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Renewable and Sustainable Energy Reviews
11 (2007) 635–653
RENEWABLE & SUSTAINABLE ENERGY REVIEWS
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Feasibility study of hybrid retrofits to an isolated off-grid diesel power plant

S. Rehman[a,*,1], I.M. El-Amin[b], F. Ahmad[a], S.M. Shaahid[a], A.M. Al-Shehri[b], J.M. Bakhashwain[b], A. Shash[a]

[a]*Center for Engineering Research, King Fahd University of Petroleum and Minerals, Dhahran 31261, Saudi Arabia*
[b]*Electrical Engineering Department, King Fahd University of Petroleum and Minerals, Dhahran 31261, Saudi Arabia*

Received 3 May 2005; accepted 5 May 2005

Abstract

The green sources of energy are being encouraged to reduce the environmental pollution and combat the global warming of the planet. A target of 12% usage of wind energy only has been agreed by the UNO country members to achieve by 2020. So, the power of the wind is being used to generate electricity both as grid connected and isolated wind-diesel hybrid power plants. This paper performed a pre-feasibility of wind penetration into an existing diesel plant of a village in north eastern part of Saudi Arabia. For simulation purpose, wind speed data from a near by airport and the load data from the village have been used. The hybrid system design tool HOMER has been used to perform the feasibility study. In the present scenario, for wind speed less than 6.0 m/s the, the existing diesel power plant is the only feasible solution over the range of fuel prices used in the simulation. The wind diesel hybrid system becomes feasible at a wind speed of 6.0 m/s or more and a fuel price of 0.1 $/L or more. If the carbon tax is taken into consideration and subsidy is abolished then it is expected that the hybrid system become feasible. The maximum annual capacity shortage did not have any effect on the cost of energy which may be accounted for larger sizes of wind machines and diesel generators. It is recommended that the wind data must be collected at the village at three different heights using a wind mast of 40 m for a minimum of one complete year and then the hybrid system must be re-designed.

*Corresponding author. Tel.: +966 3 860 3802; fax: +966 3 860 3996.
E-mail address: srehman@kfupm.edu.sa (S. Rehman).
[1]Home page: http://staff.kfupm.edu.sa/ri/srehman.

1364-0321/$ - see front matter
doi:10.1016/j.rser.2005.05.003

Contents

1. Introduction

Today, the exponential population growth, shortage of essential commodities, insufficient and inefficient waste disposal facilities, increasing soil, air, and water pollutions are the matters of concerns to individuals, scientists, engineers, politicians, and to certain extent to governments. Due to materialistic life styles and industrialization, the energy demands are increasing exponentially resulting into an exponential increase in environmental pollution. In some areas the power generation production is rarely enough to meet even the minimum requirement, causing social problems in those areas. Of the renewable, clean and inexhaustible sources of energy, wind power is catching the attention of engineers, environmentalists and financiers these days. Wind power plants consisting of a single wind machine to several in the form of wind farm are taking shapes in different parts of the world.

Rapid advancements in wind energy technologies have made it cost competitive for grid connected wind power plants in various parts of the world. The total global wind power installed capacity touched around 48,000 MW by December 2004. Germany, United States of America, Spain, Denmark and India have been the major contributors in wind power development in the world in recent years. So large scale wind power technology has been proved successful and reached commercially acceptable level. The small scale stand alone and off-grid hybrid energy systems for remote locations are yet to get the commercial acceptance. With growing awareness and lack of grid connectivity wind diesel hybrid systems are being established for remote localities in England, Spain, Germany, Denmar, Phillipine, India, Bangladesh, Pakistan, Srilanka, Morocco, Egypt, Libya, Jordan, Norway, Brazil, Australia, New Zealand, Nepal, Malaysia, Thailand, USA, and so on.

In isolated areas which are far from the grid, it is really impossible to meet the small power loads either through long-distance distribution network or by means of conventional generation. This can be accounted for high cost of transmission lines and higher transmission losses associated with distribution of centrally generated power to remote areas [1]. In the present scenario, the electric supply in these areas depend only on the stand alone diesel generation systems in most parts of the world, especially the developing world. These hybrid systems involve combination of different energy sources like wind-diesel hybrid, wind-diesel-battery hybrid, wind-photovoltaic-diesel hybrid, wind-photovoltaic-diesel-battery hybrid, photovoltaic-diesel hybrid, photovoltaic-diesel-battery hybrid, and so on.

A number of studies [2–5] related to determine the optimal hybrid system for small electrical loads (ranging from few watts to few kilo watts) have been reported in the literature. The reported studies show that renewable energy based hybrid systems can compete with power from the grid in remote areas where the grid either is not feasible or nonexistent. Moreover the hybrid systems like wind-diesel and photovoltaic-diesel with or without battery backup are now proven technologies for electric supply to remote locations as reported by Fortunato et al. [6], Lundsager and Bindner [7], and Zhang et al. [8].

