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Original Research Article

Feasibility of supplying electrical energy demands with off-grid hybrid renewable systems to supply a small hotel in the desert

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Abstract: Considering the world's ever-increasing need for energy, as well as the limited resources, pollution, and climate change caused by fossil fuels, it shows the necessity of using renewable energies more than ever. Iran has many tourist attractions. It is difficult to supply energy to welfare places in some of these areas due to the long distance from the city or the vulnerable environment, so their energy supply system is designed independently of the grid. Using a diesel generator to supply electricity can be considered the first solution for a hotel's off-grid system, but this scenario has high costs and causes pollution. The second way is to use renewable energies such as wind and solar, but these energies are not stable due to weather conditions. One suggestion to overcome the periodicity of renewable energy sources such as the sun and wind is to develop a hybrid energy system in which excess electrical energy can be converted and stored. These resources, together with energy storage, can provide a system with better reliability that is suitable for off-grid applications. In the third case, the diesel generator can be combined with renewable energy. In this article, the electricity supply is for a small hotel with an area of 3995 m^2 located in the Varzaneh desert of Isfahan province. The average electrical load required is 1530 kWh/day, and the peak load is 118.76 kW. The simulation of the system has been done with HOMER software, and the results have been categorized based on the three scenarios mentioned as well as the total net present cost of the system. With the obtained results, it is clear that the most optimal system is one with a combined supplier of a diesel generator, a photovoltaic panel, a wind turbine, and battery storage. The NPC value of this system is $1,995,016; the renewable rate is 87.1%; and its emissions are 84% lower than in the case where only the diesel generator supplier has them.

Keywords: wind turbine; grid-off system; solar panel; optimization software; pollution

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1. Introduction

The increasing use of fossil fuels for energy supply has caused many problems, such as environmental pollution and global warming[1,2]. As a result of global warming, high economic and environmental damages occur, which has drawn the attention of the world community to this problem[3]. In recent years, many investments have been made to optimize energy consumption and also to use alternative fuels, such as renewable energies[4,5].

The two biggest sources of renewable energy are the wind and the sun, and many predict that the use of these sources for construction and industrial purposes will increase greatly[6,7]. Among renewable energy sources, Iran has a high potential for solar energy[8]. The total area of Iran is about 1,600,000 km^2, with about 300 clear sunny days per year and an average solar radiation of 2200 kWh/m^2[9]. On the other hand, some areas of Iran have good wind potential[10]. Research has shown that in some areas, it is possible to install small or large wind turbines to provide energy[11]. It has been estimated that the potential of wind energy in Iran is more than 100,000 MW[12].

Renewable sources are economically and environmentally very suitable for areas that are remote and do not have access to grid electricity or areas that are more environmentally vulnerable to fossil fuel pollution[13]. Tourist areas are among the areas where access to grid electricity is sometimes difficult, expensive, or dangerous[14]. Sometimes, the electricity of buildings in these areas is supplied by diesel generators, which causes the emission of a large amount of greenhouse gases and also increases the costs[15]. These effects can be reduced by optimizing this system, but the best way to deal with this problem is to use renewable energies in the system[16]. These energies may be free and compatible with the environment, but because they depend on climatic conditions, they have an unstable load[17]. With demand load fluctuations as well as wind or solar radiation fluctuations, sometimes a system that has a renewable supplier suffers from a lack of supply load[18]. This problem can be solved by increasing the capacity of wind and solar equipment and adding more batteries, but this itself causes a significant increase in costs, which destroys the economic efficiency of the system. As a result, to solve the mentioned problems, a combination of diesel generator systems with wind and solar renewable energy systems can be used[19].

In this field, many studies have been done for regions with different climates around the world. Ngan and Tan analyzed the performance of hybrid systems using HOMER software simulations in Johor Bahru, Malaysia, and showed the economic and environmental performance of a PV/wind/diesel/battery system, which is useful and a suitable alternative to a stand-alone diesel system[20]. A feasibility study by Bekele and Palm evaluated the electricity supply using a stand-alone hybrid solar-wind system for a sample community (200 households, consisting of 1000 people in total) located in an off-grid area in Ethiopia and concluded that the hybrid system has several functional advantages[21]. Lal and Raturi optimized a hybrid energy system for the Fiji Islands using simulations performed with HOMER software and showed that the most feasible system is a hybrid photovoltaic/wind/diesel system with 200 kW of photovoltaic panels and 170 kW of diesel generators and battery storage[22]. The use of solar and wind energy to generate electricity to support the Jordanian power grid was evaluated in 2010, leading to significant electronic advances in energy conversion technologies. Okonkwo et al.[23] studied the potential of a stand-alone hybrid system consisting of photovoltaic panels and a wind turbine to meet the annual electricity demand of 34.4 MWh for a hotel in Jordan and analyzed the technical feasibility and economic viability of the system. Technical analysis shows that a 20 kW photovoltaic system and a 10 kW wind turbine can adequately meet the demand. Also, economic indicators obtained from the stand-alone system showed a net present cost (NPC) of $147,485 over its 25-year lifetime, a savings-investment ratio (SIR) of 1.924, and a payback period of 11 years. The grid-connected hybrid system showed more potential with an NPC of $98,712, a SIR of 2.84, and a payback time of 8.07 years[23].

