Techno-Economic Feasibility of a Hybrid Solar Photovoltaic and Wind Power System for Yanbu, Saudi Arabia

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ABSTRACT

Energy from renewable sources is being increasingly exploited for meeting the power demands and reducing the harmful impact of burning the fossil fuels on the environment. Solar photovoltaic and wind turbine are being incorporated with the conventional diesel generator to reduce the fuel consumption. Saudi Arabia, being a country with high intensity of solar radiation, has good potential of using solar PV system. In this study, a solar wind hybrid system is modeled using HOMER to find an optimum system to meet the load requirement of a community at Yanbu city. The primary load of the community of 500 people is 556 kWh/day with 68 kW peak. The analysis showed that 200 kW PV system is the most economically feasible to meet the proposed demand and the minimum cost of energy for this system is 0.617 $/kWh. Sensitivity analysis was carried out by varying average wind speed and solar radiation and is presented in this study.

1. INTRODUCTION

The share of fossil fuel in the primary energy consumption in recent times is almost 86% and is further increasing gradually with the industrialization (Petroleum 2015; Matsuo *et al*. 2013). This high usage of fossil fuel results in increased the amount of greenhouse gas emissions. Around 34.7 billion tons of CO_2 has been emitted in 2014 and is expected to increase by 85% within 2030 (Dudley 2013; Outlook 2013; Olivier *et al*. 2015). Incorporating renewable energy means reducing the consumption of conventional hence reducing greenhouse gas emissions. Transportation and power sectors are the major consumers of fossil fuels. Transportation sector mainly utilizes the petroleum products while coal and natural gas are used for electricity generation. There are still around two billion people around the world in different countries who are living in areas where the extension of grid electricity is not possible or is not cost efficient because of the dispersed nature of that area (Shaahid and El-Amin 2009). Diesel generator is the only option of power generation in such areas but it is expensive. Continuous supply of diesel to these remote and disperse areas is risky. Moreover, about 1.2 billion people worldwide are deprived of electricity (Rahman *et al*. 2016). However, to reduce the greenhouse gas emissions and to ensure power supply, renewable energy source with or without diesel generators is a viable option. This combination of different renewable energy and diesel generator with or without battery backup is known as a hybrid energy system and is being practiced for the last couple of years and is environmentally benign (Yang and Chengzhi 2009). This will reduce the fuel transport, storage and consumption resulting is a lower risk of fuel spills and increased engine life. Various combinations such as wind-PV diesel, wind-diesel, PV-diesel, wind-PV etc. are being used for electricity production.

Hybrid power systems are more reliable and cost efficient compared to stand alone PV, wind, or diesel power systems. PV wind system alone cannot supply power on a 24 hour basis due to unavailability of solar energy or wind continuously (Hansen 1998). Again, standalone diesel system is expensive and maintenance cost is high (Nayar *et al*. 1993). Therefore, diesel, PV, and wind energy systems can be used as a complimentary to each other. To ensure regular power supply and minimize the fluctuation; battery storage is also incorporated into the hybrid power systems (Chowdhury and Rahman 1988; De Almeida 1983). So, in order to reduce the greenhouse emission by 100%, the techno-economic analysis of a hybrid system without diesel engine system is also analyzed. Several authors have analyzed the techno-economic aspects of different hybrid power systems of different sizes. Rahman *et al*. (2016) evaluated the effect of diesel generator of the hybrid energy system on the cost of energy. In that study, they have developed seven scenarios and six of them were based on different renewable energy penetrations such as 100%, 80%, 65%, 50%, 35% and 21% and the last one was only diesel and battery system. The systems were set to meet the load requirement of 4.4 MW/day with a peak load of 772 kW. The study resulted in cost of energy of $1.48/kWh, $0.62/kWh, $0.54/kWh, $0.42/kWh, $0.39/kWh, $0.37/kWh and $0.36/kWh for 100%, 80%, 65%, 50%, 35%, 21% renewable energy and battery diesel generator system respectively. According to a study carried out by Kusakana and Vermak (2013), the cost of energy for a hybrid PV and wind system and PV, wind, and diesel only systems were $0.372/kWh, $0.393/kWh, $0.53/kWh and $1.34/kWh respectively. Shaahid and El-Amin (2009) performed a techno-economic analysis of a PV-diesel battery hybrid energy system designed for electrification of Kahfa, Saudi Arabia. The cost of generating energy from the hybrid system was found to be $0.17/kWh with 27% PV penetration. Also, Nandi and Ghosh (2010) studied the PV wind-battery hybrid system for Chittagong, Bangladesh. For 4.36 kWh/m^2/day of solar radiation and 3-5 m/s of wind speed the cost of generating energy was found to be $0.47/kWh with 53% wind energy penetration for 10% annual capacity shortage. This paper aims at analyzing the solar and wind data of Yanbu city and study the feasibility of a solar wind battery hybrid energy system to supply electricity to a community of 500 inhabitants in Yanbu.