In developing countries, interest in medium to large scale wind-diesel hybrid power system for rural electrification has grown enormously among energy officials and utility planners. Azmi [9] presented a case study of a pilot wind diesel hybrid system of 150 kW installed capacity developed in Pulau Layang-Layang, Sabah, Malaysia. During the past 30 years, the family use small wind turbines in China have a great progress through the efforts of concerned scientific research units, manufacturers, spread sectors and local governments. The accumulated installations of family-use small wind turbine reached 250000 sets throughout the country, [10].

Manwell and McGowan [11] presented the feasibility study of potential hybrid energy developments on the islands of New England. The study showed that there is a great potential for hybrid system energy development in a number of New England Islands. The Strategic Power Utilities Group (SPUG) of National Power Corporation of (NPC) in the Philippines conducted a study to estimate the potential fuel and cost savings that may be achieved by retrofitting hybrid power systems to these existing diesel plants [12]. Barley et al. [12] used time-series computer simulation models to estimate the fuel usage, maintenance expenses and cash flow resulting from various designs. The study found that wind retrofits to the existing diesel power plants in the Philippines are the most likely to be cost effective for wind speeds of approximately 5.5 m/s or more and fuel prices of US$ 0.20 to US$ 0.25/L, [12]. Recently, Khan and Iqbal [13] conducted a comprehensive study of a stand alone wind-diesel-PV hybrid system with battery and fuel cell storage option for a remote house having an energy consumption of 25 kWh/day with a peak load demand of 4.73 kW in Newfoundland, Canada. The study suggested a wind-diesel hybrid system with battery backup as most suitable solution for the house.

In Saudi Arabia work on wind resource assessment dates back to 1986 when a wind atlas was developed by using wind speed data from 20 locations [14]. Rehman [15] presented the energy output and economical analysis of 30 MW installed capacity wind farms at five coastal locations in terms of unadjusted energy, gross energy, renewable energy delivered specific yield and wind farm capacity factor using wind machines of different rated capacities. In another study, Rehman [16] presented wind speed analysis in terms of energy yield, effect of hub-height on energy yield, plant capacity factor, etc. for an industrial city situated on the northwest coast of Saudi Arabia. The author found that at 10 m the wind was available for 59% of the time during entire year above 3.5 m/s.

Rehman and Aftab [17] performed detailed wind data analysis for wind power potential assessment for five coastal locations in Saudi Arabia. Rehman et al. [18] computed the cost of energy generation at 20 locations in Saudi Arabia using net present value approach. Mohandes et al. [19,20] used the neural networks method for the prediction of daily mean values of wind speed and concluded that the performance of the neural network model was much better than the performance of the traditionally used auto-regression model. Rehman and Halawani [21] presented the statistical characteristics of wind speed and its diurnal variation. The autocorrelation coefficients were found to match the actual diurnal variation of the hourly mean wind speed. Rehman et al. [22] calculated the Weibull parameters for 10 locations and found that the wind speed was well represented by the Weibull distribution function. With growing global awareness of the usage of clean sources of energy, wind energy in particular, a lot of work is being carried out in Saudi Arabia, as can be seen from [23–28].

The aim of the present study is to perform an economical feasibility of an existing grid connected diesel power plant supplying energy to a remotely located village of about 750 inhabitants by adding wind turbine/s in the existing power system to reduce the diesel consumption and environmental pollution. National Renewable Energy Laboratory (NREL)'s Hybrid System Optimization Model for Electric Renewables (HOMER 2.14) has been used as the sizing and optimization tool. This software contains a number of energy components and evaluates suitable options based on cost and availability of energy resources [29]. The software requires information related to energy resources, economical constraints, energy storage medium and system control strategies. It also requires inputs like component type, its size, number of units, capital cost, replacement cost and operation and maintenance cost, efficiency, operational life, etc.

2. Electrical load variation of the village

The primary electrical load data for the village is shown in Fig. 1. The annual peak load of 4,231 kW was observed on August 12 at 15:00 h. Fig. 2 describes the monthly average variation of load of the village. The higher demand exists between May and September while relatively smaller load requirements are found during rest of the period of the year. The daily energy consumption is relatively lower during most of the time during 24 h except around 18:00 h when higher energy consumption observed during January,