Studies show that there is a perception in the tourism sector that RES is not capable of providing sufficient power, is unreliable, and, most importantly, is not economically viable with extended payback times[24,25]. The load required in a hotel depends on different factors, such as different seasons, holidays, or tourism events[26]. There are important research gaps in this field. The first challenge is whether a grid-off hybrid system can provide enough reliable electricity for a hotel, sometimes on a large scale. Which RES configuration provides the most economical solution using NPC as the basis of comparison[27]? What functions will each of the system's equipment have in different configurations?

In this article, different scenarios for the electricity supply of a hotel located in the Varzaneh desert in the east of Isfahan province with an average electrical load requirement of 1530 kWh/day and a peak load of

118.76 kW have been analyzed by HOMER software, and different systems in terms of the technical performance of different equipment, the amount of emissions, and economic performance are compared.

2. Data and system description

2.1. Description of the project location

The purpose of this study is to design an optimal hybrid stand-alone system to supply the electrical load of a small, four-story hotel with an area of 3995 m^2 located in the Varzaneh desert of Isfahan province[28]. Varzaneh Desert (latitude: 32.41 degrees north, longitude: 52.64 degrees east) is located near the city of Varzaneh in the eastern part of Isfahan Province, 117 km from Isfahan City and 150 km west of Yazd, and its area is about 17 thousand hectares[29,30]. This desert is about 10 km away from the city of Varzaneh and is located in the southwest of Gavkhoni International Wetland. The construction of this hotel will greatly contribute to the well-being of tourists in this area.

The wind and solar radiation information in this area was taken from the NASA website database in the form of a 24-hour profile for 365 days a year. **Figure 1** shows the average monthly solar radiation and air cleanliness index in this area. The average annual solar radiation is 5.4 kWh/m^2 per day. Also, **Figure 2** shows the average wind speed in different months of the year. The average annual wind speed is 4.43 m/s.

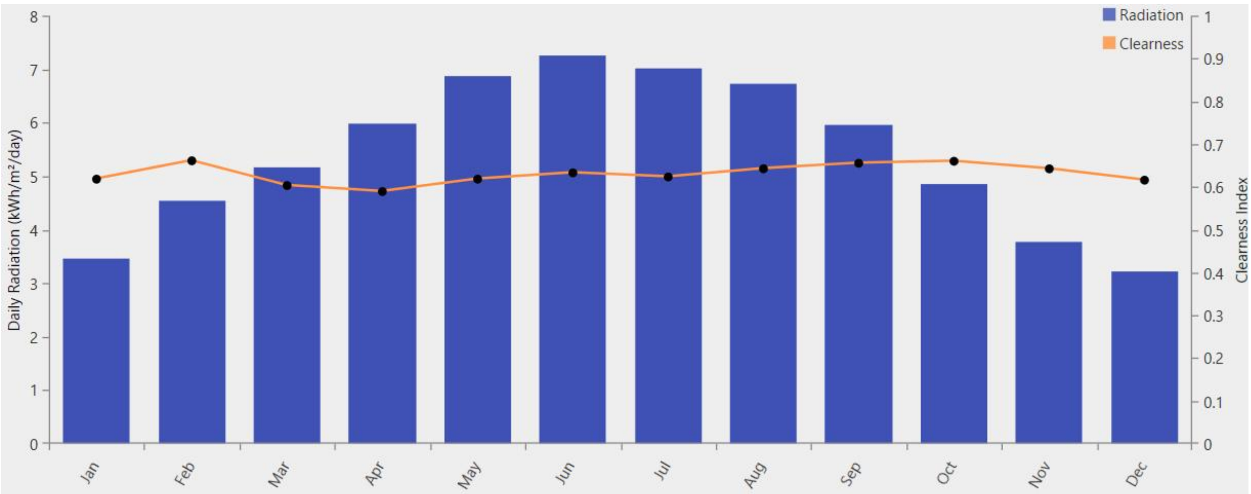

Figure 1. Average monthly solar irradiance kWh/m^2/day.

Figure 2. Average monthly wind speed m/s.

The amount of electric load required by the hotel is given to the software in the form of a 24-hour profile for 365 days of the year. In **Figure 3**, the average electrical load required in different months of the year is shown hourly. The average electrical load required is 1530 kWh/day, and the peak load is 118.76 kW.

