Journal of Fundamental and Applied Sciences

ISSN 1112-9867

Available online at http://www.jfas.info

Research Article

Special Issue

OPTIMAL DESIGN AND TECHNO-ECONOMIC ANALYSIS OF HYBRID SYSTEM FOR A REMOTE VILLAGE

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Published online: 22 March 2018

ABSTRACT

This paper describes a standalone hybrid renewable energy system (HRES) design for Al-Faowar village located at West Libya. The hybrid system comprises of Photovoltaic (PV), wind turbines, diesel generators and battery storage system. The system was designed to meet the primary load of 170 households, three commercial and government buildings, one school; and one mosque in the village. Numerous combinations of the hybrid system were assessed in HOMER to find the optimal combination based on the Net Present Cost (NPC) alongside Carbon Dioxide (CO2) emissions. The results of the most optimal hybrid system combinations for Al-Faowar village was 6,000 kW of PV system, 3,750 kW of wind power system, 500 kW of diesel generator and 1,900 Ah of battery storage system. The proposed hybrid system in this study shows promising results that capable to meet the load demand via renewable energy generations with minimal diesel generator running time.

Keywords: Hybrid system, Techno-economic analysis, HOMER, PV-Wind-Diesel-Battery.

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doi: http://dx.doi.org/10.4314/jfas.v10i5s.34

1. INTRODUCTION

The combination of conventional and renewable sources is known as a hybrid power system and considered as the best solution for supplying electricity at remote areas. These renewable power sources capable to minimize the usage of fossil fuels in the areas leading to sustainable development and reliable electricity supply. The role of battery storage system is to deliver electricity to consumer when the renewable sources unable to meet the load demand due to intermittent resources. The PV, wind turbines, and diesel generator system complement each other in the hybrid system to meet the load demand. Moreover, the combination of PV and wind system in the remote area is the best option when there are abundance of solar radiation and consistent high wind speed. However, these renewable sources are not exploited in Libya, due to the lack of research and exposure into the hybrid technologies. On the other hand, the utility company in Libya unable to generate power to meet the load demand, hence, load shedding has been implemented to solve the power issue. Power outages also were increased during the periods of peak demand such as in winter and summer when there is high demand for heating and cooling. Furthermore, load shedding frequency was increased, especially after the Libyan revolution in 2011 due to damaged transmission lines and power plant. Moreover, the load demand in Libya has increased over the past few years for several reasons such as rapid population growth and new infrastructures. Additionally, the electricity for the man-made water project designed to transport the water from the SaharaDesert in the south of the country by underground pipe to the coastal cities are supplied by the existing power plant. Due to these problems, the Libyan grid has a deficit in generation which ranges between 1,000 to 1,200 MW according to seasons and load demand [1]. Therefore, this study is aimed to provide Libya with hybrid energy system to overcome the energy issue in the country. This study also aims to assess the ability of PV and wind turbines as the main power source, with a backup system from diesel generator and battery storage in HOMER for Al-Faowar village in Libya. Several crucial parameters were taken into consideration such as renewable resources availability and the project cost where HOMER make decision on the optimal hybrid system configuration [2-3]. Firstly, HOMER software defines the specific arrangement of the system components in terms of component sizing and operating scheme to perform over a project lifecycle. Then, HOMER will rank the system configuration output in a based on their total net present cost [4]. Finally, it determines the optimal value hybrid system to meet the load demand. Typical input data for the system are load demand, solar radiation, wind speed, as well as the initial cost of each system component. The results achieved from this research will be used to overcome the outage problem and improve the Libyan energy sector through the usage of hybrid renewable energy system. Many research studies were found to use hybrid system to solve energy issue in rural areas. In [5], the author used HOMER to obtain optimal combination of a hybrid system comprises of 0.05 to 0.4 kW PV array, 0.4 kW wind turbine, a power converter of 1.5 kW, and batteries with 200 Ah capacity. The results showed that the initial cost is $ 3,455, the cost of operating is 69 $/yr, with a cost of energy (COE) of 1.74 $/kWh, and NPC of $ 4,251. Meanwhile, M. R. B Khan et al. used HOMER to carry out a techno-economic analysis for a hybrid energy system to supply electricity for Tioman Island in Malaysia [6]. The system consists of a PV,wind, micro-hydropower and diesel generator system. The obtained results show that the best combination is a hydropower-diesel generator system, with $ 34,588,928 of a total NPC, COE of 0.154 $/kWh and a renewable fraction of 88 %. Moreover, Shaahid et al. performed the technical and economic analysis of a hybrid power system consists of diesel / solar PV using HOMER; the COE was found to be 0.170 $/kWh, and the hybrid system decreased the carbon emissions by about 24 % as compared to the diesel-only option [7]. There was also research found related to hybrid system design for a location in Libya. For example, Glaisa et al. uses HOMER to meed the load demand of a school in Libya [8]. The results indicated that the most feasible power system economically is 1 kW of PV, 20 kW of wind turbine, 1 kW battery, with 0.25 $/kWh of COE. There were also other studies related to optimal hybrid system design awhere hybrid system were proposed to reduce diesel fuel consumptions in Bangladesh, Egypt and Myanmar [9-11].

