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Optimal integration of hybrid (wind–solar) system with diesel power plant using HOMER

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Abstract: Most energy worldwide is supplied through conventional energy sources, such as thermal, hydro, and nuclear. There have been serious energy crises in the last couple of years and so it is essential to consider renewable energy sources. This paper proposes a cost-effective solution for integrating a wind–solar system with an existing diesel power plant of a grid-connected site at Taxila, Pakistan. In the case of nonavailability of power from the grid, this diesel power plant acts as a standby system. Three cases were considered in this paper: 1) using the diesel power plant during load-shedding hours; 2) assisting the system using renewables when it is connected to the grid (on-grid); 3) completely relying on hybrid energy system to meet the daily load demand if excess energy is available (off-grid). The system was implemented in the software package Hybrid Optimization Model for Electric Renewables (HOMER) developed by the National Renewable Energy Laboratory. Different environmental factors were examined, including wind speeds, solar insolation, and their maximum and minimum differences from the average parameters. In the end, the most optimal solution for each case was proposed to meet the desired load demand while making the system operation economical.

Key words: Cost of energy, diesel generator, hybrid energy system, photovoltaic, renewable energy resources, wind turbine

1. Introduction

Energy technologies have an essential role in socioeconomic progression at all scales. Due to an immense increase in fuel costs and problems caused by conventional energy sources, the use of renewable energy resources (RERs) has become mandatory. These energy sources are inexhaustible and clean, and they can be used in a decentralized way [1]. In developing countries like Pakistan, renewable energy can play an important role in meeting serious energy deficits.

For many economical and environmental reasons, and to decrease the dependency on conventional energy, many countries are investing in alternative and renewable energy. Fairly extensive research, elaboration, and development are needed for this purpose. It is also possible to integrate RERs with traditional power systems to reduce the cost of energy (COE). Wind and photovoltaic (PV) systems are promising emerging technologies nowadays, but they offer many challenges to the stability and reliability of the system due to their intermittent and fluctuating nature. Many forecasting techniques and prediction models play an important role in handling these uncertainties [2]. It is imperative to consider the dynamics and intermittency of RERs while designing

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systems for their extensive use [3]. The main factors that make these systems more cost-effective are decreased fuel and operation and maintenance (O&M) costs.

Sufficient research has been done on the application and role of renewable technology in developed countries, but it is still in its initial stages of adoption in Pakistan. Payyad and Moubayed [4] discussed different configurations of PV panels, wind turbines, and diesel generators to supply the load of a typical house. The optimal solution was obtained on the basis of lowest NPC and lowest COE. Mahmud et al. [5] proposed a hybrid system for a remote island having an electricity requirement of 53 kWh/day. Different simulations were performed in HOMER and a PV/wind/diesel/battery system was found to be the most feasible. Razak et al. [6] discussed the optimal sizing and operational strategy of a hybrid energy system on the basis of total NPC. Zhang and Ma [7] did technical and economic analyses on a PV/wind system and concluded that wind speed has a great impact on system cost. Koussa et al. [8] found that when PV, wind, and diesel systems are used together, the reliability of the system is enhanced and the size of the battery storage is also reduced because there is very small reliance on one system. Simic and Mikulicic [9] presented the influence of the wind turbine power curve on COE for a small off-grid hybrid system. Many researchers have worked on the optimal design of a PV/wind/diesel hybrid system in HOMER, but none of the literature deals specifically with the issue of using hybrid energy system for load-shedding periods. This paper presents a detailed analysis of the above issue along with the total load requirements of the site under consideration. The main objective was to find the most cost-effective system configuration capable of meeting consumer demand. Different case studies were simulated in HOMER and compared with existing systems.

2. Potential aspects of RERs in Pakistan

Due to a large population of about 180 million and a rapidly developing economy, energy needs in Pakistan are potentially huge and shortfall of energy is increasing sharply. The country is facing serious imminent energy shortages as its economy and population grow while global fossil fuel prices continue to rise day by day. Load-shedding in the country has badly affected every sector of life. According to an estimation, it costs \$2.5 billion/year to the country's economy, which is an average 2% drop in its gross domestic product (GDP) [10]. In addition, it has also caused an annual unemployment rate of around 400,000 people [11]. Therefore, it is necessary to utilize available RERs to meet the required demand of consumers.