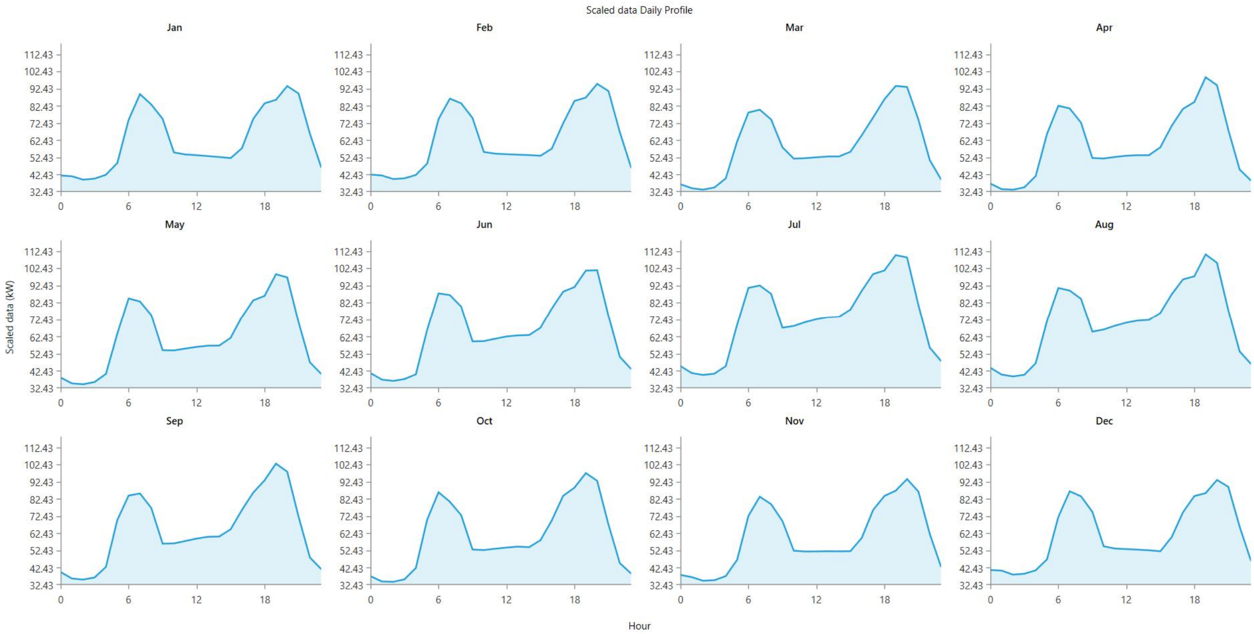

Figure 3. Average electric load required in different months of the year.

2.2. System description

The energy supply system consists of renewable sources, a diesel generator, a converter, and batteries. The system provides the required energy from wind and solar sources through a wind turbine and photovoltaic panel. The excess energy produced is stored in the battery for times of shortage, and when needed, the battery is discharged and supplies the energy needed by the system. When there is a shortage of diesel, the generator is turned on and compensates for the shortage. The schematic of the system is shown in **Figure 4**.

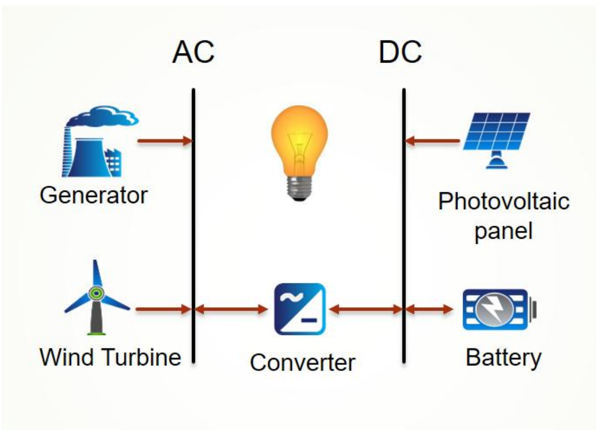

Figure 4. System schematic.

2.2.1. Photovoltaic panel

Photovoltaic panel The Canadian Solar HiKu 415W CS3N-415MS monocrystalline solar panel has been selected for this system. The purchase and replacement price of each panel is $219, and the cost of setting it up and maintaining it is $4 per year. The maximum capacity considered for the whole system is 50 kW. **Table 1** shows the specifications of the panel.

Table 1. PV specifications.

Rated power	415 W
Efficiency	20.4 %
Temperature coefficient	–0.34 %/°C
Operating temperature	–40 °C to +85 °C
Output warranty term	25 years
Dimensions	1940 mm × 1048 mm

2.2.2. Wind turbine

Three turbines named Norvento nED 22, Enercon E-53, and EWT DW 61 have been selected for this system. The specifications of the three turbines are specified in **Table 2**.

Table 2. Characteristics of the three selected turbines.

Quality \ Model	EWT DW 61	Enercon E-53	Norvento nED 22
Rated capacity (kW)	900	800	100
Rotor diameter (m)	60.9	52.9	22
Hub height (m)	75	73	24.5
Cut-in speed (m/s)	3	3	3
Cut-off speed (m/s)	25	34	20
Survival wind speed (m/s)	52.5	59.5	59.5
Initial cost ($)	1,250,000	1,030,000	405,000
Replacement cost ($)	1,250,000	1,030,000	405,000
Operating and maintenance cost ($/year)	45	45	36
Lifetime(years)	20	20	20

The output power of the wind turbine is calculated at each time step using a three-step process. First, the wind speed is calculated at the height of the hub of the wind turbine. Then it calculates how much power the wind turbine produces at that wind speed and standard air density. Finally, the output power value is adjusted for the actual air density[31].

First, in each time step, the wind speed at the height of the wind turbine hub is calculated using the inputs entered in the wind sources.