2. RESEARCH METHOD

The selected site is a village named Al-Faowar in Libya. It is in the western mountains at 31^{o} 844’ latitude and 13^{o} 989’ longitude. The village comprises of 170 households, with population of 1,020 people. The village has only one primary and secondary school, three commercial and government buildings and one mosque. The selected site for this study is Al-Faowar in Libya. It is in the western mountains at 31^{o} 844’ latitude and 13^{o} 989’ longitude.

The village comprises of 170 households, with population of 1,020 people. The village has one school; three commercial and government buildings; and one mosque. Al-Faowar village selected since it resembles typical load demand of many small villages in Libya. Hybrid Optimization Model for Electrical Renewable (HOMER) was utilized to find the optimal hybrid system combinations in this study due to several advantages. For instance, HOMER capable to simulate real-life renewable generations alongside conventions generations such as diesel and provide detailed results comprising both techno-economic and sensitivity analysis.HOMER was used to model and simulate the hybrid system that comprises of PV, wind, diesel generator and battery storage system. HOMER executes a simulation and optimization process based on the input data, such as solar radiation, wind speed, and load demand, which were estimated through the location to determine the system configuration and then ranked by NPC.

2.1Wind speed

The monthly rate of wind speed (m/s) at 50-meter height is 5.01 m/s based on the data collected from 1995 to 2005 by NASA Surface Meteorology and Solar Energy. Figure 1 shows that the maximum wind speed is 5.56 m/s in May, while the minimum wind speed is 4.67 m/s in November [12].

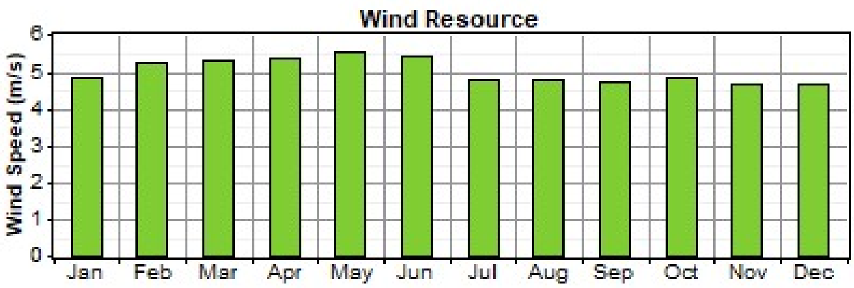

Fig.1. Monthly average wind speed

2.2 Solar radiation

Figure 2 illustrates the average solar radiation of the village from 1983-2005 with average solar radiation of 5.28 kWh/m^2/d, maximum solar radiation of 8.00 kWh/m^2/d in July, and a minimum of 2.46 kWh/m^2/d solar radiation in December [12].