Pakistan's major energy supply mix consists of fossil fuels like wood, coal, oil, and gas, which contribute to 65% of the total supply [12]. The country is blessed with abundant wind and solar resources. One study shows that the overall wind potential in Pakistan is about 346,000 MW [13]. However, this opportunity is available only in certain coastal areas of the country and transmitting this power to other cities is a huge task. Therefore, the use of wind energy is limited to remote consumers [10]. Solar insolation levels are also very high in Pakistan and average daily surface radiation in most of the areas is above 5 kWh/m^2 [14]. Another problem is the social acceptance of these energy systems as compared to other countries in the region like Malaysia, India, and China. Recently, India has injected about 1100 MW of renewable energy to its power systems [15]. Moreover, energy planners are concerned about the capital costs of these systems [16]. Therefore, proper incentives are needed to promote RERs; if these resources are properly utilized, they can greatly affect the total generation.

3. Proposed strategy for hybrid system

A simulation model was produced in HOMER to propose a cost-beneficial hybrid energy system. The main advantage of HOMER is that it helps model a minimal cost system that provides a custom-made supply to specific loads [17]. The site under consideration is connected to the grid and the diesel power plant acts as a standby system that serves the load during load-shedding hours. However, during peak load hours, the diesel system is unable to meet the required demand. COE is also very high for this system. Therefore, integrating a wind–solar hybrid system with this diesel power plant was proposed to meet the energy requirements of the area.

The main focus was to select the system with the lowest COE per kWh. Three cases are discussed in this paper. In the first case, a hybrid system was proposed for the site to meet consumer demand during load-shedding hours when the supply from the grid is not available. An on-grid system was analyzed in the second case to meet the 24 h load where the proposed hybrid system is run in parallel with supply from the grid. COE was compared for different configurations of system. Monthly load profile for total daily load and load shedding routines are discussed in later sections. The final case highlights the use of a hybrid energy system to meet the daily load demand in absence of supply from the grid and diesel generators if sufficient generation is available.

4. Energy resources for wind–PV system

The installation of renewable energy system entirely depends on the resources available for the given site. That includes wind speeds, average daily surface solar insolation, and their timely variation. The meteorological data of wind speed and solar insolation for Taxila (33° 59′N, 72° 59′E) was taken from the NASA surface meteorology and solar energy website [18]. Monthly solar radiations for the site are shown in Figure 1. There are 3 constituents of solar radiation reaching the ground: global radiation, diffused radiation, and direct radiation [19]. Global and diffused radiations are usually measured, while the direct component is estimated.

The average daily solar radiation for the site is 5.11 kWh/m^2 and average clearness index is 0.608. These insolation levels peak from April to July and are the lowest for the months of November and December. The monthly wind speed variations are shown in Figure 2 and from these values the average wind speed for the area is found to be 5.711 m/s. The load data and load-shedding schedules for the site are taken from the local grid (heavy mechanical complex grid station, Taxila).

Figure 1. Monthly solar resources.

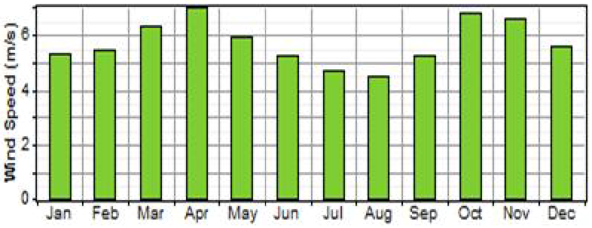

Figure 2. Monthly wind speed variations.

5. Existing system

Two Caterpillar generators, each with ratings of 256 kW and 320 KVA, operate in parallel as a backup system when supply from the grid is not available. The system schematic is shown in Figure 3.

The fuel consumption of each generator is 45 L/h and diesel costs \$1.07/L. The capital cost of a single generator is approximately \$90,112. The minimum load ratio was taken as 30% for the purpose of simulation. Cost details and diesel generator operation hours are given in Table 1. It can be seen that the COE for this system is \$0.521/kWh.

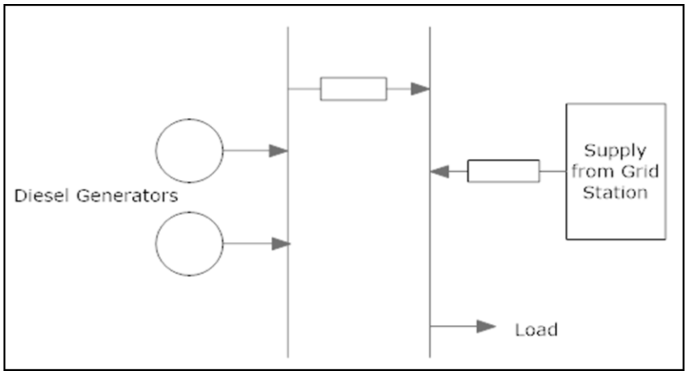

Figure 3. Existing diesel system.

Table 1. Diesel generators system.