If the logarithmic law is chosen, the wind speed at the height of the wind turbine is calculated as Equation (1):

$$U_{hub} = U_{anem} \cdot \frac{\ln(Z_{hub}/Z_0)}{\ln(Z_{anem}/Z_0)} \tag{1}$$

U_{hub} = wind speed at the height of the wind turbine [m/s]
U_{anem} = wind speed at the height of the anemometer [m/s]
z_{hub} = wind turbine height [m]
z_{anem} = anemometer height [m]
z_0 = surface hardness length [m]

After determining the wind speed and hub height, in the second step, the power curve of the wind turbine is referred to to calculate the expected output power from the wind turbine at that wind speed under standard conditions of temperature and pressure. In the diagram below, the red dotted line represents the wind speed at hub height, and the blue dotted line represents the wind turbine power output that the power curve predicts for that wind speed. If the wind speed at the height of the turbine hub is not within the range defined in the power curve, the turbine will not produce electricity, assuming that wind turbines don't produce electricity at wind speeds lower than the minimum cutoff or higher than the maximum cutoff wind speeds.

In the third stage, the power curves usually specify the performance of the wind turbine in standard temperature and pressure (STP) conditions. To adapt to real conditions, we must multiply the power value predicted by the power curve by the air density ratio, according to Equation (2):

$$P_{WTG} = \left(\frac{\rho}{\rho_0}\right) \cdot P_{WTG,STP} \tag{2}$$

P_{WTG} = wind turbine output power [kW]
$P_{WTG,STP}$ = wind turbine output power at standard temperature and pressure [kW]
ρ = real air density [kg/m^3]
ρ_0 = air density at standard temperature and pressure [1.225 kg/m^3]

2.2.3. Converter

The function of the converter is to combine AC and DC electric currents. In the modeling, the converter capacity is chosen between 0 kW and 100 kW. The initial and replacement cost is 300 $/kW.

2.2.4. Batteries

A generic 1 kWh lead acid battery is used for energy storage in this system. The initial cost of each battery is $300, the replacement cost is $300, and the start-up and maintenance cost is $10 per year. Battery specifications are specified in **Table 3**.

Table 3. Selected battery specifications in the system.

Nominal voltage (V)	12
Nominal capacity (kWh)	1
Maximum capacity (Ah)	83.4
Capacity rate	0.403
Maximum charging current (A)	16.7
Maximum discharging current (A)	24.3
Lifetime (years)	10
Operating power (kWh)	800

2.2.5. Diesel generator

To compensate for the lack of capacity, two generators with capacities of 100 kW and 400 kW have been used. The fuel for diesel generators is diesel, and the price of each liter of fuel is $1. **Table 4** shows the specifications of the generators.

Table 4. Specifications of selected generators.

Generator	Generic 100 kW fixed capacity genset	Generic 500 kW fixed capacity genset
Fuel curve intercept (L/hr)	2.8	7
Fuel curve slope (L/hr/kW)	0.253	0.244
CO emission (g/L fuel)	17.794	13.566
Unburned hydrocarbons emission (g/L fuel)	0.72	0.72
Particle emission (g/L fuel)	0.0712	0.116
NO_x emission (g/L fuel)	1.4235	2.6
Initial cost ($)	40,000	150,000
Replacement cost ($)	40,000	150,000
Operating and maintenance cost ($/year)	2	5
Lifetime (h)	15,000	15,000

3. Modeling

3.1. HOMER software

This software is a hybrid renewable network optimizer that designs and evaluates systems in two modes: connected to the network or independent from it for various applications. To use this software, first, the inputs must include the required load of the system, the type of technology chosen, the equipment used, the cost of the equipment, and the available resources. Then HOMER simulates different system arrangements with different equipment combinations and classifies the results in the form of a list of different arrangements based on their total net present cost (NPC)[32].

3.1.1. Net present cost (NPC)

The net present cost of a piece of equipment is equal to the present value of all the installation and operating costs of that piece of equipment minus all the income earned from the same piece of equipment during the life of the project. HOMER calculates the current net current for each device in the system and the entire system. The net present cost is obtained from Equation (3).

$$NPC = \frac{total\ annualized\ cost}{capital\ recovery\ factor} \tag{3}$$

where the capital recovery factor (CRF) is obtained from Equation (4).

$$CRF(i, N) = \frac{i(1+i)^N}{(1+i)^N - 1} \tag{4}$$

where i is the real annual interest rate and N is the number of years of project review. HOMER assumes that all prices rise at the same rate and uses the “annual real interest rate” instead of the “nominal interest rate”. This method allows inflation to be factored out of the analysis. The annual total real interest rate (i) was assumed to be 6% in the simulations.

3.1.2. Levelized cost of energy

The cost of energy per kilowatt hour of useful electrical energy produced is called the cost of energy (COE) of a system[33]. To calculate COE, the annual cost of electricity production (total annual cost minus the cost of thermal load service) is divided by the total electrical load provided using Equation (5):

$$COE = \frac{C_{ann,tot} - C_{boiler} H_{served}}{E_{served}} \tag{5}$$

$C_{ann,tot}$ = total annual system cost [$/yr]
C_{boiler} = final cost of the boiler [$/kWh]
H_{served} = total thermal load provided [kWh/yr]
E_{served} = total electrical load served [kWh/yr]

The second term in the counter is a part of the annual cost that results from the thermal load service. In systems such as wind or solar that do not provide thermal load (Hthermal = 0), this expression is zero. COE is a convenient measure to compare systems.

