Renewable Energy 38 (2012) 258–268

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

Technical Note

Feasibility study of a wind–pv–diesel hybrid power system for a village

Shafiqur Rehman [a,b,*], Md. Mahbub Alam [b], J.P. Meyer [b], Luai M. Al-Hadhrami [a]

[a] Center for Engineering Research, Research Institute, King Fahd University for Petroleum and Minerals, Dhahran-31261, Saudi Arabia
[b] Mechanical and Aeronautical Engineering Department, University of Pretoria, Pretoria, South Africa

ARTICLE INFO

Article history:
Received 2 December 2010
Accepted 18 June 2011
Available online 31 July 2011

Keywords:
Renewable energy
Wind–pv–diesel hybrid system
Solar radiation
Wind
Solar
Saudi Arabia

ABSTRACT

A wind–pv–diesel hybrid power system has been designed for a village in Saudi Arabia which is presently powered by a diesel power plant consisting of eight diesel generating sets of 1,120 kW each. The study found a wind–pv–diesel hybrid power system with 35% renewable energy penetration (26% wind and 9% solar PV) to be the feasible system with cost of energy of 0.212 US$/kWh. The proposed system was comprised of 3 wind turbines each of 600 kW, 1000 kW of PV panels, and four diesel generating sets each of 1120 kW rated power. The system was able to meet the energy requirements (AC primary load of 17,043.4 MWh/y) of the village with 4.1% energy in excess. The annual contributions of wind, solar pv and the diesel generating sets were 4713.7, 1653.5, and 11,542.6 MWh, respectively. The proposed hybrid power system resulted in avoiding addition of 4976.8 tons of GHG equivalent of CO_2 gas in to the local atmosphere of the village and conservation of 10,824 barrels of fossil fuel annually.

1. Introduction

So for a safe globe and better life of all living beings on this planet new, clean and renewable sources of energy and related technologies are being sought, developed and implemented worldwide. These alternative sources of energy include wind, solar, geothermal, tidal, wave, and biofuels. The applications of these sources include the very small to large isolated, grid connected and hybrid power systems. Moreover, the hybrid power systems exhibit higher reliability and lower cost of generation than those that use only one source of energy [1,2]. A power generating system which combines two or more different sources of energy is called a hybrid system. The hybrid energy generating systems (such as wind–diesel, pv–diesel, wind–pv–diesel etc. with and without battery storage options) are not new technologies or systems rather existed in practice for the last two decades as mentioned by Yang et al. [3]. The authors have recommended an optimal design model for hybrid solar–wind system which employed battery banks to calculate the system's optimum configurations in China. In another study, Yang et al. [4] recommended an optimal sizing method to optimize the configurations of a hybrid solar–wind system with battery banks. The authors used a genetic algorithm (GA) to calculate the optimum system configuration that could achieve the customers required loss of power supply probability (LPSP) with minimum annualized cost of system (ACS).

Furthermore, small off-grid standalone hybrid power systems provide an important option for decreasing the electricity gap in remote areas of the developing and developed world, where progress in grid extension remains slower than population growth [5,6]. According to Celik [7], these small-scale systems though generate relatively little power but can significantly improve quality of life in remote areas [7]. Cavello and Grubb [8] stated that 1 kWh of electricity provides ten times more electricity services in India than in Indiana and further added that two small wind generators, which would supply only two homes with electric heating in the United States, could pump water for 4000 people in Morocco [8].

Recently, Dihrab and Sopian [9] proposed a hybrid power system to generate power for grid connected applications in three cities in Iraq. Results showed that it is possible for Iraq to use the solar and wind energy to generate enough power for villages in the desert and rural areas. Ekren et al. [10] designed and developed an optimum sizing procedure of wind–pv–diesel hybrid system for small applications in Turkey. Saheb-Koussa [11] designed a wind/pv/diesel hybrid energy system with battery backup and conducted its techno-economical feasibility for remote applications in Algeria. Their simulation results indicated that the hybrid system is the best option for all the sites considered, provided higher system performance than photovoltaic or wind alone systems, the reliability of

* Corresponding author. KFUPM Box 767, Dhahran-31261, Saudi Arabia. Tel.: +966 3 8603802, +966 502085496(mobile); fax: +966 3 8603996.
E-mail address: srehman@kfupm.edu.sa (S. Rehman).
URL: http://faculty.kfupm.edu.sa/ri/srehman

0960-1481/$ – see front matter
doi:10.1016/j.renene.2011.06.028

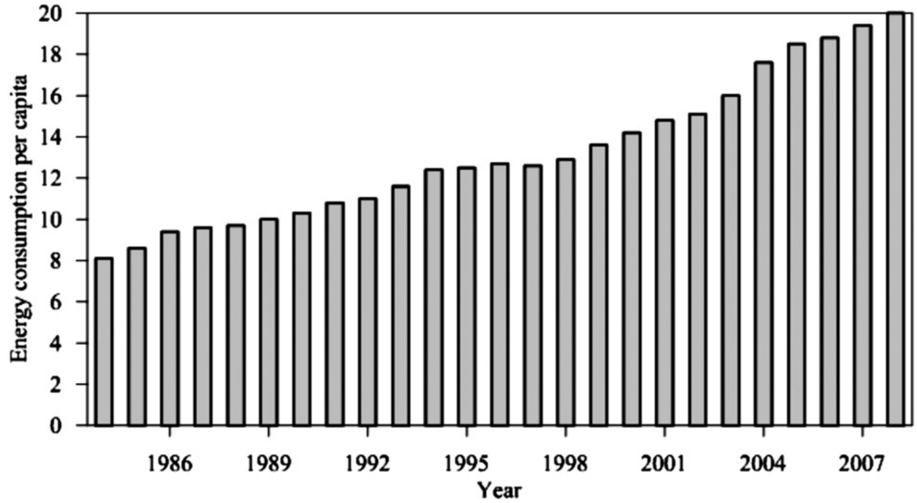

Fig. 1. Trend of per capita energy consumption in Saudi Arabia.

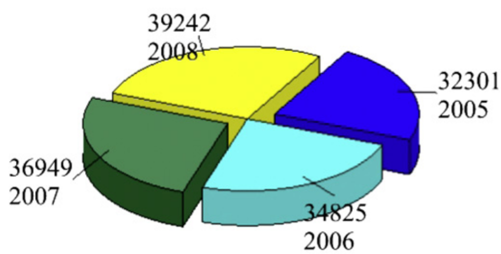

Fig. 2. Cumulative power installed capacity (MW) of Saudi Arabia.

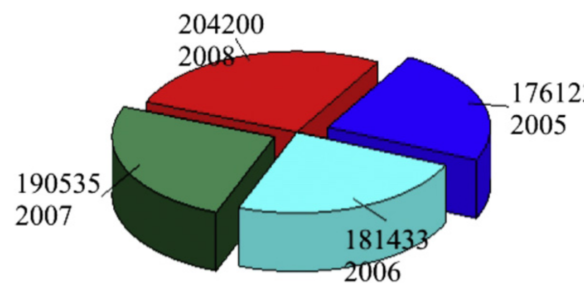

Fig. 4. Annual energy production (GWh) in Saudi Arabia.

the system enhanced, and finally it was revealed that the energy cost depends largely on the renewable energy potential. Nfah et al. [12]. studied a solar/diesel/battery hybrid power systems to meet the energy requirements of a typical rural household in the range 70–300 kWh/yr and found that a hybrid power system comprising a 1440 Wp solar pv array and a 5 kW single-phase generator operating at a load factor of 70%, could meet the required load.

Jose et al. [13] presented a comprehensive techno-economical analysis of wind–pv hybrid power system for the production of hydrogen and that the selling price of hydrogen produced by means of electrolysis should be high in order to recover the initial investment of a pv–wind system in a reasonable lapse of time (ten years). Arribas et al. [14] presented the guidelines suitable for long-term assessment hybrid power systems with different combinations and also for the assessment of components and of the short-term performance of the systems necessary at the actual stage of development. The study also recommended that, at least for demonstration projects, the monitoring activity should be used not only for long-term assessment, but also for the characterization of components and for the analysis of the system, in order to gain more understanding on hybrid systems. Sopian et al. [15] presented the performance of an integrated pv–wind hydrogen energy production system. Their system was capable of producing 130–140 ml/min of hydrogen, for an average global solar radiation and wind speed ranging between 200 and 800 W/m2 and 2.0 and 5.0 m/s, respectively.