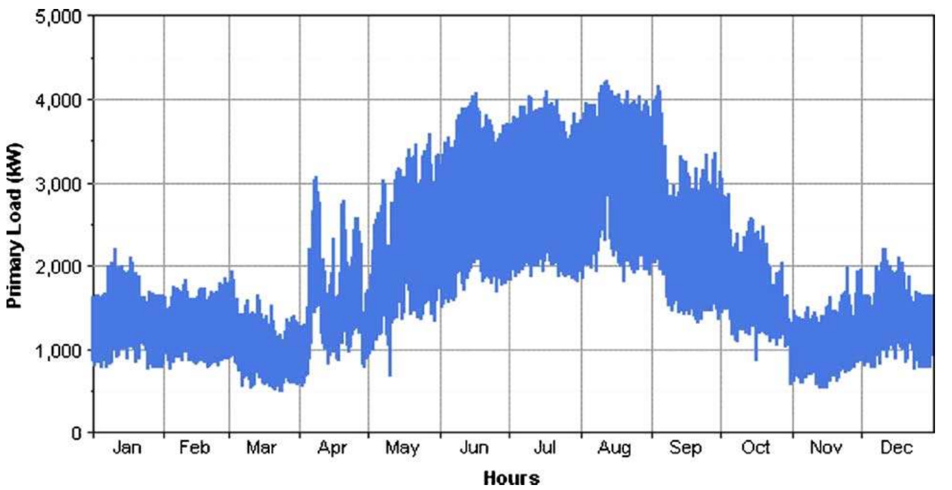


Fig. 1. Hourly load variation at the village for the year 2003.

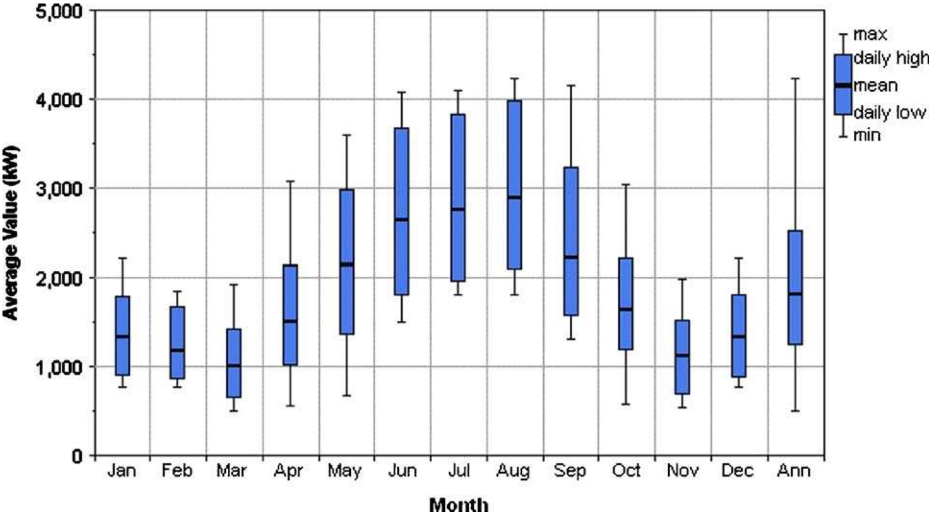


Fig. 2. Monthly average load variation at the village for the year 2003.

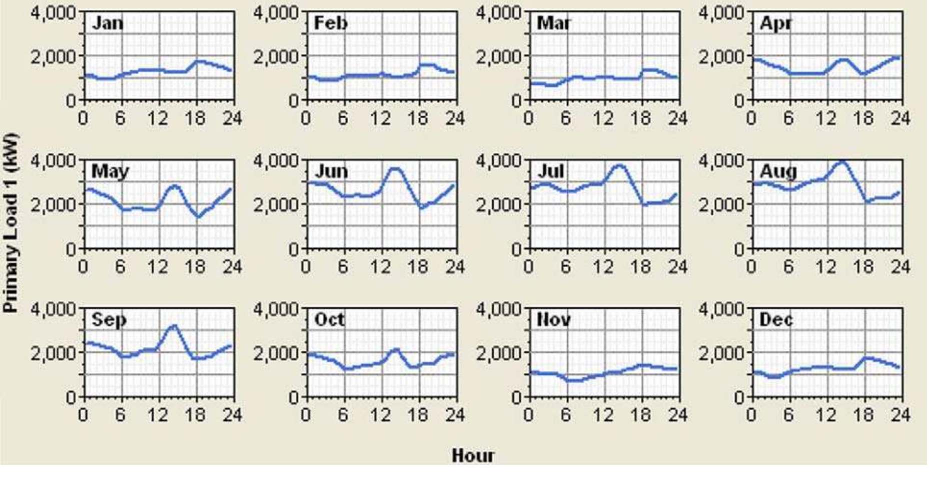


Fig. 3. Monthly average load variation at the village for the year 2003.

February and March, as shown in Fig. 3. Between April to June three energy peaks are observed namely in the morning, evening and around 14:00 h. Almost the same energy consumption pattern is observed between July and September with peaks around 14:00 h. Lower energy consumption is seen during October to December during the day. The percent frequency of occurrence of a certain load is shown in Fig. 4. Almost 11% of time the load requirement was found to be 1000 kW and 15% of time to be 1200 kW.The power demand was found to be around 2000 ± 400 kW for 50% of the time and 2–3% around 3000 kW and more.