3.1.3. Problem-solving method

In solving the problem, the two main steps are simulation and optimization. At its core, HOMER is a simulation model that attempts to simulate a viable system for all possible combinations of equipment considered. Depending on how the model is set up, HOMER may simulate hundreds or even thousands of systems. The optimization phase follows all simulations. The simulated systems are sorted and filtered based on the defined criteria. Although HOMER is primarily an economic optimization model, fuel consumption can be minimized[32]. **Figure 5** shows the step-by-step flowchart of this process.

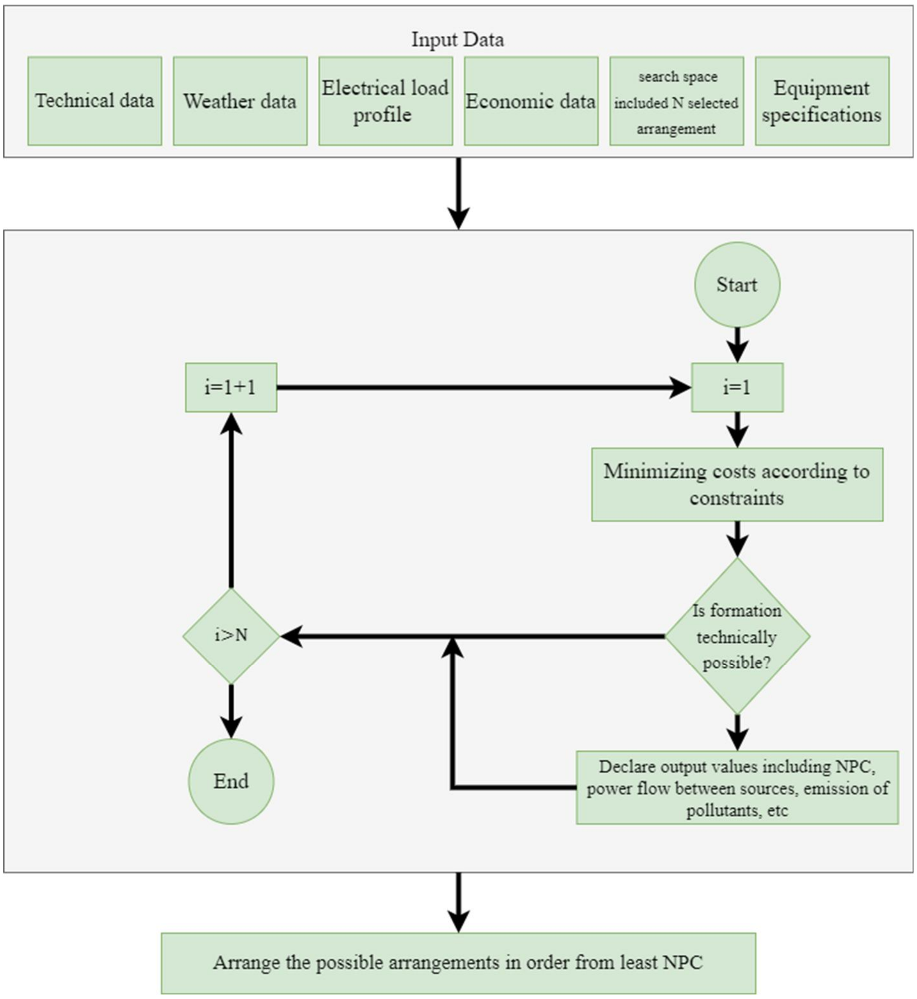

Figure 5. Problem-solving method by HOMER.

4. Results

By simulating the system and optimizing it, various proposed systems are presented. The reviewed systems are classified based on energy cost and are technically and economically evaluated in three different modes. In the first scenario, the energy source is only a generator with diesel fuel and battery storage. In the second scenario, the generator is removed, and only wind and solar renewable energy sources are used with battery storage. In the third scenario, renewable resources and a diesel generator are combined, and when wind or solar energy is not enough to supply electricity, a diesel generator and battery come to the system's aid and provide energy. Economically, the best systems in the first, second, and third scenarios are called diesel-backap, renewable-only, and hybrid-energy, respectively. **Table 5** shows the different components of these three systems.

Table 5. Comparison of the best-obtained systems for each scenario.

Properties / System	EWT DW 61 (number)	Enercon E-53 (number)	Norvento nED 22 (number)	PV (kW)	Generic 100kW (number)	Generic 500kW (number)	1kWh Battery (number)	100kWh Battery (number)	Converter (kW)
Diesel-backup	-	-	-	-	1	-	80	-	-
Renewable-only	1	-	-	47	-	-	-	16	150
Hybrid-energy	-	1	-	50	1	-	-	2	90

Table 6 compares the above systems in terms of economy and renewable percentage.

Table 6. Economic comparison and the renewable fraction of final optimal systems.

System	Initial cost ($)	COE ($)	NPC ($)	Renewable fraction (%)
Diesel-backap	70,000	0.380	3,347,029	0
Renewable-only	2,243,812	0.390	3,426,289	100
Hybrid-energy	1,260,000	0.227	1,995,016	87.1

The diesel-backap system with a diesel generator supplier is by far the cheapest, and the renewable-only system with a renewable supplier is the most expensive in terms of initial cost due to the high cost of batteries and wind turbines, but due to the high consumption of diesel fuel that costs $1 per liter, the current net cost of these two systems is not much different. But if these two scenarios are combined and form the optimal hybrid energy system, the cost of energy supply will decrease significantly. although the hybrid energy system is not completely renewable, it is much cheaper than the renewable-only system and can be implemented at a lower initial cost.

