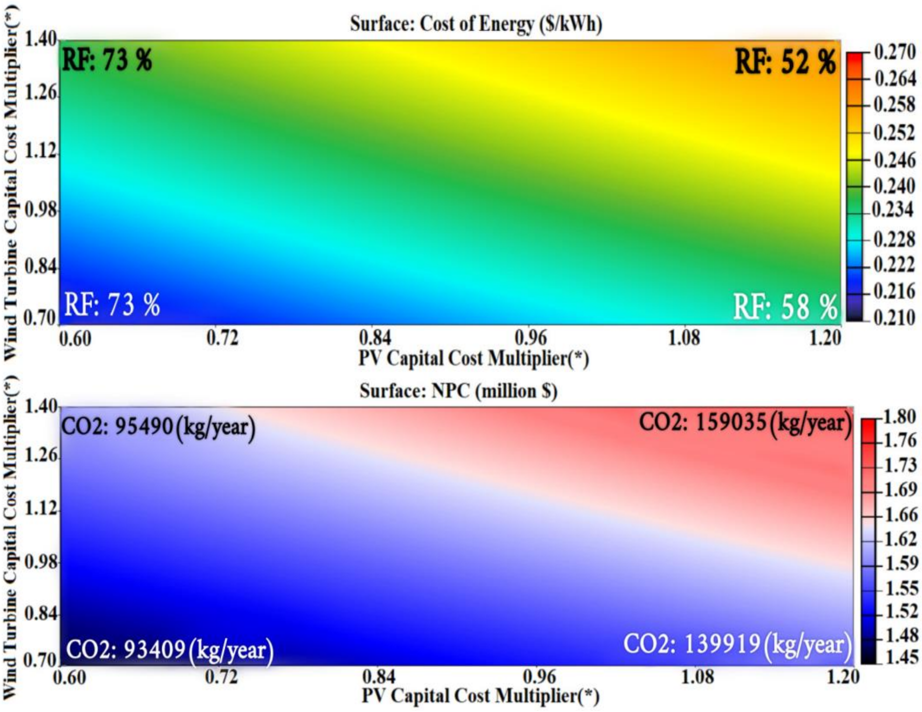

Figure 10. Sensitivity analysis on the PV and wind turbine capital cost.

Figure 11 shows the sensitivity analysis results on the capital cost of the battery and diesel fuel price. As seen in this figure, increasing the capital cost of the battery by 0.7 to 1.2 of the current price will not significantly change the RF, CO_2 emission, COE, or NPC values. In contrast, increasing the diesel fuel price from 0.5 to 1.1 ($/L) would increase the RF values from 51% to 93%. In addition, the COE, NPC, and CO_2 emission values will be changed from 0.2 to 0.3 ($/kWh), from 1.4 to 2.1 (million $), and from 161,146 to 27,723 (kg/year), respectively.

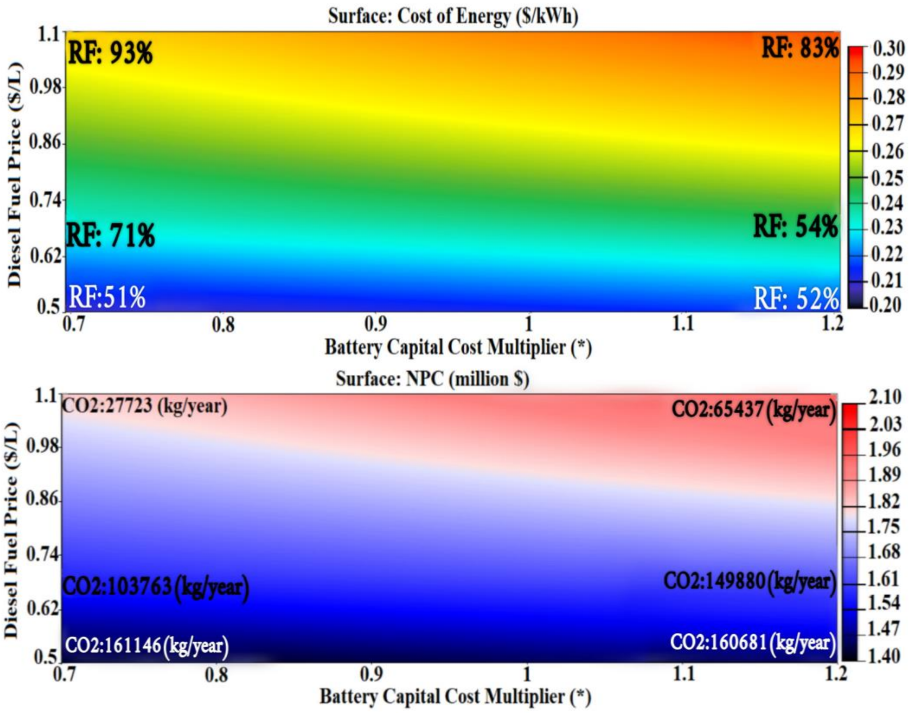

Figure 11. Sensitivity analysis on the battery and diesel prices.

4. Conclusions

In the current study, typical components that have been used in some of the studies conducted in the case-study region were investigated, and their combination has created 32 different scenarios. All the proposed systems were modeled in HOMER software to find the optimal sizing of the components. Using the MCDM method and considering 15 economic, technical, and environmental parameters as the criteria, the scenarios were sorted to find the best solution. The main findings of this study are as follows.

- The most economic and environmentally friendly system is scenario 421, where the considered criteria are NPC, COE, and emissions, including Canadian Solar MaxPower CS6X-325P as PV, Eocycle EO10 10 kW as wind turbine, and generic 1 kWh Li ion as the battery. The COE, NPC, and emission values are 0.21 ($/kWh), 1.42 (million $), and 82,244 (kg/year), respectively.
- If all the economic, technical, and environmental parameters are considered together, the best choice is scenario 221, which included SunPower E20-327 as PV, Eocycle EO10 10 kW as wind turbine, and generic 1 kWh Li ion as the battery. This system's COE, NPC, and emissions are 0.24 ($/kWh), 1.64 million ($), and 150,881 (kg/year), respectively.
- These two mentioned points showed that systems with the lowest NPC, COE, and pollutant emissions cannot always be the best choice. This fact becomes clearer when all the technical, economic, and environmental parameters are considered as the criteria since the best economic or environmental option is not necessarily the best choice executable.
- Changing the wind turbine's capital cost by 0.7 to 1.4 current price and PV panels' price from 0.6 to 1.2 current price would drive the RF, COE, and NPC values from 52% to 73%, 0.210 to 0.270 ($/kWh), and 1.45 to 1.80 (million $), respectively, and increase the CO_2 emissions from 93,409 to 139,909 (kg/year).
- Changing the batteries' capital cost by 0.7 to 1.2 of the current price and diesel fuel price from 0.5 to 1.1 ($/L) would increase the RF, COE, and NPC values by 51% to 83%, 0.2 to 0.3 ($/kWh), and 1.4 to 2.1 (million $), respectively, and decrease the CO_2 emissions from 161,146 to 27,723 (kg/year).

Other suggestions for future studies would be investigating other locations, other components, other resources, and grid-connected hybrid renewable systems.

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