2. RENEWABLE ENERGY AND HYBRID SYSTEM SETUP

Hybrid power system allows the different combination of PV, wind, battery and diesel engines. This benefit in establishing a system according to any sites available energy resources, cost and load demands. The hybrid renewable energy system considered in this study is a combination of wind, PV, battery and an inverter and it is designed to meet the load requirement of the community under investigation. The schematic diagram of the hybrid system used here is presented in Figure 1. The output from the Renewable Energy System (RES) being insufficient to meet the load requirement, the battery will discharge to meet the demand. On the other hand, if the

RES produces more than the required demand, the excess energy will be stored in the battery. In the case when the battery is full and output from RES is more than the required load demand, the energy will be dumped. The hybrid power optimization tool HOMER (Hybrid Optimization Model for Electric Renewable) has been used in this study to simulate the best size of the hybrid system and meet the certain demand of the city based upon the minimum net present cost and then the cost of generating energy is being evaluated for that selected sizing.

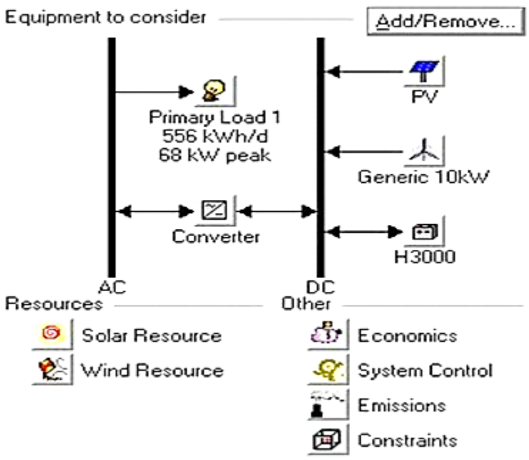


Fig. 1 Schematic diagram of the hybrid renewable energy system.

3. SIMULATION TOOLS

HOMER is a computer model developed by National Renewable Energy Laboratory (NREL) to design standalone renewable energy power systems (Lambert 2006). Both off grid and grid connected power systems can be designed by this sophisticated computer model for different applications. Based upon the inputs, given as technology options, components costs, and resource availability, the software simulates different system configurations, components combinations and generates the result of feasible configurations based on Net Present Cost (NPC). NPC is the representation of the life cycle cost of a system which takes into consideration all costs occurring within the project lifetime such as initial cost, replacement cost, operation and maintenance cost etc. and all of these are assumed to be increasing at the same rate over the years based on an annual real interest rate. The software also takes in to consideration the salvage value of all the components at the end of the lifetime. To analyze the effect of different factors on the cost effectiveness of different system configuration, this tool allows sensitivity analysis. The software simulates each system configuration over the range of the sensitivity variables which allows seeing the effect of changes of sensitivity variables on the simulation results.