These three systems are comparable in terms of pollutant emissions. **Table 7** examines the performance of three systems in terms of fuel consumption and pollutant emissions.

Table 7. Performance of systems in terms of fuel consumption and pollutant emissions.

System	Fuel consumption (L/yr)	CO_2 (kg/yr)	CO (kg/yr)	Unburned hydrocarbons (kg/yr)	Particle (kg/yr)	SO_2 (kg/yr)	NO_x (kg/yr)
Diesel-backap	166,020	434,239	2,954	120	11.8	1,064	264
Renewable-only	0	0	0	0	0	0	0
Hybrid-energy	22,225	58,130	195	16	1.58	142	31.6

The highest emission of pollution occurs in the diesel-backap system, which is due to the high consumption of diesel fuel, but by combining the system with renewable sources in the hybrid-energy system, fuel consumption and emissions of pollutants are reduced by about 84%. Also, by removing the generator and relying only on renewable energy, fuel consumption, and pollutant emissions will be zero.

These systems can also be compared in terms of the performance of the components.

4.1. Diesel generator performance

In diesel-backap and hybrid-energy systems, there is a Generic 100 kW Fixed Capacity Genset diesel generator, and **Table 8** compares their performance.

Table 8. Performance table of diesel generator in diesel-backup and hybrid-energy systems.

Properties	Diesel-backup	Renewable-only
Electrical production (kWh/yr)	559,227	71,841
Mean electrical output (kW)	63.8	49.7
Fuel consumption (L/yr)	166,020	22,255
Fuel energy input (kWh/year)	1,633,638	218,690
Mean electrical efficiency (%)	34.2	32.9
Hours of operation (hours/yr)	8760	1446
Operational life (years)	1.71	10.4
Capacity factor (%)	63.8	8.2

In the diesel-backap system, the diesel generator is the only energy supplier, which is why it works with a high capacity and has a high fuel consumption, which causes the working life of the generator to end early and be replaced. But in the hybrid-energy system, since most of the energy is provided by the wind turbine and photovoltaic panel, it is turned on only when the required load is high and comes to the aid of the system; that is why it consumes less fuel and works with a lower capacity. **Figure 6** shows the annual performance of generators in both systems.

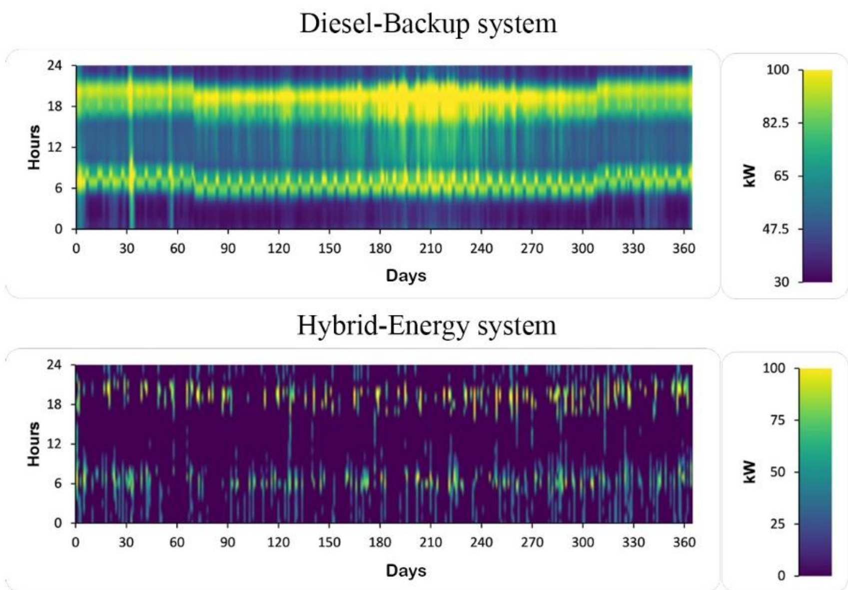

Figure 6. Annual graph of generator performance in diesel-backup and hybrid-energy systems.

4.2. The performance of wind turbines

There is an EWT DW 61 wind turbine in the renewable-only system and an Enercon E-53 wind turbine in the hybrid-energy system. **Table 9** shows the performance of these two turbines.

Table 9. Performance of wind turbines in renewable-only and hybrid-energy systems.

Properties	Renewable-only	Hybrid-energy
Electrical production (kWh/yr)	2,511,044	2,120,139
Hours of operation (hours/yr)	8147	8610
Leveliezed cost of energy ($/kWh)	0.0372	0.0363
Total rated capacity (kW)	900	800
Mean output (kW)	287	242
Capacity factor (%)	31.8	30.3
Percentage of total energy production (%)	96.8	93

Figure 7 shows the annual performance of turbines in both systems. During the hours when there is the strongest wind, the energy produced by the turbine increases. Contrary to the photovoltaic panels, which have their peak performance in the middle of the day and do not produce any energy when it is dark, the performance of the wind turbine is spread out over different hours of the day and does not follow a specific pattern. In the last months of the year, as the average wind intensity decreases, the electricity produced by the turbine also decreases.