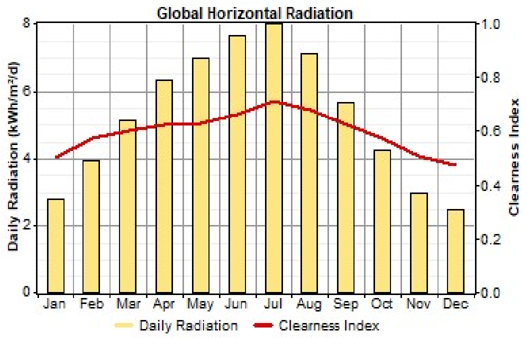

Fig.2. Monthly solar radiation

2.3Load Demand

The load for the village was estimated through typical energy consumptions of each houses; schools; commercial and government building and mosque in a daily basis [13]. It is found that the average load is 607 kW, while the peak demand is 856.150 kW taking place at 6:00 PM to 7:00 PM. Figure 3 shows the daily load profile of the village in January (winter season) that has the highest demand throughout the year. HOMER uses the input data and produces load profile that represent actual load profile of the village.

Fig.3. Daily load demand profile

2.4 Hybrid System Design

The system design consists of PV and wind system as primary renewable sources to produce the electricity for the village, with diesel generator and battery storage as a back up power sources. Figure 4 shows the proposed hybrid system configuration in HOMER.

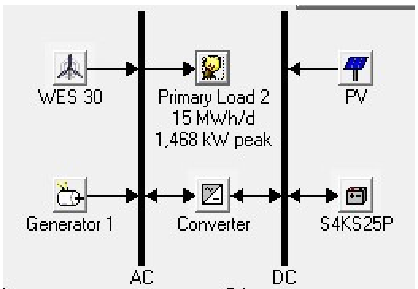

Fig.4. Hybrid system configuration using HOMER

2.5. Wind System

The type of wind turbine used for this simulation is the WES 30 with 250 kW rated power, 2-bladed upwind turbine, asynchronous generator and a rotor diameter of 30 m. The number of wind turbines considered is 0 - 30 by range step of 5 units. The wind power curve of the WES 30 is shown in Figure 5. The technical and economic specification of the wind turbine illustrated in Table 1.

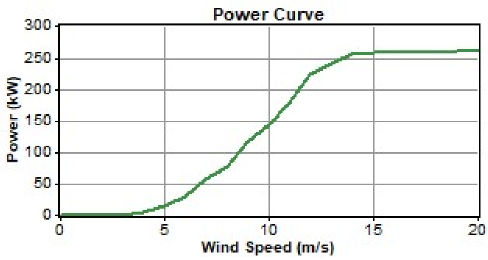

Fig.5. Wind turbine power curve

The estimated capital cost of a wind turbine was 750 $/kW [14]. The cost reduction for a wind turbine is around 12% between 2015 and 2025, which leads to replacement cost to be $165,000 [14]. The cost of operation and maintenance is 50 $/kW per year [15].

Table 1. Technical and economic details of the wind turbine [14]

Description	**Specification**
Manufacturer	WindEnergy Solution
Rated power	250 kW
Rotor diameter	30 M
Hub hight	50 M
Lifetime	20 years
Nominal voltage	230/400 V (AC)
Cut out wind speed	25 M/sec
Cut in wind speed	< 3 M/sec
Rated wind speed	13 M/sec
Capital Cost	$187,500
Replacement Cost	$156,000
O&M Cost	12,500 $/year

2.6. PV System

The initial and replacement cost of a PV are 1810 $/kW, 790 $/kW, respectively, while the operation and maintenance cost are 14 $/yr based on the Q1 2016 National Renewable Energy Laboratory (NREL) report [16]. The PV sizes ranges from 0 to 7,500 kW with a range step of 500 kW with no tracking system. The PV modules rated power is 327 W with lifetime of 20 years. The specifications of the PV modules are shown in Table 2.

Table 2. Specification of solar PV array [17]

Description	**Specification**
Manufacturer	Sun power
Solar Cells	Monocrystalline Maxeon
Module Number	SPR-E20-327
Nominal Power	327W
Average Panel Efficiency	20.4%
Rated Voltage (Vmpp)	54.7 V
Rated Current (Impp)	5.98 A
Open-Circuit Voltage (Voc)	64.9 V
Short-Circuit Current (Isc)	6.46 A
Max. System Voltage	600 V
Capital Cost	1,810 $/kW
Replacement Cost	790 $/kW
O&M Cost	14 $/year