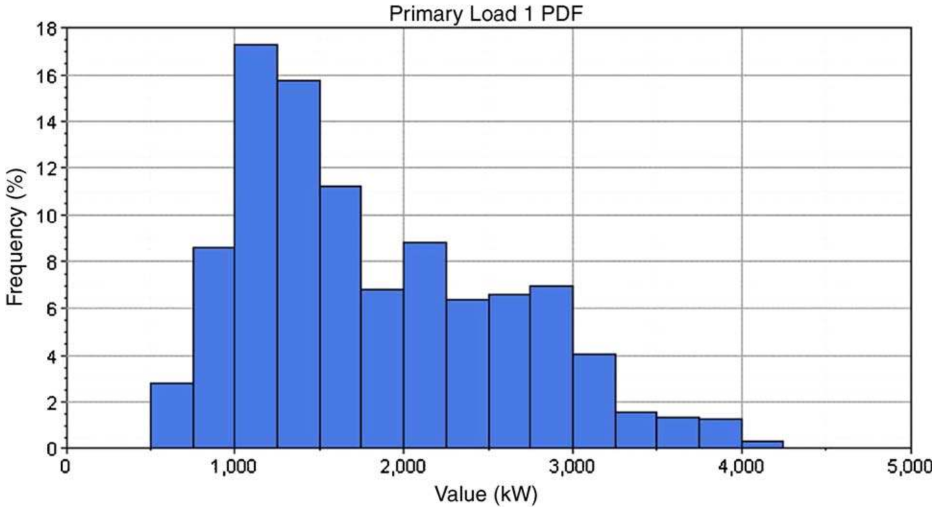


Fig. 4. Electrical load frequency variation at the village for the year 2003.

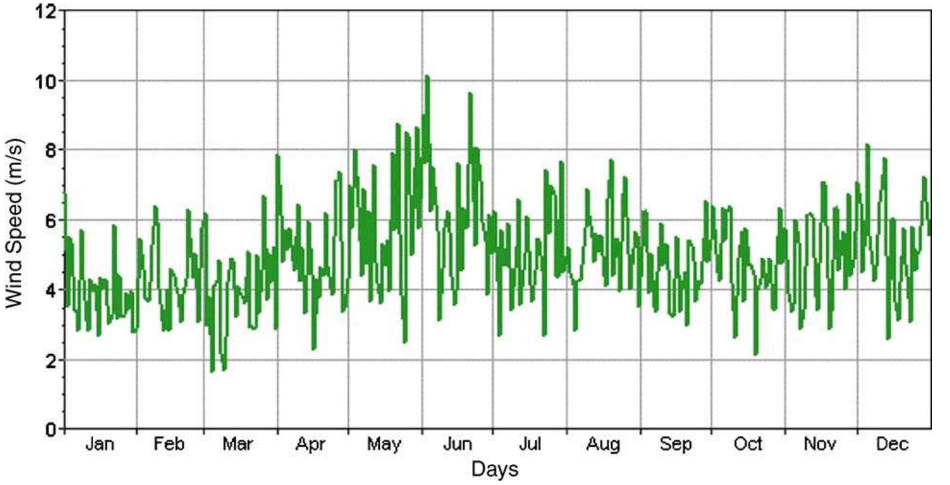


Fig. 5. Daily average wind speed variation.

3. Wind speed variation analysis

Since wind data was not available for the village, so it was taken from Presidency of Meteorology and Environment (PME) for Rafha airport which is in close proximity of the village. This section only describes the wind speed data for the year 2003 which coincides with the load data of the village described in the preceding section. The wind data available from PME is collected at 12 m above the ground.

Since the rotors of the modern wind machines are placed at heights varying between 40–110 m, so this data was calculated at 60 m hub height using 1/7 power law. At this

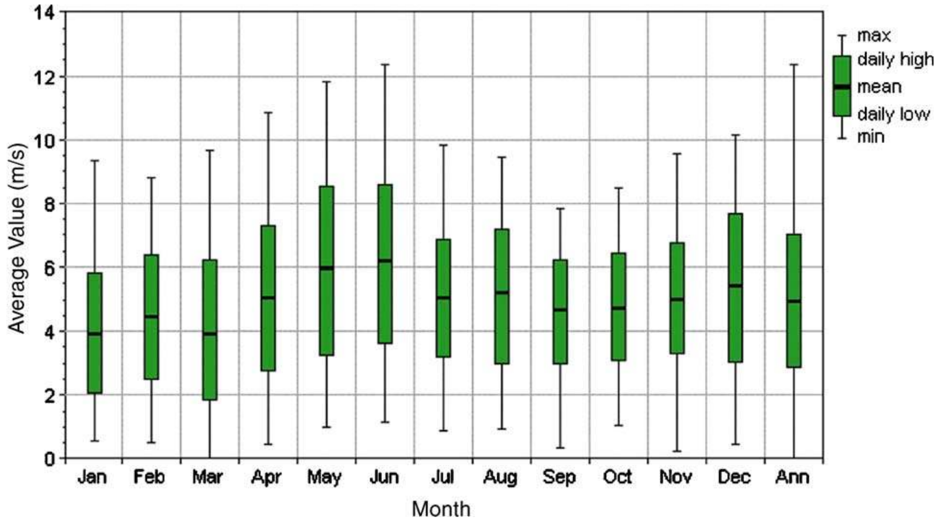


Fig. 6. Monthly average wind speed variation.