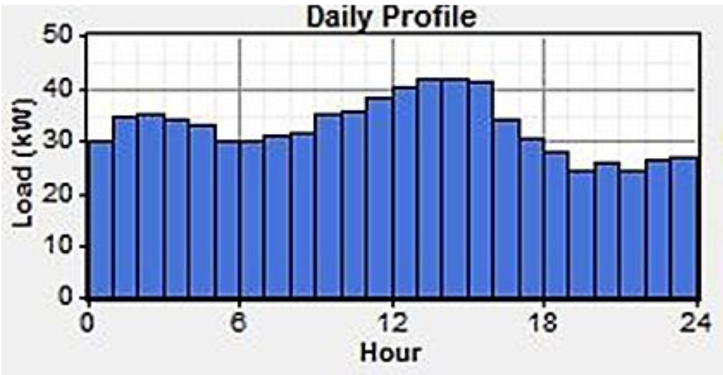
4. SITE SELECTION AND RESOURCE ASSESSMENT

4.1 Site selection and

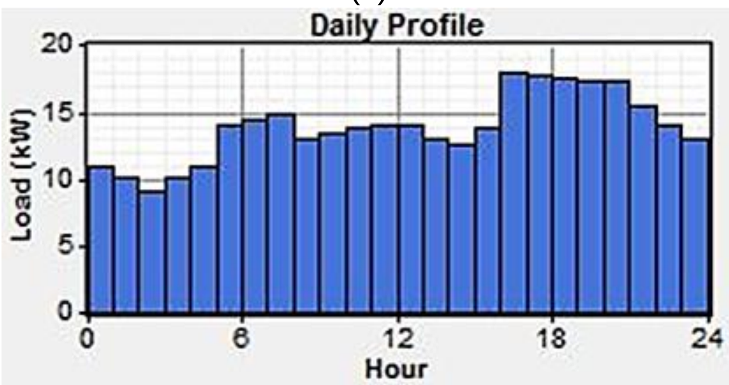
The site considered in this study is a community of Yanbu, a port city in the Al Madinah state of KSA. It is approximately 330 km northwest of Jeddah. Its geographical coordinates are 24°05′N 38°00′E. Being Yanbu a port city, it has good wind energy potential as well. The average temperature varies from 27.7°C in the month of January to 40.4°C in the month of August.

4.2 Load demand

The energy consumption of the community under consideration is 556 kWh/day with a peak load of 67.9 kW. The maximum value of load is assumed to be recorded as 42 kW in the summer months (April to September) between 14:00 and 15:00 hours. This high load is mainly due to high energy consumption by air conditioning, fan and refrigeration units. The minimum load of 9 kW is observed at 03:00 hours in winter months (October to December and January to March). The annual load factor is 0.341. The houses in the community are close to each other and hence distribution cost is neglected. The load demand for the typical summer and winter season are presented in Figure 2.



(a)



(b)

Fig. 2 (a) Typical summer day load demand for the community. (b) Typical winter day load demand for the community. (Shaahid and El-Amin 2009)

5. RENEWABLE ENERGY RESOURCES

HOMER can synthesize hourly solar radiation data for the whole year for any location using Graham algorithm, latitude, and monthly average values. The data generated in this way will not perfectly replicate the characteristics of solar radiation data of the area (Mondal and Denich 2010). In this study, the solar insolation data were taken from the NASA surface meteorology and solar energy database. Yearly average solar insolation for Yanbu city is 5.95 kWh/m^2/day. The average clearness index is 0.65. Figure 3 illustrates the monthly solar radiation and clearness index at Yanbu. During the summer months, solar radiation is higher compared to other months and hence higher energy yield is expected. The wind speed data were also taken from the NASA surface meteorology and solar energy database. These data were taken at a height 50m above the surface of the earth. The annual average and monthly peak wind speed are 4.74 and 5.4 m/s respectively. Wind speed is higher in the months of December to April compared to other months as shown in Figure 4. However, in this study wind speeds are varied from 4.5 to 7.5 m/s for sensitivity analysis. The parameters such as Weibull distribution factor, autocorrelation factor, diurnal pattern strength and the hours of peak wind speed were found to be 2, 0.85, 0.25 and 15 hours respectively.