2.7. Diesel Generator

The selected diesel generator for the hybrid system is Caterpillar C18 [18]. The proposed capacity is 500 kW to 6,000 kW by range steps of 500 kW with 15,000 hours of lifetime. The price of diesel fuel in Libya was $ 0.25 in the 1990s, but it dropped at the beginning of 2002 to $ 0.1 and has remained stagnant to this day [19]. Figure 6 shows the fuel curve diagram, which describes the fuel consumption of the generator to generate electricity. The hourly fuel consumption was calculated using Equation 1 [19], [20]:

where:

$$\mathbf{F} = \mathbf{F_0 P_{gen}} + \mathbf{F_1 g_{gen}} \quad \text{Equation 1}$$

F is the diesel generator consumption of fuel in L/hr.

F_0 is the intercept coefficient = 0.08 (L/kWh).

P_(gen)is the nominal generator capacity (kW)

F_1 is the fuel curve slope = 0.25 (L/kWh).

g_(gen)is the generator output in (kW).

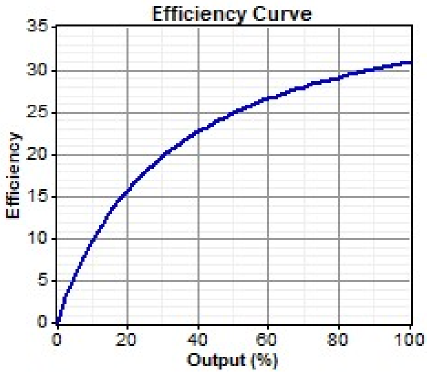

Fig.6. Fuel curve diagram

The technical and cost specifications of the selected diesel generator are indicated in Table 3 below:

Table 3. Diesel generator specification [18]

Description	Specification
Manufacturer	Caterpillar
Minimum Rating	500 kW
Maximum Rating	600 kW
Voltage	208-600 V
Frequency	60 Hz
Speed	1,800 RPM
Initial capital cost	$ 371
Replacement cost	$ 371
O &M cost	$ 1.77/hr

2.8. Battery Storage

The storage battery selected in this proposed hybrid system is the Surrette 4KS25P, with a rated capacity of 1,900 Ah and 4 V rated voltage. The amount of energy stored for one battery is 10.949 kWh. The initial cost of the battery is $ 1,295 per unit, with $ 1,295 of a replacement cost, and the operation and maintenance cost are 10 $/year [21-22].

2.9. Power converter

The selected converter has a size step range of 1,000 kW, from 0 kW to 5,000 kW, with an efficiency of 90%. The converter's initial cost is 1,000 $/kW based on the National Renewable Energy Laboratory report Q1 2015 with lifetime of 15 years [23]. The cost for a converter could fall by 39 % between 2015 and 2025 and based on that the replacement cost is 610 $/kW [15].

3. RESULTS AND ANALYSIS

HOMER simulates possible hybrid system combinations and ranked from the most optimal to the least optimal results based on NPC while meeting the electricity load demand.

3.1. Optimisation results

The optimal hybrid system combinations for a fuel price of 0. 1 $/L using the HOMER software are listed in Figure 7. The most cost-efficient hybrid system consists of a solar PV with a capacity of 6,000 kW, 15 wind turbines with a total power of 3,750 kW, 500 kW of a diesel generator, a power converter with a capacity of 1,500 kW, and 6,000 batteries with a capacity of 1,900 Ah each.

PV (kW)	WES30	CAT (kW)	S4KS25P	Conv. (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Diesel (L)	CAT (hrs)
6000	15	500	6000	1500	$ 23,128,000	978,084	$ 35,631,200	0.524	0.98	81,458	525
6000		1000	8000	1500	$ 23,091,000	1,059,238	$ 36,631,616	0.539	0.96	140,023	424
6000	30		8000	1500	$ 28,345,000	1,046,202	$ 41,718,976	0.614	1.00		
7000			14000	1500	$ 32,300,000	1,014,499	$ 45,268,708	0.666	1.00		
	30	1000	4000	1000	$ 12,176,000	4,296,429	$ 67,098,784	0.987	0.58	1,140,285	3,374
		1000	2000	1000	$ 3,961,000	6,890,079	$ 92,039,336	1.354	0.00	2,175,126	6,310
6000	30	1500		1500	$ 18,541,500	8,311,589	$ 124,791,4...	1.835	0.83	1,480,114	4,918
7500		1500		1500	$ 15,631,500	8,649,412	$ 126,200,0...	1.856	0.78	1,709,865	5,382
	30	1500			$ 6,181,500	12,178,099	$ 161,858,4...	2.381	0.50	2,200,421	7,426
		1500			$ 556,500	13,877,772	$ 177,961,0...	2.617	0.00	2,734,354	8,759