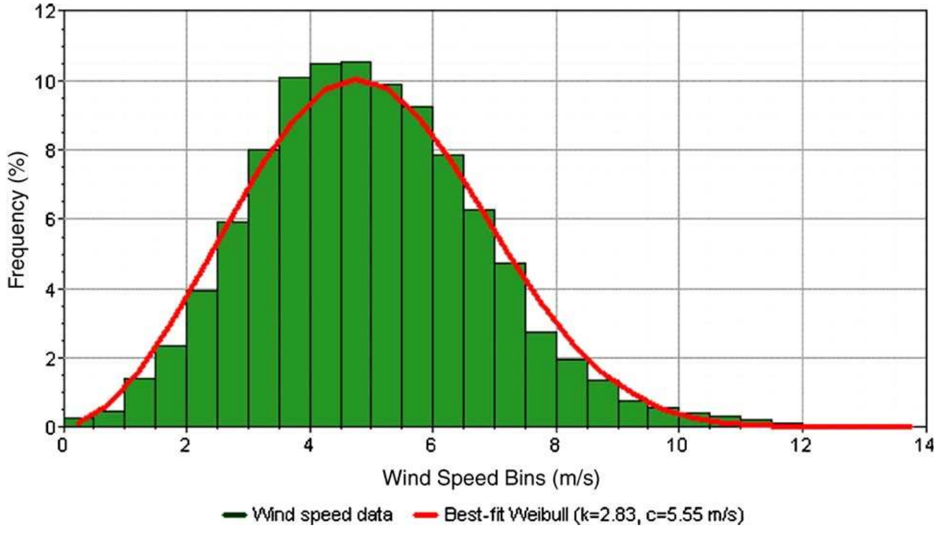


Fig. 7. Frequency distribution hourly mean wind speed.

height, the average wind speed became 4.95 m/s while at 12 m it was only 3.93 m/s. As seen from Fig. 5, the wind remained relatively low during January, February, March, October and November compared rest of the months. This trend is also reflected by the monthly mean values of the wind speed in Fig. 6. The frequency distribution of wind data shows that wind remained 4 m/s and below it for about 32% of the time during the entire year and above it for rest of the period, as shown in Fig. 7. This means, that the energy could be harnessed for almost 68% of time using wind machines with cut-in-speed of 3.5 m/s or more.

4. Wind-diesel hybrid power system components

The main components of an isolated grid connected wind-diesel hybrid system are diesel generators and wind turbines. A typical wind-diesel hybrid system used in HOMER software is shown in Fig. 8. The system consists of three diesel generators, the wind turbines, an AC bus and the primary load. The cost of each component, the number of units used in simulation, the economical and control parameters required by the software are discussed in the forthcoming paragraphs.

4.1. Diesel generating sets

The diesel power plant at the remote village consists of 6 diesel units of 1120 kW each. At present, of these six units three or four are sufficient to meet the load of the village. In fact, initially the load of the village was more and hence six units were required. With time the people moved to nearby big cities as a result the population decreased and accordingly the electrical load. The technical information on diesel generating units, being used at the village, was obtained from the power plant. The details of various parameters are given in

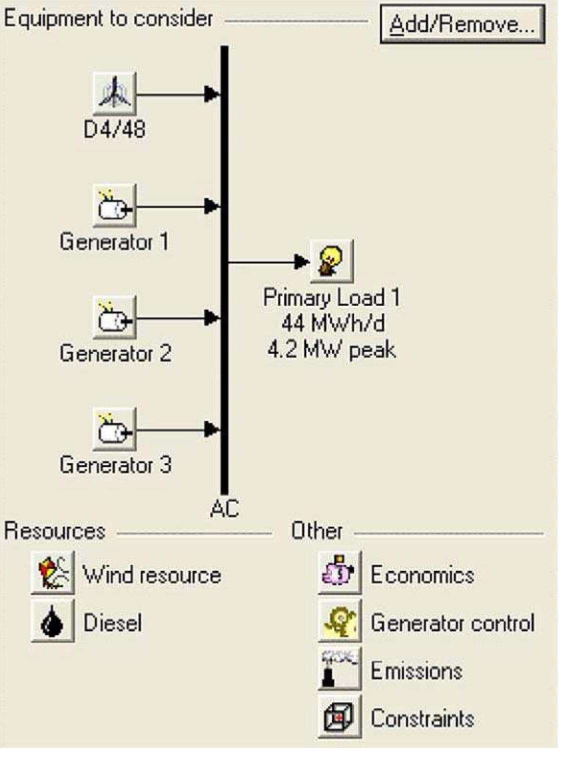


Fig. 8. Wind-diesel energy system for an isolated grid.