To meet the energy requirement of seawater greenhouse in the Oman, Mahmoudi et al. [16] used hourly wind speed and solar radiation data and designed a wind-solar power system. Dufo-Lopez et al. [17], for the first time, presented a triple multi-objective design of isolated hybrid systems minimizing, simultaneously, the total cost throughout the useful life of the installation, pollutant emissions (CO_2) and unmet load. To achieve the task, the authors, used a multi-objective evolutionary algorithm (MOEA) and a genetic algorithm (GA) to find the best combination of

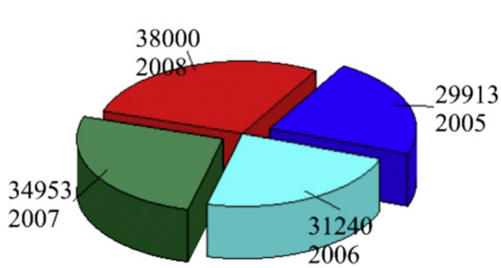

Fig. 3. Annual peak load (MW) of Saudi Arabia.

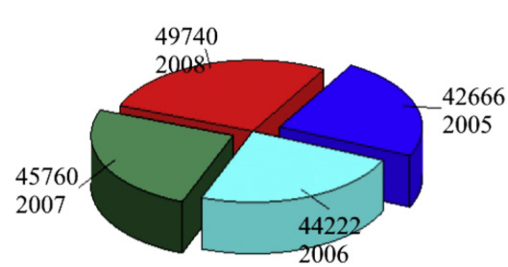

Fig. 5. Annual fuel consumed (Thousands TOE) in Saudi Arabia.

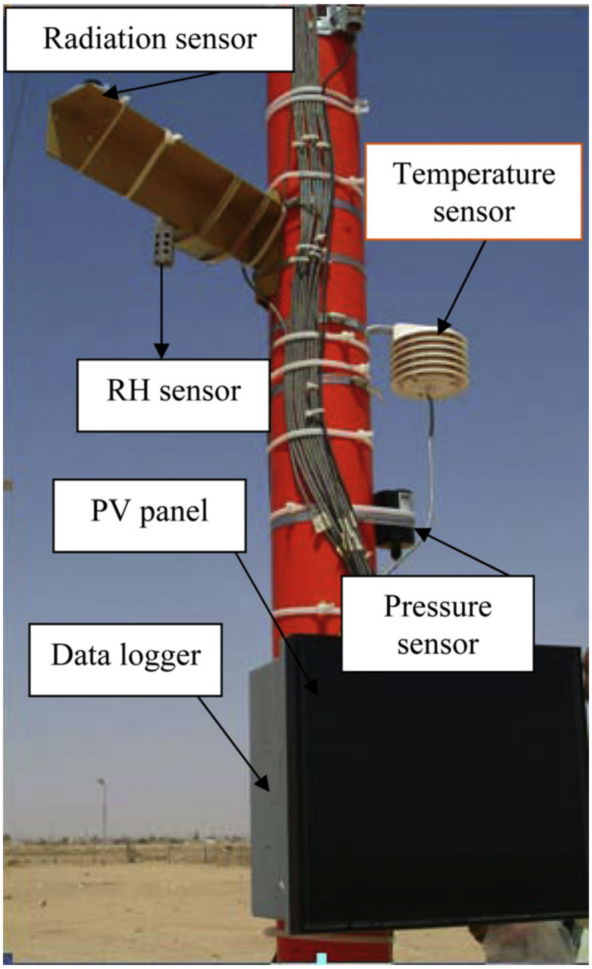

Fig. 6. Meteorological sensors used for measurements.

components of the hybrid system and control strategies. Shakya et al. [18] studied the feasibility of standalone hybrid wind–pv system incorporating compressed hydrogen gas storage in Australia. Tina et al. [19] assessed the long-term performance of a hybrid solar–wind power system for both standalone and grid connected applications.

Since Saudi Arabia is a huge country and there are small villages located in remote and hilly areas so the grid extension to populations living in such areas is neither cost effective nor feasible. In such situations decentralized renewable energy based power generating options can provide feasible alternatives options. These alternatives may include hybrid power systems like wind–pv–diesel, wind–diesel, pv–diesel and others with and without battery backup option. With continuous research and development efforts, it has been established that the hybrid systems, if optimized properly, are both cost effective and reliable compared to single power source systems. In this study, an attempt is made to design an optimal wind/pv/diesel hybrid power system for a village where the wind speed measurements were made at different heights using a 40 m tall tower and solar radiation along with other meteorological parameters. The main aim of the study is to reduce the diesel consumption and at the same time maintain a continuous supply of power to the inhabitants of the village.

2. Background

Saudi Arabia is a vast country with total area of 2,149,690 sq km and having international boundary of 4431 km (bordering countries: Iraq 814 km, Jordan 744 km, Kuwait 222 km, Oman 676 km, Qatar 60 km, UAE 457 km, Yemen 1458 km). Most of the cities and village are either connected with the national electrical grid or with the isolated grids. Most of the remotely located villages get power through diesel generating power plants. It is really cumbersome to maintain regular supply of fuel and to ensure the continuous electricity supply during breakdowns and scheduled shutdowns of the diesel units.

In Saudi Arabia, the per capita energy consumption has reached to 20 kWh/day in 2008 compared to 19.4 kWh/day in 2007 i.e. a net increase of 3.1% in one year [17], as shown in Fig. 1. A maximum of 10% increase in per capita energy was observed in 2004 compared to that in 2003. On an average over 25 years period from 1984 till 2008, 4.1% annual increase in per capita energy per day has been observed [17] which is really significant and needs to be addressed immediately. Moreover, the total installed capacity of the Kingdom in year 2005 was 32,301 MW which increased to 34,825 MW in 2006, an increase of 7.81% and then further increased by 6.1% and 6.21% in the years 2007 and 2008 compared to 2006 and 2007, respectively, as can be seen from Fig. 2. A jump of 11.89% (i.e. from 31,240 MW to 34,953 MW) was observed in peak load in year 2007

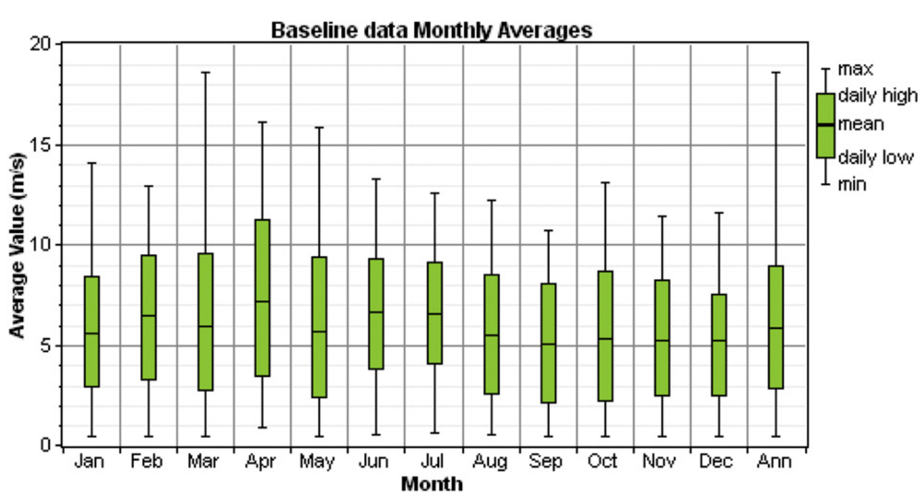

Fig. 7. Monthly mean and extreme wind speed at 40 m AGL.