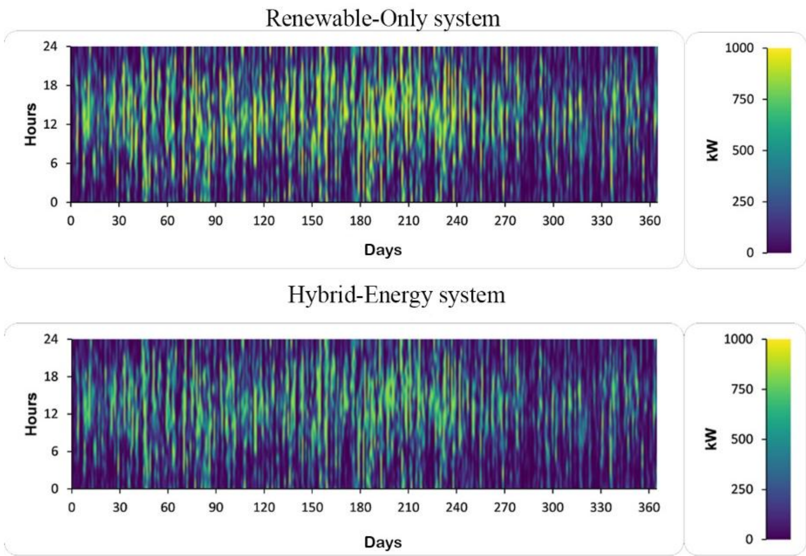

Figure 7. Performance diagram of wind turbines in renewable-only and hybrid-energy systems.

4.3. PV performance

There are 47 kW and 50 kW photovoltaic panels in renewable-only and hybrid-energy systems, respectively. In **Table 10**, the performance of the panels in these two systems has been examined. **Figure 8** shows the output performance of the solar panel in the systems. The peak of electricity produced is approximately 12 o'clock, and the peak of solar radiation is also in the summer. When there is more radiation during the period, the energy produced is also higher. When there is no radiation from the sun, no electricity is generated from the panels.

Table 10. PV performance table in renewable-only and hybrid-energy systems.

Properties	Renewable-only	Hybrid-energy
Electrical production (kWh/yr)	83,230	88,560
Hours of operation (hours/yr)	4387	4387
Leveliezed cost of energy ($/kWh)	0.0247	0.0244
Total rated capacity (kW)	47	50
Mean output (kW)	9.5	10.1
Capacity factor (%)	20.2	20.2
Percentage of total energy production (%)	3.21	3.88

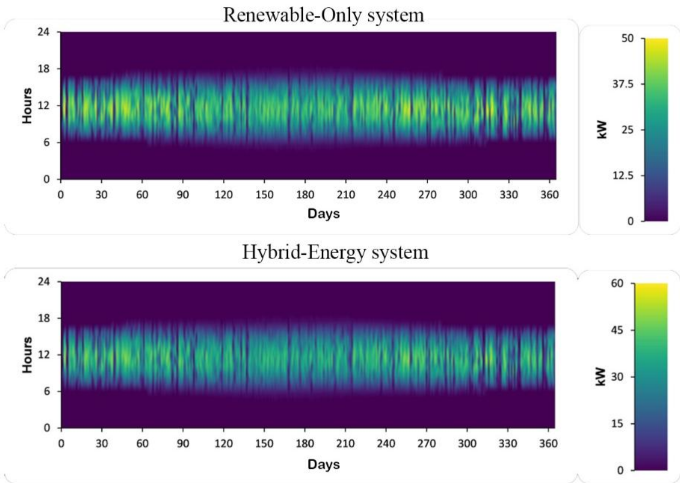

Figure 8. Annual performance of PV in renewable-only and hybrid-energy systems.

4.4. Battery performance

In all three systems, the battery, as a storage device when the supplied energy is more than the required load, stores the excess energy and gives it to the system when the required load is high. **Table 11** shows the performance of the battery in all three systems.

Table 11. Performance of batteries for each system.

Properties	Diesel-backup	Renewable-only	Hybrid-energy
Rated capacity (kWh)	80	1600	200
Leveliezed cost of energy ($/kWh)	0.333	0.246	0
Energy input (kWh/yr)	2588	114,970	43,974
Energy output (kWh/yr)	2070	103,509	39,633
Storage depletion (kWh/yr)	0.0527	38.3	59.5
Losses (kWh/yr)	518	11,499	4,400
Annual throughput (kWh/yr)	2315	109,108	41,777
Autonomy (hours)	0.753	20.1	2,51
Storage wear cost ($/kWh)	0.419	0.246	0.246
Usable nominal capacity (kWh)	48	1280	160
Lifetime throughput (kWh)	23,148	1,636,624	600,000

In the diesel-backap system, the battery is discharged during peak hours and helps the system, especially in the summer when the temperature and load increase. In renewable-only and hybrid-energy systems, the battery takes and stores the excess energy during the hours when the wind is high, and more energy is produced in the turbine and given to the system during the hours when the wind is low. The highest battery performance is in the renewable-only system, and the lowest is in the diesel-backap system. **Figure 9** shows the performance of the batteries in the system.