Table 1
Diesel generator information from diesel power plant

Parameters	Value/Information
Manufacturer	Cummins Power Generation
Rated Power	1,120 Kw
Minimum Allowed Power	400 kW
No Load Fuel Consumption	87.46 L/Hour (assumed)
Full Load Fuel consumption	342.99 L/Hour (assumed)
Power Factor	0.8
Voltage	480 Volts
Rated Current	1,347 Amperes
Frequency	60 Hz
Rotating Speed	1,800 RPM
Battery Voltage	24 Volts

Table 2
Diesel generator cost data obtained locally

Manufacturer	Rating (kW)	Capital cost ($)	Replacement cost ($)	O and M Cost ($/Hour)
Cummins	1,120	180,000	120,000	3.01
Cummins	2,240	234,000[a]	156,780	3.01

[a]Cost of 2240 kW unit is assumed to 30% more than the cost of 1120 kW.

Table 3
Fuel cost and technical data

Parameters	Value
Cost	0.102 ($/L) (34 Halalah/L + 9% transportation)
Lower Heating Value	0.0385 MBTU/L
Density	820 (kg/m^3)
Carbon Content	80%

Table 1. The cost data, obtained from local manufacturer through informal personal communication, is given in Table 2. The operation and maintenance cost of 3.01$/hour was used in the simulation run. The fuel cost obtained locally, including the transportation cost, was 0.102 $/L, as given in Table 3. This table also includes the other technical information related to diesel fuel.

4.2. *Wind energy conversion system (WECS)*

The other major component of the wind diesel hybrid system after diesel generating set is the wind energy conversion system or wind turbine. The modern wind machines are very efficient and found in big sizes, capacity wise. Today's market standard size of the wind machine is greater than 1.5 MW. The rotor diameter of these machines varies between 40–120 m and tower height between 40–110 m and more. The modern WECS produce

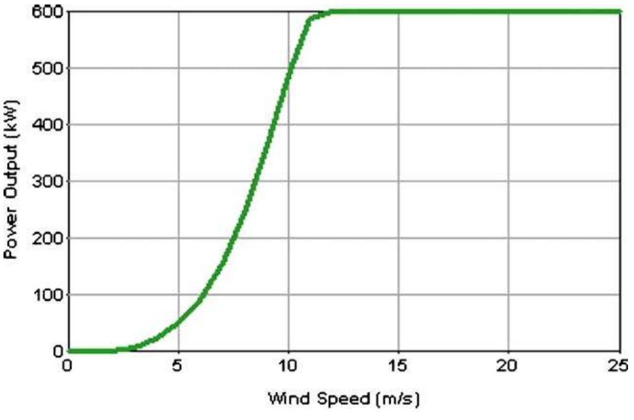


Fig. 9. Wind power curve of D4/48 wind machine from DeWind of 600 kW rated power.

Table 4
Wind energy conversion system (WECS) technical data

Parameters	Value/Information
Manufacturer	DeWind
Hub height	60 M
Rotor diameter	48 M
Cut-in-speed	3.0 m/s
Cut-out-speed	22.0 m/s
Rated speed	11.5 m/s
Rated power	600 kW
Overhaul period	25 Years
Wind power scale factor	1
Wind power response factor	1.5
Voltage	690 Volts
Wind turbine capital cost ($)	575,000 (Assumed)
Replacement or overhaul cost	400,000 (Assumed)

more energy due to high wind speeds at higher hub heights. Since the energy yield from the WECS depends on the availability of wind and its variation. In the present case WECS of 600 kW from DeWind are used. The wind power curve of the D4/48 wind machine, obtained from [30], is shown in Fig. 9. The technical and cost information of the wind machine is summarized in Table 4. The operation and maintenance cost of $13,000 per wind turbine per year has been assumed based on literature data.

4.3. Economical parameters and hybrid system constraints

The project life time was taken as 25 years and the annual real interest rate as 4%. The fixed capital cost of the system was assumed US$ 200,000 while fixed O and M cost as US$ 10,000 per annum. Furthermore, the capacity shortage penalty was not considered.

Table 5
System controls used in software

Parameters	Options	Option used
Cycle charging	Yes or No	Yes
Apply set point	Yes or No	Yes
Load following	Yes or No	Yes
Set point state of charge		80(%)
Multiple generators can operate in parallel	Yes or No	Yes

Table 6
Spinning reserve inputs in software

Parameters	Value (%)
Percent of annual peak load	0
Percent of hourly load	10
Percent of hourly solar output	0
Percent of hourly wind output	40

Table 7
Constraints used in software

Parameters	Value
Maximum unserved energy	0 (%)
Minimum renewable fraction	0, 5, 10, 15, 20, and 25 (%)
Minimum battery life	N/A
Maximum annual capacity shortage	0, 3, 5, 7 and 10%