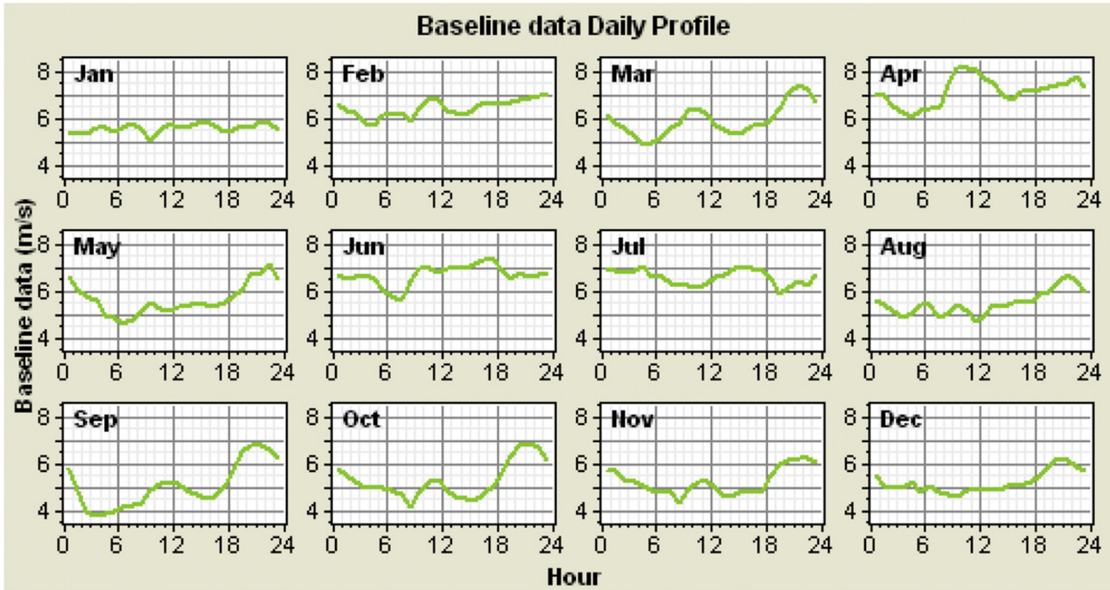

Fig. 8. Diurnal variation of hourly mean wind speed at 40 m AGL.

compared to that in 2006, as shown in Fig. 3. Again, in 2008, the peak load demand increased by another 8.72% which shows a continuous increasing trend in peak load.

The annual energy production (as shown in Fig. 4) from all conventional sources increased by 3.01%, 5.02% and 7.17% during 2006, 2007, and 2008 compared to 2005, 2006 and 2007, respectively. These numbers indicate a progressively increasing production of energy which is reflective of growing energy demands. The total fuel consumption reached 49,740 thousands TOE in year 2008 compared to that of 45,760 TOE in 2007, a net increase of 8.7%, as seen from Fig. 5. Around 3.5% increases were observed in the years 2007 and 2006 compared to those in 2005 and 2006, respectively. Kingdom of Saudi Arabia has vast open land and is the largest producer and supplier of fossil fuels in the world but still encouraging utilization of clean and renewable sources of energy.

3. Site and data description

The data collection site at Rawdat Ben Habbas village is an open area from all directions except a couple of warehouse shades and diesel storage tanks in the far vicinity of the wind mast. The meteorological data (wind speeds, wind direction, air temperature, relative humidity, surface station pressure, global solar radiation) were measured at Rawdat Ben Habbas village from 13th September 2005 till 18th November 2008. The global solar radiation data was measured using a pyranometer. The 40 m tall tower is shown in Fig. 6. The geographical coordinates of the data collection/proposed project site were 29° 8.282′ N latitude, 44° 19.817′ E longitude and 443 m altitudes above mean sea level.

3.1. Meteorological data

Data were scanned every 3 s and recorded by averaging every 10 min on a removable data storage card. The wind speed data were measured at 20, 30, and 40 m height above the ground. At each height two sensors were installed. The surface air temperature (°C), relative humidity (%), surface station pressure (mbar), and global solar radiation (GSR, W/m^2) data were also measured at 2 m above the ground surface. The monthly mean wind speed was always above 6 m/s at 40 m AGL except during September to November, as

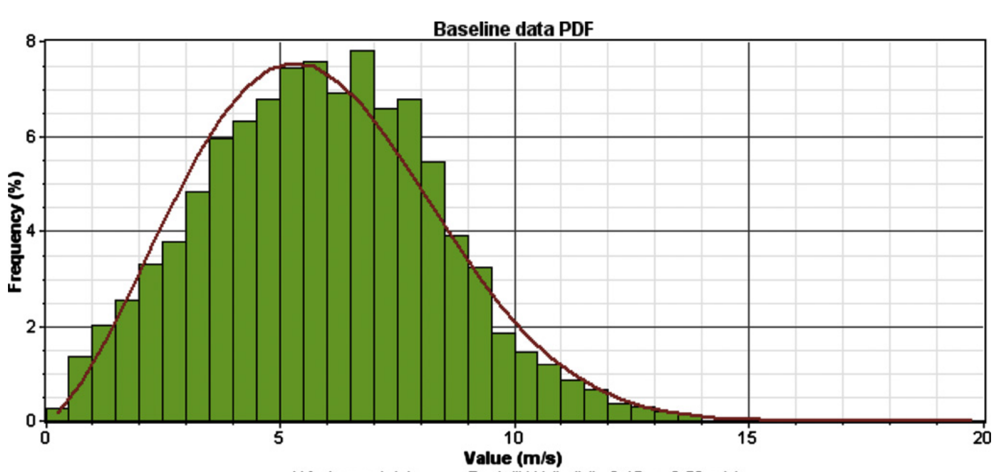

Fig. 9. Frequency distribution of wind speed at 40 m AGL.

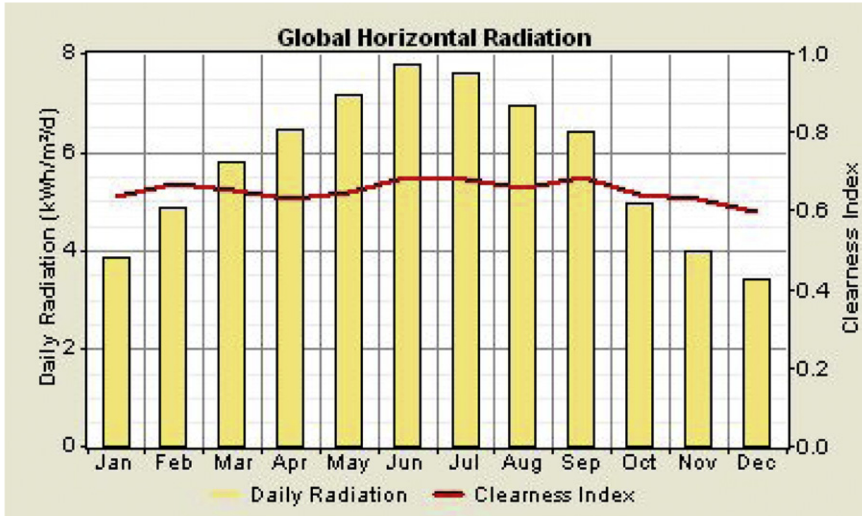

Fig. 10. Monthly mean daily global solar radiation at the site.