Parameters	Values
COE, \$/kWh	0.521
Initial capital, \$	0
Operation cost, \$	438,750
Total NPC, \$	5,608,700
Fuel, L/year	268,607
Diesel gen 1, h/year	1951
Diesel gen 2, h/year	1903

6. Hybrid system components

6.1. Wind turbine

A Fuhrländer-FL250 model wind turbine was used with rated power 250 kW AC. The rotor diameter is 29.5 m and tower height is 42 m. Cut-in speed for this wind turbine is 3 m/s, which can be observed in the power curve shown in Figure 4. This turbine initially costs \$525,000.

6.2. PV panels

A decrease in the price of PV panels has been observed in the past few years. The cost fell by 60% between 2008 and 2011 to \$0.7/Wp [20]. The PV panels used here cost \$4000/kW. Most of the PV panels come with a lifetime of 25 years, although they most likely last longer than that. For energy storage, Hoppecke H3000 6-kWh batteries were used in the analysis.

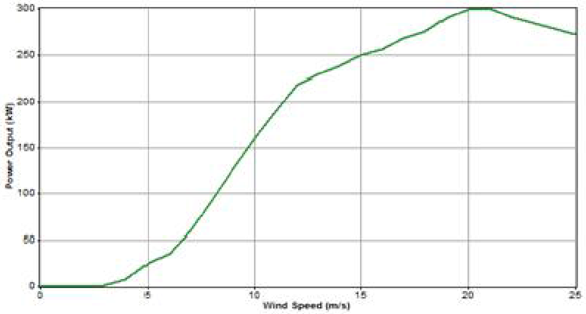

Figure 4. Power curve for FL250 wind turbine.

7. System analysis and simulations

In the optimization process, different sizes of PV panels, wind turbines, power convertors, and batteries were used and the most economical system was selected after running the simulations several times. The search space for the optimization process is shown in Table 2. There were 8 sizes for PV panels, 5 sizes for wind turbines, two 256-kW diesel generators (considered separately because the diesel plant is already acting as a standby system), 11 sizes for batteries (included in case they are needed), and 7 sizes for power converters. Zero is included in the search space of each component for more optimal results.

Table 2. Search space for components of hybrid system.

PV panels (kW)	250-kW wind turbines (no. of units)	256-kW diesel gen #1	256-kW diesel gen #2	Batteries (6 kWh)	Converter (kW)
0	0	0	0	0	0
40	1	1	1	1	10
50	2			2	20
60	3			3	30
70	4			4	40
80				5	50
90				6	60
100				7	
				8	
				9	
				10	

HOMER simulations were performed for these components to find the best possible solution to meet the desired energy requirements. Three kinds of component cost were examined in the system analysis: capital cost, replacement cost, and O&M cost. Capital cost is the price of the component at the beginning of the project when it is installed. Replacement cost is the price of replacing the component at the end of its lifetime and it can be different from the initial capital cost. O&M costs include fuel cost, labor cost, and energy shortage penalties [17].

Table 3 shows the cost for different components of the hybrid system; on the basis of these values, cost for components with larger ratings was derived. For the purpose of calculation, the maximum annual shortage capacity was taken as 10%. It is the ratio between total capacity shortage throughout the entire year and total load [17]. Capacity shortage is basically the deficit that exists between the required operating capacity and the actual operating capacity of the power system. The 3 cases that we considered are briefly discussed below.

Table 3. Cost of components of hybrid system.

Components	Capital cost ($)	Replacement cost ($)	O&M cost
1 kW PV panel	4000	3200	$10/year
250 kW wind turbine	525,000	420,000	$3500/year
256 kW diesel gen 1	0	71,936	$0.001/h
256 kW diesel gen 2	0	71,936	$0.001/h
6 kWh battery	1200	400	$10/year
1 kW converter	700	560	$10/year

7.1. For load-shedding hours

The schematic of this system is shown in Figure 5. A renewable energy system was operated with diesel generators to serve the area during load curtailment.

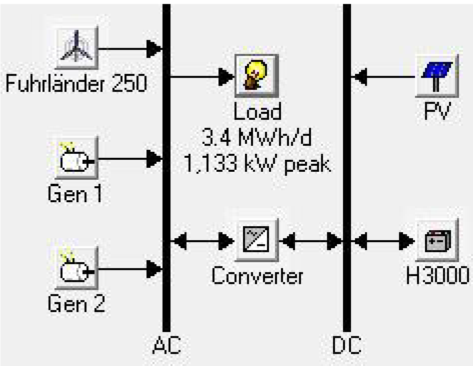

Figure 5. Hybrid system in HOMER.