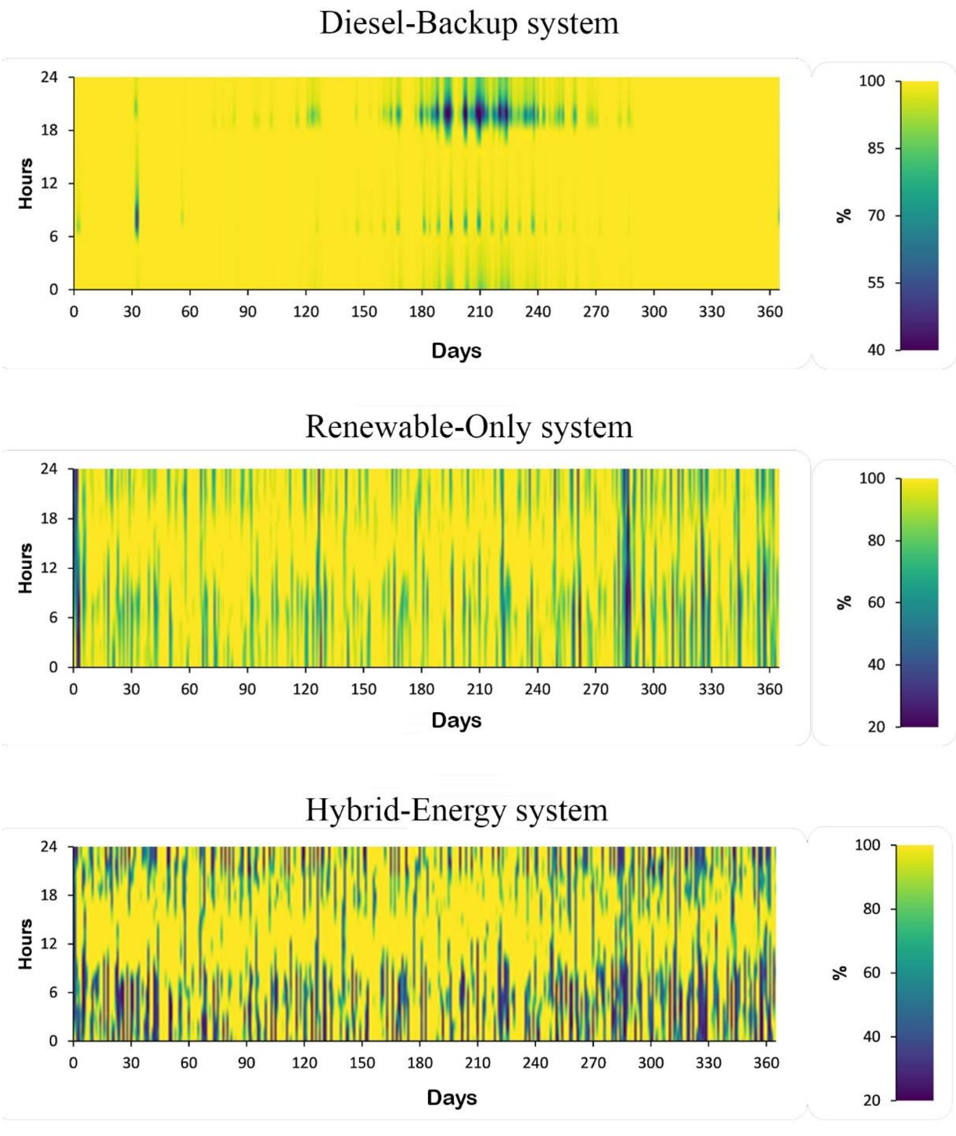

Figure 9. Annual battery performance for each system.

5. Conclusion

The feasibility and design of a grid-off power supply system for a small, four-story hotel with an area of 3995 m^2 were simulated by HOMER software. For this purpose, three different scenarios were proposed and evaluated, and different systems were selected in terms of the lowest possible NPC. Diesel-backap system with a diesel generator supplier, renewable-only system with a PV or wind supplier, and hybrid-energy system with a combined diesel generator and PV or wind supplier were named. Also, the mentioned systems were compared in terms of environmental pollution.

The results showed that while the diesel-backap system with the diesel generator supplier was the cheapest in terms of initial cost, the hybrid-energy system with the combined diesel and renewable supplier is the cheapest system with an energy cost of $0.227. The reason for this is the high consumption of diesel fuel. In comparison with systems based on pollution, the renewable-only system, which is pollution-free, is the most ideal. The diesel-backap system is the most polluting due to the high consumption of diesel fuel, and adding renewable resources to it in the hybrid-energy system reduces pollutant emissions by 84%.

Author contributions

Conceptualization, MG and SFM; methodology, MG; software, MG and SFM; validation, AH and SFM; formal analysis, MG; investigation, MG; resources, SFM; data curation, AH; writing—original draft preparation, MG; writing—review and editing, AH; visualization, AH and SFM; supervision, AH; project administration, MG. All authors have read and agreed to the published version of the manuscript.

Conflict of interest

The authors declare no conflict of interest.

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