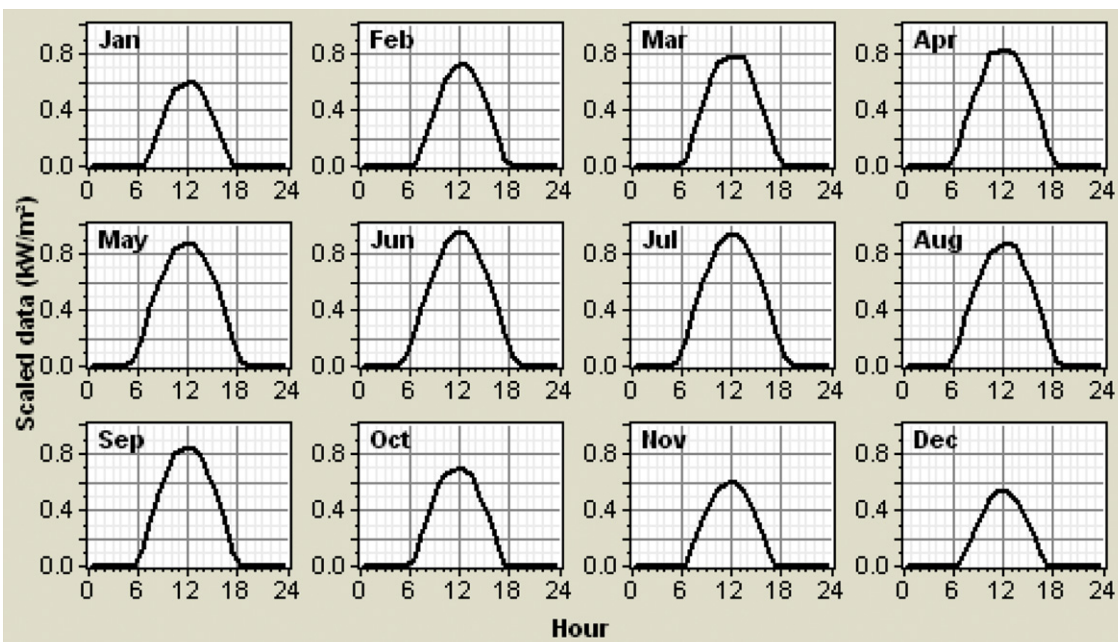

Fig. 11. Diurnal variation of global solar radiation during different months of the year.

shown in Fig. 7. The diurnal pattern of hourly mean wind speed in different months, especially during summer, coincides with the peak load demand of the village, as can be seen from Fig. 8. Furthermore, the frequency distribution of wind speed in different wind speed bins confirmed the availability of wind above 4 m/s at 40 m AGL for 76% of the time during the year, see Fig. 9. The monthly mean values of the GSR obtained using daily totals during each month are shown in Fig. 10. April to September higher radiation intensities were observed with highest in June and lowest in December. Similarly, the monthly average diurnal profiles of GSR showed peak intensity around 12 o'clock during all the months of the year as can be seen from Fig. 11.

3.2. Villageload data description

The hourly electrical load data for the year 2005 was obtained for the village and load analysis was performed. The maximum value of the load recorded was 4.370 MW and occurred on 14th July, 21st July, 31st July and 18th August 2005. The peak was recorded at 15:00 h. The annual load factor for this area was 0.45. However, the monthly load factor varied between 0.49 in April (low demand) and

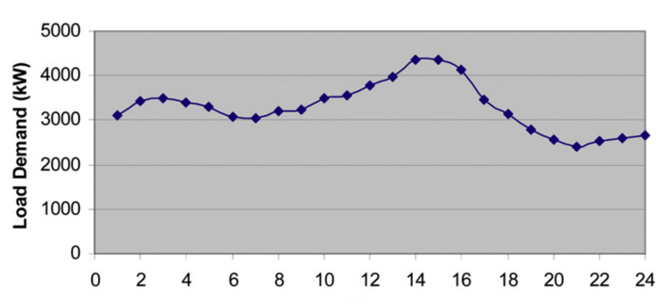

Fig. 12. Typical summer day load demand for the village (July 14, 2005).

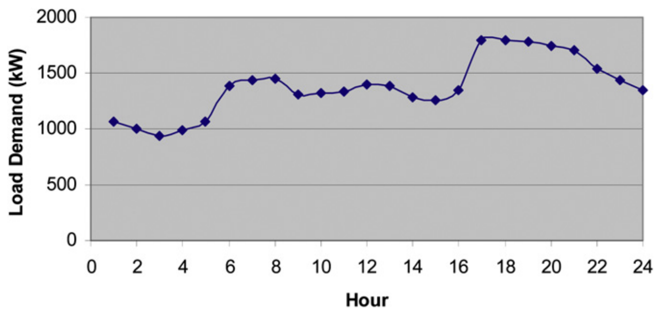

Fig. 13. Typical winter day load demand for the village (January 03, 2005).

0.71 in August (high demand). Fig. 12 shows the hourly load demand for the peak summer day (July 14, 2005). As evident from the graph, the demand increased during the day time due to higher air conditioning load. The average demand for the day was approximately 3.3 MW. The load variation for a typical winter week day (January 03, 2005) is shown in Fig. 13. As shown, the demand was much lower than the summer day. The peak value for the day was only 1.8 MW and was recorded in the evening. During January to February and November to December, the peak load appeared at around 18:00 h while two peaks were observed during March and April at 00:00 and 14:00 h, as shown in Fig. 14. From June to October the peak load was found to be around 14:00 with highest load of more than 4000 kW during the month of August.

4. Wind–pv–diesel hybrid power system

Hybrid power systems can consist of any combination of wind, photovoltaics, diesel, and batteries. Such flexibility has obvious advantages for customizing a system to a particular site's energy resources, costs, and load requirements. In the present case, a wind–pv–diesel hybrid power system and a power converter is used to design and meet the load requirements of the village under investigation. The schematic diagram of the wind–pv–diesel hybrid model used in this study is depicted in Fig. 15. The hybrid power system optimization tool HOMER [20] developed by NREL has been used in the present study and the details of the same are given in next paragraph.

4.1. HOMER software hybrid power system modeling tool

HOMER [20] is primarily an optimization software package which simulates varied renewable energy sources (RES) system configurations and scales them on the basis of net present cost (NPC) which is the total cost of installing and operating the system over its lifetime. Net present cost (NPC) represents the life cycle cost of the system. The calculation assesses all costs occurring within the project lifetime, including initial cost (IC), component replacements within the project lifetime, maintenance and fuel. HOMER assumes that all prices escalate at the same rate, and applies an 'annual real interest rate' rather than a 'nominal interest rate'. NPC estimation in HOMER also takes into account salvage costs, which is the residual value of power system components at the end of the project lifetime. Annual savings are estimated by subtracting the annualized costs for each supply method from each other, giving the overall saving or loss for each year. Year 0 will have a negative figure as the initial cost (IC) of the hybrid RES exceeds that of the grid-only system. Finally, the annual savings are cumulatively summed to provide the cash flow for the duration of the project. Published payback times for grid-connected small-scale systems range from 7 years (IC aided by large rebates) [21] to 11.2 years [22], 15 years [23] and as high as 30 years [24].

4.2. HOMER software input data

The main input data include the hourly mean wind speed, hourly total solar radiation and load data; technical specifications and cost data of diesel generators, wind turbines, photovoltaic modules, power converters; system controls; economic parameters; and system constraints. The details of solar radiation and load data has been given above in the preceding paragraphs and the values of remaining data are given below:

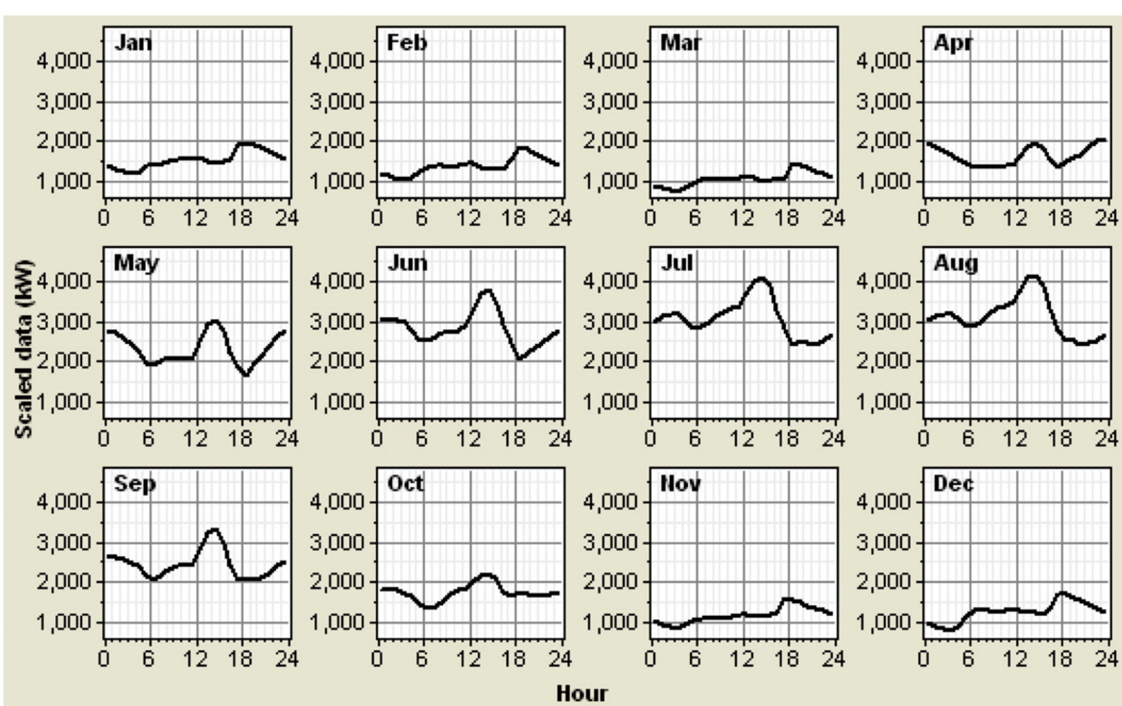

Fig. 14. Diurnal variation of load during different months of the year.

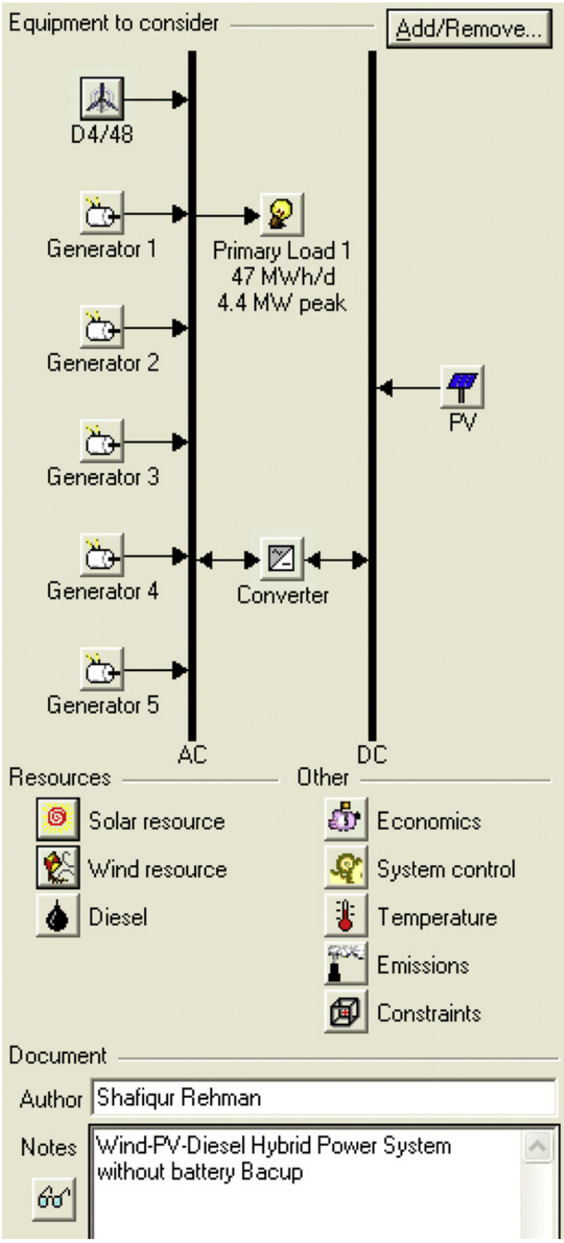

Fig. 15. Wind–pv–diesel hybrid model used in the study.

4.2.1. Control parameters

Minimum renewable energy fractions (MRF) considered = 0%, 20%, and 40%
Annual real interest rate = 6%
Plant working life span = 20 years
Diesel price considered (US$/l) = 0.2, 0.4, 0.6, 0.8, and 1.0
Operating reserve:
As percent of load, hourly load = 10%
As percent of renewable output, solar power output = 5%

4.2.2. Wind turbines

Wind turbine sizes considered (kW) = 0, 600, 600 × 2, 600 × 3
Cost of wind turbine (US$/turbine) = 1,000,000
Cost of replacement of wind turbine (US$/turbine) = 800,000
Operation and maintenance cost (US$/turbine/year) = 12,000
Operation life of the wind turbines (Years) = 20

4.2.3. Photovoltaics modules

Photovoltaic sizes considered (kW) = 0 and 1000
Cost of photovoltaic array (US$/kW) = 3500
Replacement cost of photovoltaic array (US$/kW) = 3500
Operation and maintenance cost of PV array (US$/kW/year) = 25
Photovoltaic modules were considered as fixed Working life of photovoltaic panels (years) = 20

4.2.4. Power converter

Power converter sizes considered (kW) = 0 and 500
Cost of power converter (US$/kW) = 900
Replacement cost of power converter (US$/kW) = 900
Operation and maintenance cost of power converter (US$/kW/year) = 0
Working life span of power converter (years) = 15
Inverter efficiency (%) = 90

4.2.5. Diesel generators

Generator 1 sizes considered (kW) = 0 and 1120
Generator 2 sizes considered (kW) = 0 and 1120
Generator 3 sizes considered (kW) = 0 and 1120
Generator 4 sizes considered (kW) = 0 and 1120
Generator 5 sizes considered (kW) = 0 and 1120
Life time operating hours (hours) = 20,000
Minimum load ratio (%) = 30
Capital cost (US$/kW) = 1521
Replacement cost (US$/kW) = 1521
Operation and maintenance cost (US$/hour) = 0.012

5. Results and discussion

Based on the above input, a total of 276,480 runs were made which comprised of 540 sensitivities and 512 simulations for each sensitivity run. A high speed computer, Pentium D, with 3.2 GHz speed and 2 GB ram took 40 min and 27 s to complete the required simulation. The HOMER suggested an optimal wind–pv–diesel hybrid power system for the village with three wind turbines each of 600 kW (26% wind penetration), 1000 kWp pv panels (9% solar energy penetration); five generators with rated power of 1120 each, and 500 kW sized power converter. The suggested optimal hybrid power system was found to have a capital cost of 13,764,080$ with an annual operating cost of 2,408,521$, total net present cost (NPC) of 41,389,628$ and levelized cost of energy (COE) of 0.212 $/kWh, as shown in Table 1. The diesel only power system was found to be the uneconomical power systems (COE 0.232 $/kWh) even at a diesel price 0.2 $/l. The energy output and the economical analysis of the proposed hybrid systems and the related sensitivity analysis are provided in the forthcoming paragraphs.

5.1. Energy yield analysis

The proposed wind–pv–diesel hybrid system was able to meet the energy requirement of the village with 35% of renewable energy

Table 1
Optimal wind–pv–diesel hybrid power system for the village.

Sensitivity Results | Optimization Results

Sensitivity variables

Global Solar (kWh/m²/d) 5.75 | Wind Speed (m/s) 5.85 | Diesel Price ($/L) 0.2 | Min. Ren. Fraction (%) 0

Double click on a system below for simulation results. ○ Categorized ◉ Overall | Export... | Details...