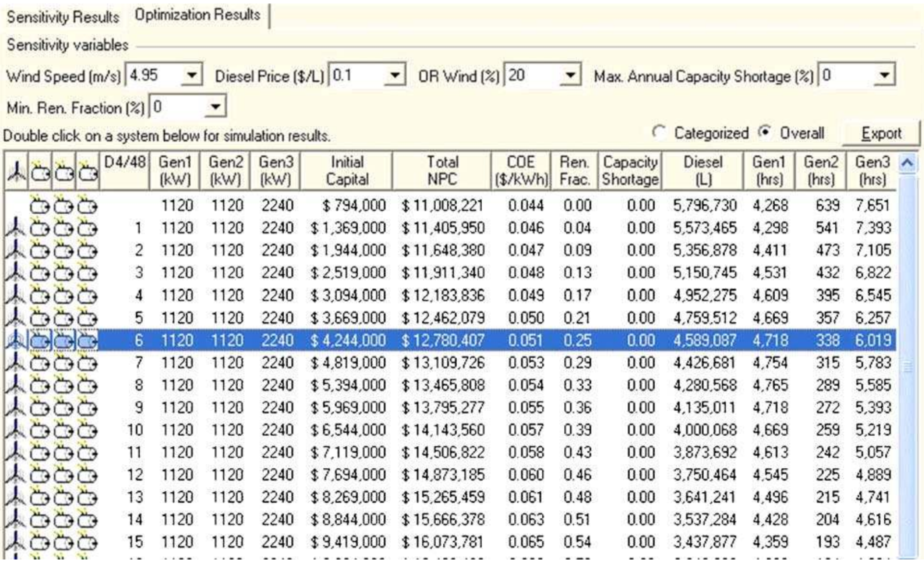
The system control parameters used in the simulation run are summarized in Table 5. The spinning reserve input options and system constraints are given in Tables 6 and 7, respectively.

5. Results and discussion

The simulation software provides the results in terms of optimal systems and the sensitivity analysis. In this software the optimized results are presented categorically for a particular set of sensitivity parameters like wind speed, maximum annual capacity shortage (MACS), minimum wind energy penetration (MWEP) and fuel price in the present case. The optimization and sensitivity results are presented in the forthcoming paragraphs.

5.1. Optimization results

The optimization results for a wind speed of 4.95 m/s, the MACS of 0%, MWEP of 0% and a fuel price of 0.1 $/L are summarized in Fig. 10. In this case, a diesel power system



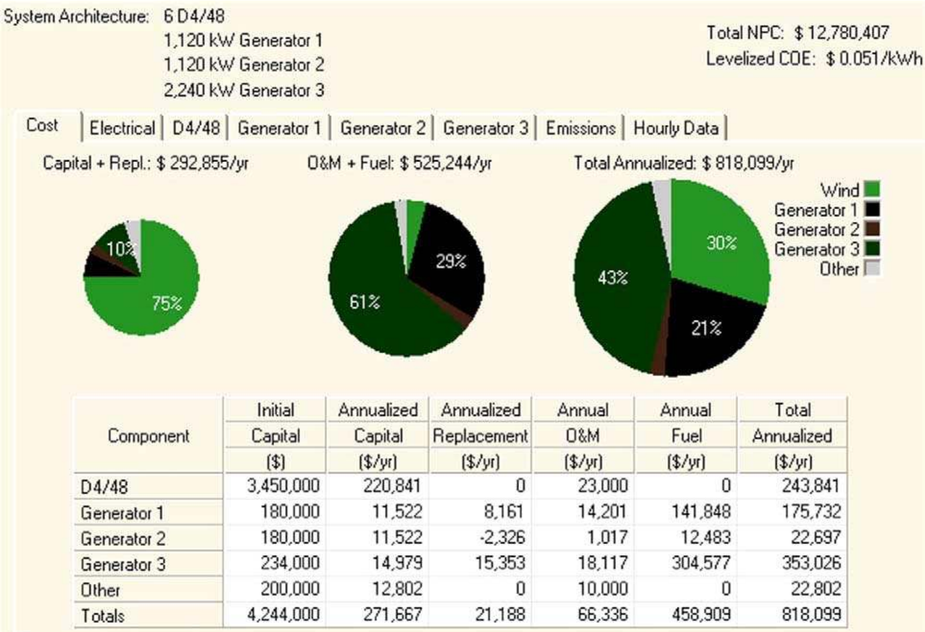
D4/48	Gen1 (kW)	Gen2 (kW)	Gen3 (kW)	Initial Capital	Total NPC	COE ($/kWh)	Ren. Frac.	Capacity Shortage	Diesel (L)	Gen1 (hrs)	Gen2 (hrs)	Gen3 (hrs)
	1120	1120	2240	$ 794,000	$ 11,008,221	0.044	0.00	0.00	5,796,730	4,268	639	7,651
1	1120	1120	2240	$ 1,369,000	$ 11,405,950	0.046	0.04	0.00	5,573,465	4,298	541	7,393
2	1120	1120	2240	$ 1,944,000	$ 11,648,380	0.047	0.09	0.00	5,356,878	4,411	473	7,105
3	1120	1120	2240	$ 2,519,000	$ 11,911,340	0.048	0.13	0.00	5,150,745	4,531	432	6,822
4	1120	1120	2240	$ 3,094,000	$ 12,183,836	0.049	0.17	0.00	4,952,275	4,609	395	6,545
5	1120	1120	2240	$ 3,669,000	$ 12,462,079	0.050	0.21	0.00	4,759,512	4,669	357	6,257
6	1120	1120	2240	$ 4,244,000	$ 12,780,407	0.051	0.25	0.00	4,589,087	4,718	338	6,019
7	1120	1120	2240	$ 4,819,000	$ 13,109,726	0.053	0.29	0.00	4,426,681	4,754	315	5,783
8	1120	1120	2240	$ 5,394,000	$ 13,465,808	0.054	0.33	0.00	4,280,568	4,765	289	5,585
9	1120	1120	2240	$ 5,969,000	$ 13,795,277	0.055	0.36	0.00	4,135,011	4,718	272	5,393
10	1120	1120	2240	$ 6,544,000	$ 14,143,560	0.057	0.39	0.00	4,000,068	4,669	259	5,219
11	1120	1120	2240	$ 7,119,000	$ 14,506,822	0.058	0.43	0.00	3,873,692	4,613	242	5,057
12	1120	1120	2240	$ 7,694,000	$ 14,873,185	0.060	0.46	0.00	3,750,464	4,545	225	4,889
13	1120	1120	2240	$ 8,269,000	$ 15,265,459	0.061	0.48	0.00	3,641,241	4,496	215	4,741
14	1120	1120	2240	$ 8,844,000	$ 15,666,378	0.063	0.51	0.00	3,537,284	4,428	204	4,616
15	1120	1120	2240	$ 9,419,000	$ 16,073,781	0.065	0.54	0.00	3,437,877	4,359	193	4,487