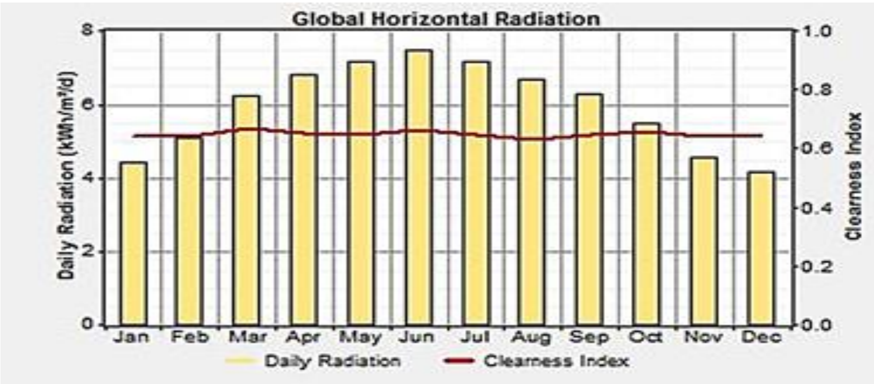


Fig. 3 Monthly solar radiation and clearness index at Yanbu.

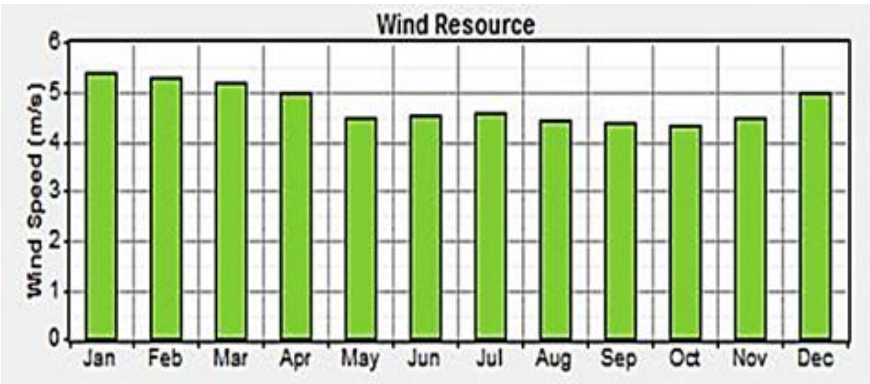


Fig. 4 Monthly average wind speeds variation during year at Yanbu.

6. HOMER SOFTWARE INPUT DATA

The hybrid system considered in this study consists of a PV array, wind turbine, battery and a converter for conversion of DC to AC. The details of these components are provided in the Tables 1, 2, 3 and 4 respectively. For PV modules and wind turbines the replacement cost is assumed to be 0 because the PV module and wind turbine lifetime are assumed to be 20 years which is same as the system lifetime. The slope of the PV module is taken as 24.2° and is allowed to vary from 5° to 40° for sensitivity analysis. For the wind energy a 'Generic 10 kW' wind turbine and 'Hoppecke 244 OPzS 3000' batteries are used. Generic 10 kW wind turbine power curve is shown in Figure 5. When calculating the present value of the components the software assumes that all prices increase at the same rate over the lifetime known as real interest rate rather than the nominal interest rate. This study considers real interest rate of 6% and the project lifetime as 20 years. The maximum annual capacity shortage and percentage of annual peak load are 0% and the percentage of hourly load, hourly solar output and hourly wind output are 10%.

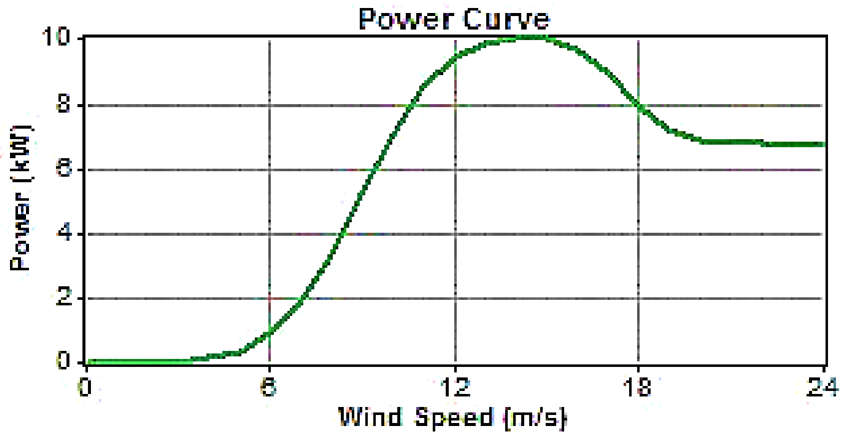


Fig. 5 Generic 10 kW wind turbine power curve.