PV (kW)	D4/48	G1 (kW)	G2 (kW)	G3 (kW)	G4 (kW)	G5 (kW)	Conv. (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Diesel (L)	G1 (hrs)	G2 (hrs)	G3 (hrs
	3	1120	1120	1120	1120			$ 9,814,080	2,605,263	$ 39,696,244	0.203	0.27	4,907,834	8,571	6,718	2,98
	3	1120	1120	1120		1120		$ 9,814,080	2,605,263	$ 39,696,244	0.203	0.27	4,907,834	8,571	6,718	2,98
	3	1120	1120		1120	1120		$ 9,814,080	2,691,583	$ 40,686,324	0.208	0.27	4,907,834	8,571	6,718	
	3	1120		1120	1120	1120		$ 9,814,080	2,691,583	$ 40,686,324	0.208	0.27	4,907,834	8,571		6,71
	3		1120	1120	1120	1120		$ 9,814,080	2,691,583	$ 40,686,324	0.208	0.27	4,907,834		8,571	6,71
	3	1120	1120	1120	1120	1120		$ 11,517,600	2,565,658	$ 40,945,496	0.209	0.27	4,914,286	8,571	6,718	2,98
	2	1120	1120	1120	1120			$ 8,814,080	2,817,480	$ 41,130,352	0.210	0.18	5,339,599	8,756	7,271	3,41
	2	1120	1120	1120		1120		$ 8,814,080	2,817,480	$ 41,130,352	0.210	0.18	5,339,599	8,756	7,271	3,41
1000	3	1120	1120	1120	1120		500	$ 13,764,080	2,408,521	$ 41,389,628	0.212	0.36	4,485,265	8,427	6,082	2,75
1000	3	1120	1120	1120		1120	500	$ 13,764,080	2,408,521	$ 41,389,628	0.212	0.36	4,485,265	8,427	6,082	2,75
	2	1120	1120		1120	1120		$ 8,814,080	2,916,170	$ 42,262,316	0.216	0.18	5,339,599	8,756	7,271	
	2	1120		1120	1120	1120		$ 8,814,080	2,916,170	$ 42,262,316	0.216	0.18	5,339,599	8,756		7,27
	2		1120	1120	1120	1120		$ 8,814,080	2,916,170	$ 42,262,316	0.216	0.18	5,339,599		8,756	7,27
1000	3	1120	1120		1120	1120	500	$ 13,764,080	2,488,035	$ 42,301,648	0.216	0.36	4,485,265	8,427	6,082	
1000	3	1120		1120	1120	1120	500	$ 13,764,080	2,488,035	$ 42,301,648	0.216	0.36	4,485,265	8,427		6,08
1000	3		1120	1120	1120	1120	500	$ 13,764,080	2,488,035	$ 42,301,648	0.216	0.36	4,485,265		8,427	6,08
	2	1120	1120	1120	1120	1120		$ 10,517,600	2,778,991	$ 42,392,412	0.217	0.18	5,347,125	8,756	7,271	3,41
1000	3	1120	1120	1120	1120	1120	500	$ 15,467,600	2,362,492	$ 42,565,192	0.218	0.36	4,485,533	8,427	6,082	2,75
1000	2	1120	1120	1120	1120		500	$ 12,764,080	2,611,454	$ 42,717,252	0.219	0.27	4,907,984	8,709	6,596	3,17
1000	2	1120	1120	1120		1120	500	$ 12,764,080	2,611,454	$ 42,717,252	0.219	0.27	4,907,984	8,709	6,596	3,17
1000	2	1120	1120		1120	1120	500	$ 12,764,080	2,703,348	$ 43,771,268	0.224	0.27	4,907,984	8,709	6,596	
1000	2	1120		1120	1120	1120	500	$ 12,764,080	2,703,348	$ 43,771,268	0.224	0.27	4,907,984	8,709		6,59
1000	2		1120	1120	1120	1120	500	$ 12,764,080	2,703,348	$ 43,771,268	0.224	0.27	4,907,984		8,709	6,59
	1	1120	1120	1120	1120	1120		$ 9,517,600	2,991,013	$ 43,824,288	0.224	0.09	5,819,484	8,759	7,914	3,76
1000	2	1120	1120	1120	1120	1120	500	$ 14,467,600	2,565,424	$ 43,892,808	0.225	0.27	4,908,253	8,709	6,596	3,17

Table 2
Energy contribution of different energy sources at annual mean wind speed and global solar radiation of 5.85 m/s and 5.75 $kWh/m^2/d$, respectively.

Item description	Wind	PV	Diesel generating units			
			G1	G2	G3	G4
Rated capacity, kW	1800	1000	1120	1120	1120	1120
Percent contribution, %	26	9.7	64.3			
Capacity factor, %	29.9	18.9	69.8	34.9	10.9	2.0
Mean output power, kW	538	189	813	564	387	337
Annual energy output, (MWh)	4713.7	1653.5	6851.2	3427.7	1066.4	197.3
Annual hours of operations, (hours)	8310	4382	8427	6082	2758	585

penetration (wind power = 26% and solar power = 9%) in to the existing diesel only power system with average wind speed of 5.85 m/s and global solar radiation of 5.75 $kWh/m^2/d$. Table 2 summarizes the energy contribution by wind, solar pv system and the existing four generators. As seen from this table, 65% of the energy is supplied by the diesel generators and the remaining 35% by the wind and solar pv system. The proposed 35% wind and solar pv hybrid power penetration system was found to be optimal in terms of excess energy i.e. only 4.1% or 734,606 kWh of the energy was in excess.

The monthly mean power contribution of pv systems to the hybrid power system remain almost the same with slight variation of maximum and minimum of 194.7 kW and 173.8 kW in September and December, respectively, as shown in Fig. 16. However, the wind power contribution varied between a maximum of 805 kW in April and a minimum of 387 kW in September. The wind power contribution during February till April was almost the same as that of diesel. The total power generated by all the generators (Gen) was found to be maximum in August and minimum in March.

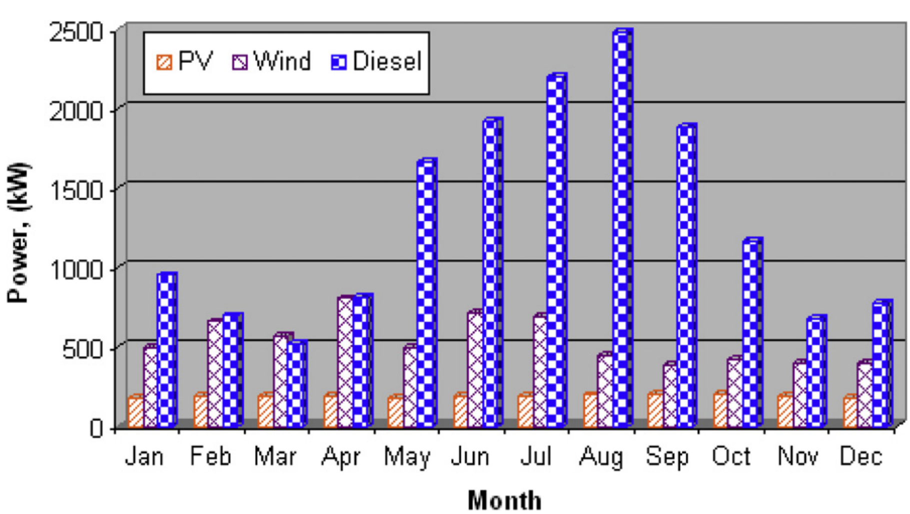

Fig. 16. Monthly mean power contribution by wind, solar pv and diesel power systems.

Table 3
Annual GHG emissions from diesel only and hybrid power systems.

Pollutant	Emissions (kg/yr)	
	Diesel only	35% RE penetration
Carbon dioxide	16,657,316	11,811,177
Carbon monoxide	41,116	29,154
Unburned hydrocarbons	4554	3229
Particulate matter	3100	2198
Sulfur dioxide	33,451	23,719
Nitrogen oxides	366,883	260,145
Total GHG	17,106,420	12,129,622

5.2. Green house gas (GHG) emissions

The proposed wind–pv–diesel hybrid power system with 35% renewable energy penetration could avoid addition of 4976.8 tons of GHG equivalent of CO_2 annually in to the local atmosphere of the village under consideration. Furthermore, during the life time of the hybrid power plant, a total of 99,536 tons of GHG could be avoided from entering in to the local atmosphere of the village which will further improve the health of the local inhabitants and results in reduction of their medical bills. The reduction in the quantity of different air pollutants for 35% renewable energy penetration compared to that diesel only power plant is given in Table 3. A 29% decrease in each pollutant is noticed for a 35% RE penetration in to the existing diesel only power system.