Fig.7. Categorized optimization results for diesel price of 0.1 $/L

3.2. Cash flow summary results

As shown in Figure 8 and Table 4, the total NPC is $ 35,631.204, the initial cost is $ 23,128.000, the operating and maintenance cost is $ 7,633,586 and the COE is 0.524 $/kWh. The highest component cost contributed by the battery storage system which is $12,657,947 that represents 36 % of the total system NPC. This is due to high cost and capacity of the batteries. The second highest component cost is the PV system, which represents 33 % with a cost of $ 11,933,802. The wind turbines have the third highest cost with $ 5,548,594 representing 16 % of the total NPC. Meanwhile, the diesel generator has $3,680,128 NPC followed by converter which represents around 5% with capital cost of $1,810,733.

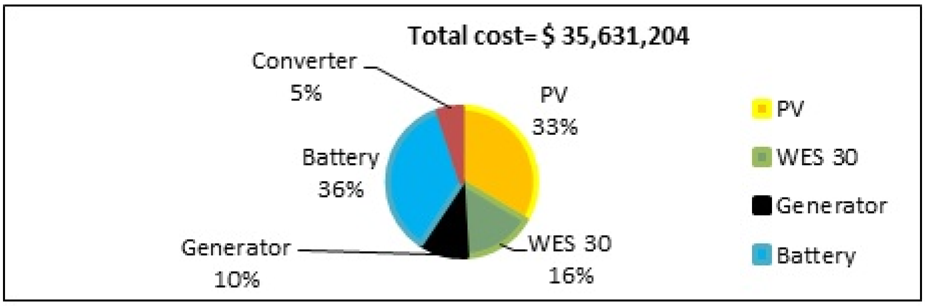

Fig.8. Hybrid systemNPC

Table 4. Cash flow summary

Component	Initial cost ($)	O&M ($)	Salvage ($)	Fuel ($)	Replacement ($)	Total ($)
PV	10,860,000	1,073,802	0	0	0	11,933,802
Wind	2,812,500	2,396,881	-432,504	0	771,718	5,548,594
Diesel Gen.	185,500	3,395,900	-5,403	104,131	0	3,680,128
Battery	7,770,000	767,002	-1,659,535	0	5,780,480	12,657,947
Converter	1,500,000	0	-71,065	0	381,798	1,810,733
Overall System	23,128,000	7,633,586	-2,168,507	104,131	6,933,996	35,631,204

3.3. Energy production results

Figure 9 refers to the monthly average of the electric production for the hybrid system with total electricity production which of 12,444,410 kWh/yr. The results indicate that the electricity produced by the PV contributes 80 % of total power generation with 10,011,731 kWh/yr. Meanwhile, the wind turbines produce 18% of power generation with 2,211,848 kWh/yr. Finally, the diesel generator has 220,832 kWh/yr of power generation which represents 2 %. of the total electricity productio. The excess electricity is 5,996,823 kWh/yr, representing 48.2 %, and the small capacity of the unsatisfied load is estimated at 1,163 kWh /yr, which represents 0.009 % of the total energy produced.