The AC load profile for load-shedding hours is shown in Figure 6. It had a scaled annual average of 3382 kWh/day and the peak load was 1133 kW. Scaled data were used for calculations in HOMER [17]. Only load values for load-shedding hours were used in the primary load inputs of HOMER; the rest of the fields in 24-h load profiles were set to zero. The average load shedding duration is 5 h per day; however, this may vary accordingly with the load requirements of the consumers. Consumption is very high in summer (from May to August) compared to rest of the months; shortfall in the country increases to 5000–6000 MW during this period.

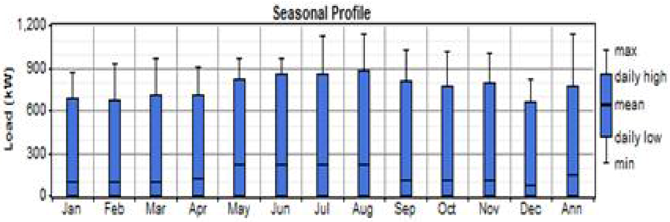

Figure 6. Monthly load profile for load shedding hours.

On the basis of load profile given for load-shedding hours and costs of different components of system along with their sizes, simulations were performed in HOMER to determine the most economical system configuration. Due to high load demand, only 2 feasible systems were identified. These 2 systems are compared in Table 4. For the first model of the system, PV panels of 80 kW were used and 3 wind turbines of 250-kW AC ratings were considered. Total NPC of the component includes capital cost, replacement cost, and O&M cost minus the salvage [17]. Capital costs of diesel generators were not included because they were already present in the system as a backup generation. As the output of PV panels is DC, a converter of 40 kW was used. The architecture of system 2 is given in Table 4.

Table 4. Optimization results for load-shedding hours.

Parameters	*System 1	*System 2
COE, $/kWh	0.420	0.442
Initial capital, $	1,923,000	2,287,000
Operation cost, $	315,405	316,025
Total NPC, $	5,954,953	6,326,861
Fuel, L/year	268,607	261,146
Diesel gen 1, h/year	1876	2014
Diesel gen 2, h/year	1615	1507
PV, %	7	3
Wind, %	56	66
Diesel, %	37	31

*System 1: Two 256-kW diesel generators + 80-kW PV panels + three 250-kW wind turbines + 40-kW converter.

*System 2: Two 256-kW diesel generators + 40-kW PV panels + four 250-kW wind turbines + 10 batteries + 10 kW converter.

Findings:

1. When compared with system 2, it is seen that system 1 was more cost-effective. It offered low COE per kWh, low capital cost, and low NPC. The O&M cost of this system was also low.
2. To meet the required load demand by using system 1, the PV system contributed 7% and wind turbines added 56% to the total kWh generation per year, whereas generator 1 and generator 2 provided 21% and 16%, respectively.
3. COE values for individual systems are compared in Table 5. Although renewable energy systems had the highest capital cost, they had the lowest COE/kWh.
4. The COE for diesel generators was the highest out of all the systems due to their high fuel cost and O&M cost.
5. In system 2, 40-kW PV panels were used, which reduced their capital cost compared to system 1, but 4 wind turbines were considered to meet the load, which makes this system more costly.
6. The simulation results show that system 1 is the most economical option to serve the area during load shedding hours.

Table 5. COE for individual systems.

Energy sources	COE ($/kWh)
Wind	0.123
PV	0.185
Diesel	0.268

7.2. System is connected to the grid

In this case, the hybrid system was operated in conjunction with the supply coming from the local grid. The schematic of the system is given in Figure 7. The purchase capacity taken from the grid was 500 kW and the rest of the load was met by using a hybrid energy system.

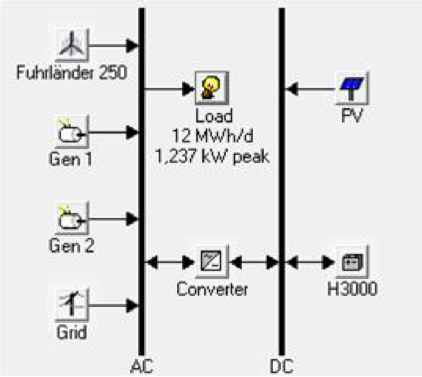

Figure 7. Grid-connected hybrid system in HOMER.

Load profile for daily demand on a monthly basis is shown in Figure 8. The scaled annual average was 12099 kWh/day and the peak load was 1237 kW. Load-shedding routines, search space, and costs of system components are the same as discussed in the previous case. However, the rate of buying electricity from the grid is $0.148/kWh. Multiple rates can also be used in HOMER to indicate when each rate applies.