5.3. Economical analysis

The total costs of each component of the hybrid power systems, including mainly the wind turbines, pv panels, four generators, and power converter, are shown in Fig. 17 and the breakup of capital, replacement, O & M, fuel and salvage costs is given in Table 4 and the corresponding annualized costs are summarized in Table 5. It is evident, that bulk of the total net present cost (NPC) is accounted for diesel generating sets and the least for converter. The capital cost of the proposed hybrid power system was worked out to be 13,764,080US$ with replacement, O & M, and fuel cost of 15,233,948US$, 3,451,656US$, and 10,289,131US$ respectively. The annualized capital cost of wind turbines was 266,154US$, pv panels was 305,146US$ while that of diesel units it was 594,084US$ but the corresponding O & M costs were 36,000US$, 25,000US$ and 239,931US$. Furthermore, the annualized fuel cost for diesel sets was 897,053US$ and zero in case of wind and pv systems.

Furthermore, each MWh of electricity produced from renewable sources results in to conservation of about 1.7 barrels of fuel which means a revenues earning of 136US$ at 80US$ per barrel price of the fossil fuel. In the present case, the wind–pv system contributes 6367.2 MWh electricity which means a saving of 10,824 barrels of fuel and hence a foreign earning of 865,939US$ annually. In twenty years time, the integration of wind–pv system in to the existing diesel only system can result in revenue savings of more then 17 millions US dollars. Additionally, the utilization of renewable energy sources will also result in earning carbon credits of around 20US$ for each ton of GHG avoided from entering in to the atmosphere. In the present scenario, a total of 99,536$ could be earned annually as a result of avoidance of 4976.8 tons of GHG from entering in to the local atmosphere. Over the life time of the hybrid power plant around two millions of dollars could be collected as part carbon credit benefit.

6. Sensitivity analysis

The contribution of wind and solar energy in the hybrid energy system depend on the intensity and the duration of

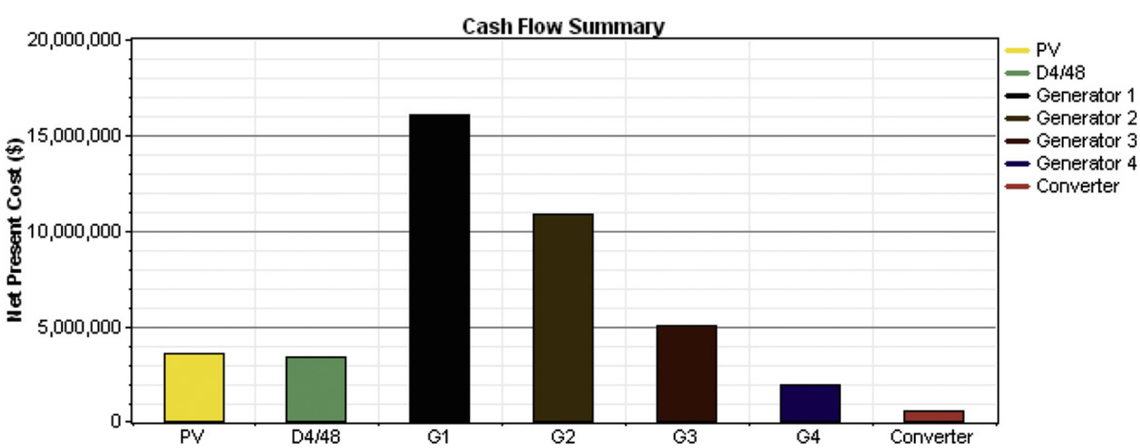

Fig. 17. Cash flow summary of various components of the hybrid power system.

Table 4
Summary of various costs related to the wind–pv–diesel hybrid power system.

Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
PV	3,500,000	0	286,748	0	−218,264	3,568,485
D4/48	3,000,000	0	412,917	0	0	3,412,917
Generator 1	1,703,520	7,686,923	1,299,071	5,661,295	−304,358	16,046,451
Generator 2	1,703,520	5,511,115	937,576	3,215,963	−487,610	10,880,563
Generator 3	1,703,520	1,848,143	425,162	1,178,456	−128,542	5,026,739
Generator 4	1,703,520	0	90,181	233,416	−116,857	1,910,261
Converter	450,000	187,769	0	0	−93,542	544,228,
System	13,764,080	15,233,948	3,451,656,	10,289,131	−1,349,172	41,389,640

Table 5
Summary of annualized cost of the hybrid power system.

Component	Capital ($/yr)	Replacement ($/yr)	O&M ($/yr)	Fuel ($/yr)	Salvage ($/yr)	Total ($/yr)
PV	305,146	0	25,000	0	−19,029	311,117
D4/48	261,554	0	36,000	0	0	297,554
Generator 1	148,521	670,181	113,259	493,578	−26,535	1,399,033
Generator 2	148,521	480,484	81,742	280,382	−42,512	948,617
Generator 3	148,521	161,130	37,068	102,743	−11,207	438,254
Generator 4	148,521	0	7862	20,350	−10,188	166,545
Converter	39,233	16,371	0	0	−8155	47,448
System	1,200,015	1,328,165	300,931	897,053	−117,627	3,608,538

availability of the respective sources of energy. For annual mean GSR of 5.75 kWh/m^2/d and annual solar energy contribution of 9% i.e. 1653.5 MWh, the wind energy contribution at a wind speed of 4.5 m/s was 13% while at 5.0 m/s was 18% as given in Table 6. It is evident from this table that for every 0.5 m/s increase in wind speed, there is an increase of 5% in wind energy contribution to the hybrid power system. Similarly, the COE decreased linearly and the overall achievable renewable energy fraction (REF) increased linearly as observed from 5th and 7th columns of the Table 6.

The contribution of solar energy in the hybrid system with change in GSR was found to be minimal because for a change of 0.5 kWh/m^2/d in GSR intensity only 1% increase in solar energy contribution was observed as can be seen from Table 7 and at higher values of GSR ($>$6.0 kWh/m^2/d) no additional energy could be achieved. At lower values of GSR, the solar energy fraction contributed more towards the excess energy compared to wind energy contribution at lower wind speeds as can be crossed

Table 6
Effect of annual mean wind speed (WS) on wind energy (WE) contribution, excess energy, COE, diesel consumed, REF achieved and total running hours for annual mean GSR of 5.75 kWh/m^2/d, annual mean solar energy of 1653.48 MWh and 9% contribution of solar energy in the wind/pv/diesel hybrid power system.

WS (m/s)	WE (%)	Excess energy (MWh/y)	Excess energy (%)	COE ($/kWh)	Diesel (1000L)	REF (%)	Running (Hours)
4.50	13	297.72	1.7	0.232	5168.9	22	19852
5.00	18	433.02	2.5	0.225	4934.8	27	19202
5.50	23	596.17	3.4	0.217	4671.2	32	18397
5.85	26	734.61	4.1	0.212	4485.3	36	17852
6.00	28	794.59	4.4	0.209	4400.2	37	17565
6.50	33	1008.15	5.6	0.201	4132.4	42	16734

Table 7
Effect of annual mean global solar radiation (GSR) on solar energy (SE) contribution, excess energy, COE, diesel consumed, REF achieved and total running hours for a diesel price of 0.2 US$/l, annual mean WS of 5.85 m/s, annual mean wind energy of 1653.48 MWh and 27% contribution of wind energy in the wind/pv/diesel hybrid power system.