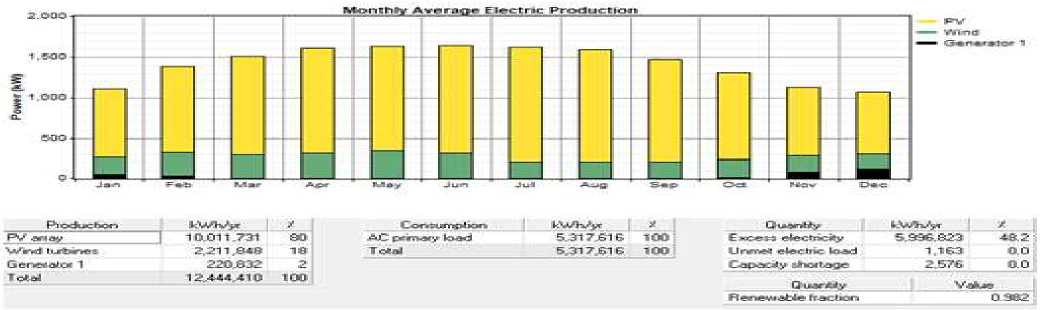

Fig.9. Monthly average electric production

Figure 10 demonstrates the monthly average unmet load of the system. The unmet electrical load is about 125 kW during February, and in December with less than 400 kW.

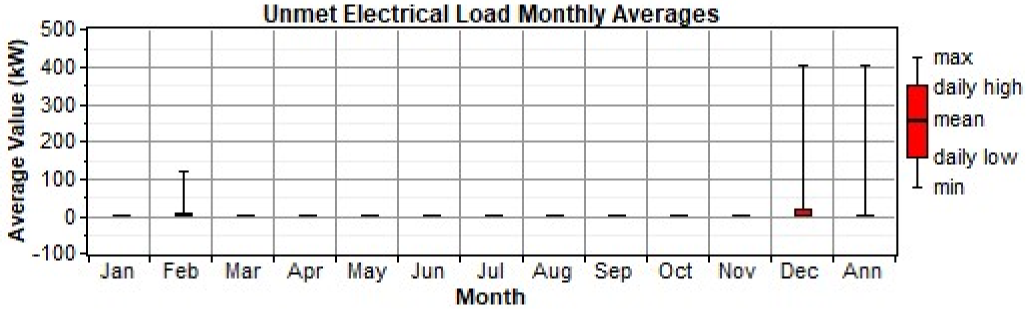

Fig.10. Monthly unmet electrical load

3.4. Sensitivity Analysis

Figure 11 presents the effect of diesel price variation on the COE which of the hybrid system. A decrease in diesel price from 0.25 $/L to 0.1 $/L leads to a reduction in the COE of 0.38%, from 0.526 $/kWh to 0.524 $/kWh. The changes also reduce 0.43% of the total NPC from $ 35,787,396 to $ 35,631,200. The operational cost also has 1.2% decrement from $ 990,303 to $ 978,084. These percentages are small and can be neglected because they are no significant changes in the overall system cost. The operational time of the diesel generator also decreased to 525 hr/yr, which contributes 6% of the operational time throughout the year.

Diesel ($/L)	PV (kW)	WES30	CAT (kW)	S4KS25P	Conv. (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Diesel (L)	CAT (hrs)
0.100	6000	15	500	6000	1500	$ 23,128,000	978,084	$ 35,631,200	0.524	0.98	81,458	525
0.250	6000	15	500	6000	1500	$ 23,128,000	990,303	$ 35,787,396	0.526	0.98	81,458	525

Fig.11. Sensitivity analysis results of different diesel prices

4. CONCLUSION

In this paper, the most optimal hybrid system components for Al-Faowar village are 6,000 kW PV, 15-unit 3,750 kW wind turbines, 500 kW diesel generator, 6,000 units S4KSP25 batteries, and 1,500 kW power converter. The primary goal of the hybrid system is to supply electricity for the village located with minimal cost and low CO2 emission. In conclusion, this study shows the possibility of exploiting renewable energy system to generate electricity in Libya, due to shortage of electricity from the utility company. Moreover, the fluctuations of diesel fuel prices simulated in HOMER show no significant changes in the optimal system configuration and total NPC. Therefore, this system will exhibit optimal generations despite diesel fuel fluctuations in the future.

5. ACKNOWLEDGEMENTS

The author would like to thank Universiti Tenaga Nasional for supporting this research under UNIIG 2017 (J510050687).

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How to cite this article:
Abdullah Ali Yosof M Abodwair, Jagadeesh Pasupuleti and M. Reyasudin Basir Khan.Optimal Design and Techno-Economic Analysis of Hybrid System for A Remote Village. J. Fundam. Appl. Sci., 2018, *10(5S), 411-425.*