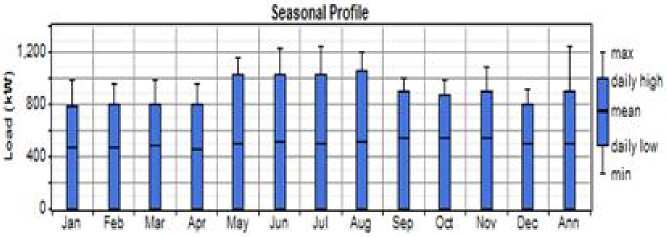

Figure 8. Monthly load profiles for total load.

With this load profile and all the cost data of the components with their sizes discussed earlier, 16 feasible systems were found. The 3 cheapest systems are compared here, as shown in Table 6.

7.2.1. Grid-, wind-, and diesel-based system

System 3 comprised three 250-kW wind turbines, a 256-kW diesel generator, and 500 kW from the grid, which is same for all the system combinations. Supply from the grid contributed 61% to the total system generation on a yearly basis. The share of the wind turbine and diesel generator was 26% and 13%, respectively.

7.2.2. Grid-, PV-, wind-, and diesel-based system

In system 4, 10-kW PV panels were used with a converter. The energy produced by the PV system was 0.36% and that of the diesel generator was 12.64%. The rest of the system was the same as discussed previously (system 3), but these small changes in the system configuration greatly impacted the cost.

7.2.3. Grid-, PV-, wind-, diesel-, and battery-based system

System 5 considered batteries as well the other energy sources. Inclusion of batteries increased the PV penetration in the system from 0.36% to 1%, whereas the wind turbines contributed 25% and the diesel generator contributed 14%. Supply from the grid was 60% in this configuration.

Table 6. Optimization results for grid connected system.

Parameters	*System 3	*System 4	*System 5
COE, $/kWh	0.191	0.191	0.197
Initial capital, $	1,575,000	1,622,000	1,674,000
Operation cost, $	699,726	697,870	720,263
Total NPC, $	10,519,850	10,543,115	10,881,372
Fuel, L/year	234,405	233,209	253,646
Diesel gen, h/year	3867	3852	4370
Grid, %	61	61	60
PV, %	-	0.36	1
Wind, %	26	26	25
Diesel, %	13	12.64	14

*System 3: 500 kW from grid + three 250-kW wind turbines + one 256-kW diesel generator.

*System 4: 500 kW from grid +10-kW PV panels + three 250-kW wind turbines + one 256-kW diesel generator + 10-kW converter.

*System 5: 500 kW from grid + 20-kW PV panels + three 250-kW wind turbines + one 256-kW diesel generator + 10 batteries + 10-kW converter.

Findings:

1. System 3 offered the lowest capital cost, NPC, and O&M cost when compared with system 4 and system 5, but its COE was the same as that of system 4. The COE per kWh for each energy system was the same as described in Table 4.
2. The overall optimization results also included a system with 2 diesel generators facilitating the supply from grid to meet the load. However, the O&M cost and the COE for this combination were very high; therefore, it was not considered in the discussion.
3. System 4 had the same COE as system 3 because the penetration of PV panels decreased the diesel generator operating hours and, as a result, fuel cost was reduced.
4. From the optimization results, it can be seen that system 5 was the most expensive of all, due to the increase in the size of the PV system from 10 kW to 20 kW.
5. On the basis of COE and other mentioned costs, it is clear that system 3 was the most cost-effective option when the site was connected to the grid.

7.3. Completely relying on a renewable energy system

Since from the above two cases, it can be seen that the load demand of the selected site is very high, it is impossible to serve the area while relying completely on wind–solar systems. In order to meet the load requirements, the proposed hybrid system must be run with the existing diesel system or supply from the local grid station.

8. Conclusion

In this paper, a wind–solar hybrid system was proposed to integrate with a diesel power plant of a local site in Taxila, Pakistan. After investigating different case studies, it was concluded that the initial capital cost of the proposed renewable energy system is high but it offers the lowest COE per kWh compared to the existing diesel system. For load-shedding hours, a PV/wind/diesel system is suggested, which costs $0.42/kWh. In the second case, 3 system configurations were investigated when the site is connected to the grid. The combination with diesel, wind, and grid was found to be more feasible. The COE for this case is $0.191/kWh, which was the most economical system configuration. For the off-grid case, it was observed that completely depending on the hybrid energy system was not possible due to excessive load demand. Hybrid energy systems present many benefits, including reduced COE and O&M costs, and negligible environmental effects as compared to traditional systems. Since these systems are dispersed, energy demand at local and regional level can be met with more resiliency and reduced losses.

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