GSR (kWh/m^2/d)	SE (%)	Excess Energy (MWh/y)	Excess Energy (%)	COE ($/kWh)	Diesel (1000L)	REF (%)	Running (Hours)
4.50	7	593.3	3.3	0.214	4565.8	34	18123
5.00	8	634.1	3.6	0.213	4528.7	34	18011
5.50	9	695.9	3.9	0.212	4498.1	35	17905
5.75	9	734.6	4.1	0.212	4485.3	36	17852
6.00	10	775	4.3	0.211	4473.8	36	17804
6.50	10	858.8	4.8	0.211	4455.5	36	17737

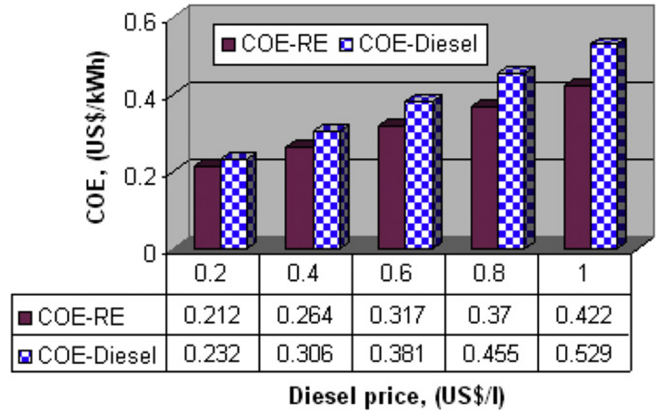

Fig. 18. Effect of diesel price on COE of hybrid power system at annual average wind speed of 5.85 m/s and global solar radiation of 5.75 kWh/m^2/d.

checked from columns 3 and 4 in Tables 6 and 7 and vice versa. The diesel consumption and diesel generating sets running hours at designed GSR of 5.75 kWh/m^2/d were more at lower WS values and higher at WS greater than the designed WS of 5.85 m/s as can be seen from columns 6 and 8 of Tables 6 and 7. This simply means that wind energy contributes more efficiently to the proposed hybrid power system than the solar energy.

The cost of the fuel, diesel in the present case, has direct impact on the COE of hybrid power system, as can be seen from Fig. 18. It is evident that the wind–pv–diesel hybrid power system is always feasible compared to diesel only system for all price range of diesel fuel considered in the present study. The COE of diesel only system increases more rapidly than the COE of hybrid power system with an increase in diesel price.

7. Concluding remarks

An attempt was made to explore the possibility of utilizing power of the wind and sun to reduce the dependence on fossil fuel for power generation to meet the energy requirement of a small village Rowdat Ben Habbas located in the north eastern part of Saudi Arabia. The wind–pv–diesel hybrid system with 35% renewable energy penetration (26% wind and 9% solar) and 65% diesel power contribution (five units of 1120 kW each) was found to be the most economical power system with COE of 0.212 US$/kWh at a diesel price of 0.2 US$/l. The COE for diesel only system at same diesel price was found to be 0.232 US$/kWh i.e. around 9.4% more than the hybrid system. The sensitivity analysis showed that for every 0.5 m/s increase in wind speed, there was an increase of 5% in wind energy contribution to the hybrid power system and the COE decreased linearly and the overall achievable renewable energy fraction (REF) also increased linearly. Furthermore, the wind energy contributed more efficiently to the proposed hybrid power system than the solar pv energy. Lastly, the COE of diesel only power system was found to be more sensitive to diesel price than the COE of hybrid power system.

Acknowledgement

The authors are thankful to the Research Institute of King Fahd University of Petroleum and Minerals for providing financial and technical support required for the study presented in this paper.

References

[1] Muselli M, Notton G, Louche A. Design of hybrid-photovoltaic power generator, with optimization of energy management. Solar Energy 1999;65(3): 143–57.
[2] Bagen BR. Evaluation of different operating strategies in small stand-alone power systems. IEEE Transactions on Energy Conversion 2005;20(3):654–60.
[3] Yang H, Wei Z, Chengzhi L. Optimal design and techno-economic analysis of a hybrid solar-wind power generation system. Applied Energy 2009;86:163.
[4] Yang H, Zhou W, Lu L, Fang Z. Optimal sizing method for stand-alone hybrid solar-wind system with LPSP technology by using genetic algorithm. Solar Energy 2008;82:354.
[5] Barley CD. Optimal dispatch strategy in remote hybrid power systems. Solar Energy 1996;58:165–79.
[6] Bryne J, Shen B, Wallace B. The economics of sustainable energy for rural development: a study of renewable energy in China. Energy Policy 1998;26: 45–54.
[7] Celik AN. A simplified model for estimating yearly wind fraction. Renewable Energy 2006;31:105–18.
[8] Cavello AJ, Grubb AM. Renewable energy sources for fuels and electricity. London: Earthscan; 1993.
[9] Dihrab SS, Sopian K. Electricity generation of hybrid PV/wind systems in Iraq. Renewable Energy 2010;35:1303–7.
[10] Ekren O, Ekren BY, Ozerdem B. Break-even analysis and size optimization of a PV/wind hybrid energy conversion system with battery storage – a case study. Applied Energy 2009;86(7–8):1043–54.
[11] Saheb-Koussa D, Haddadi M, Belhamel M. Economic and technical study of a hybrid system (wind–photovoltaic–diesel) for rural electrification in Algeria. Applied Energy 2009;86:1024–30.
[12] Nfah EM, Ngundam JM, Tchinda R. Modelling of solar/diesel/battery hybrid power systems for far-north Cameroon. Renewable Energy 2007;32:832–44.
[13] Bernal-Agustın Jose L, Dufo-Lopez R. Techno-economical optimization of the production of hydrogen from PV-Wind systems connected to the electrical grid. Renewable Energy 2010;35:747–58.
[14] Arribas L, Cano L, Cruz I, Mata M, Llobet E. PV–wind hybrid system performance: a new approach and a case study. Renewable Energy 2010;35: 128–37.
[15] Sopian K, Ibrahim MZ, Daud WRW, Othman MY, Yatim B, Amin N. Performance of a PV–wind hybrid system for hydrogen production. Renewable Energy 2009;34:1973–8.
[16] Mahmoudi H, Abdul-Wahab SA, Goosen MFA, Sablani SS, Perret J, Ouagued A, et al. Weather data and analysis of hybrid photovoltaic-wind power generation systems adapted to a seawater greenhouse desalination unit designed for arid coastal countries. Desalination 2008;222:119.
[17] Dufo-Lopez R, Bernal-Agustın Jose L. Multi-objective design of PV– wind– diesel– hydrogen– battery systems. Renewable Energy 2008;33:2559–72.
[18] Shakya BD, Aye L, Musgrave P. Technical feasibility and financial analysis of hybrid wind-photovoltaic system with hydrogen storage for Cooma. International Journal of Hydrogen Energy 2005;30:9.
[19] Tina G, Gagliano S, Raiti S. Hybrid solar/wind power system probabilistic modeling for long-term performance assessment. Solar Energy 2006;80:578.
[20] Lambert T and Lilienthal P. HOMER: the micro-power optimization model. Software Developed by NREL. Available from: <www.nrel/gov/HOMER>; 2004 http://www.mistaya.ca/homer/MicropowerSystemModelingWithHOMER.pdf.
[21] Rhoads-Weaver H, Grove J. Exploring joint green tag financing and marketing models for energy independence. In: Conference proceedings of global windpower. NREL, http://www.ourwind.org/windcoop/pdfs/AWEA_Paper.pdf.
[22] Yang D. Local photovoltaic wind hybrid system with battery storage or grid connection. NREL, http://www.chem.jyu.fi/ue/frame_left/UEsem2005-Yang.pdf.
[23] Edwards JL, Wiser R, Bolinger M, Forsyth T. Building a market for small wind: the break-even turnkey cost of residential wind systems in the United States. Berkeley, CA (US): Ernest Orlando Lawrence Berkeley National Laboratory, http://www.osti.gov/energycitations/product.biblio.jsp?osti_id1/4823465.
[24] Forsyth T, Tu P, Gilbert J. Economics of grid-connected small wind turbines in the domestic market. National Renewable Energy Laboratory (NREL). Available from: http://www.nrel.gov/docs/fy00osti/26975.pdf.