7. RESULTS AND DISCUSSIONS

Several component configurations were simulated for finding the best renewable energy configuration. Search space showed the different sizing options of the different component for making a simulation as shown in Table 1.

Table 1. Search space optimization

PV Array, kW	Generic 10, Quantity	H300, Strings	Converter, kW
0	0	0	10
10	1	10	20
20	2	14	30
30	3	18	40
40	4	20	50
-	-	-	-
-	-	-	-
-	-	-	-
290	9	37	90
300	10	40	100

Sensitivity inputs of wind speed and slope of PV array are not shown in the search space. A total number of 4,139,520 alternatives consisting of 9,240 systems with 448 sensitivities were formed and consumed around 12 hours and 9 minutes computation time. The optimal system for the original case of 4.74 m/s wind speed and 24° PV array slope doesn't contain any wind turbine as shown in Figure 6. This is because of the poor wind energy resource compared to high solar energy potential. The effect of higher wind speed than the average, that has been used in the base case, is shown later in the sensitivity analysis. The optimal solution obtained here consists of a 200 kW PV, 350 batteries, and 80 kW converters. Hence, 100% of the energy demand is met by solar energy. Energy contribution of PV array is shown in Table 2 and the monthly average electricity production from PV is illustrated in Figure 6.

Table 2. PV energy contribution

Item Description	PV
Rated Capacity, kW	200
Capacity Factor, %	21.4
Mean output power, kW	42.8
Annual energy output, kWh/year	375,139
Annual hour of operation, hours	4401
Penetration, %	100

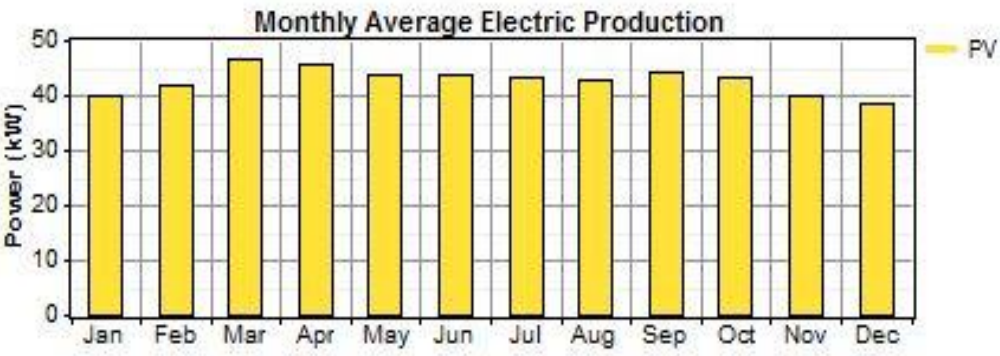


Fig. 6 Monthly average electric power production.

8. ECONOMIC ANALYSIS

The total cost of different component of the hybrid system is shown in Figure 8 and NPC of different component are shown in Figure 9. It is clear that most of the NPC is due to PV and the converter contributes the minimum NPC. Total NPC of the system is found to be 1,434,950$. Leveled cost of energy is estimated to be 0.617 $/kWh. The capital cost of the proposed system is 1,257,000$. The replacement cost, O & M cost and salvage value are found to be 30,043$, 162,043$ and -14,967$ respectively. The corresponding annualized value of the capital, replacement, O & M costs and salvage values are 109,591$, 2,619$, 14,200$ and -1,305$ respectively. Since no diesel generator has been used all fuel costs are zero.

9. CONCLUSIONS

This study was performed with a view to find an optimal wind-PV-battery hybrid power system to supply electricity to a community of Yanbu, a port city of KSA using HOMER. However, due to high solar energy intensity and poor wind resources at the site, the simulation results showed that a PV-battery power system is the best solution with cost of energy of 0.617$/kWh at an average solar radiation of 5.95 kWh/m^2/day and a wind speed of 4.74 m/s. From the sensitivity analysis, it is evident that if the wind speed is more than almost 5.75 m/s or if the solar radiation is 5.5 kWh/m2/day or less then the optimal system would be a wind-PV-battery hybrid system.

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