Fig. 10. Optimization results for wind speed of 4.95 m/s, diesel price of 0.1 $/L, wind operating reserve of 20% and maximum annual capacity shortage of 0%.

seems to be most feasible economically with a minimum total net present cost (NPC) of 11,008,221 $ and a minimum cost of energy (COE) of 0.044 $/kWh. This is merely due to low cost of fuel in Saudi Arabia, no carbon tax, no incentive on the usage of clean energy sources but subsidy on traditional energy usage and low intensity of wind speed at the location under investigation. Even at 6 m/s wind speed, the diesel system was found to be the most feasible solution with COE of 0.044 $/kWh but at 7 m/s the hybrid system with 5 wind machines and three generators was found to be the most feasible answer. In this case a 51% of wind penetration was achieved with a COE of 0.041 $/kWh and NPC of 10,158,187.

The Fig. 10 shows that for 25% of wind energy penetration the NPC was 12,780,407 $ and the COE of 0.051 $/kWh. This shows that with little hike of 0.007 $/kWh in COE, a 25% of wind energy penetration could be achieved compared to diesel only case. Furthermore, the diesel power system consumed 5,796,730 liters of diesel annually while the wind diesel hybrid power system with 25% wind energy penetration resulted into 4,589,087 liters diesel consumption i.e. a reduction of 20.83% in diesel consumption. As seen from Fig. 11, about 75% of the initial cost of the wind diesel hybrid system was accounted for wind equipment but the more than 90% of the O & M and fuel cost was accounted for diesel system. Similarly, the total annualized cost for wind equipment accounted for 243,841 $ (29.8% of the entire wind diesel power plant cost) while for diesel power system 551,355 $ (67.4% of the entire wind diesel power plant cost).

The energy yield from different components of the wind diesel hybrid system is shown in Fig. 12. Of the total primary energy requirement of the village, the wind machines produced 4,103,553 kWh (25% of the total energy served) while the diesel generators produced almost 74% of the energy i.e. 12,229,602 kWh. Although an excess energy of 390,390 kWh (2%) was produced but a capacity shortage of only 72 kWh was experienced



Component	Initial Capital ($)	Annualized Capital ($/yr)	Annualized Replacement ($/yr)	Annual O&M ($/yr)	Annual Fuel ($/yr)	Total Annualized ($/yr)
D4/48	3,450,000	220,841	0	23,000	0	243,841
Generator 1	180,000	11,522	8,161	14,201	141,848	175,732
Generator 2	180,000	11,522	-2,326	1,017	12,483	22,697
Generator 3	234,000	14,979	15,353	18,117	304,577	353,026
Other	200,000	12,802	0	10,000	0	22,802
Totals	4,244,000	271,667	21,188	66,336	458,909	818,099

Fig. 11. Wind diesel hybrid power system cost analysis for 25% wind penetration.

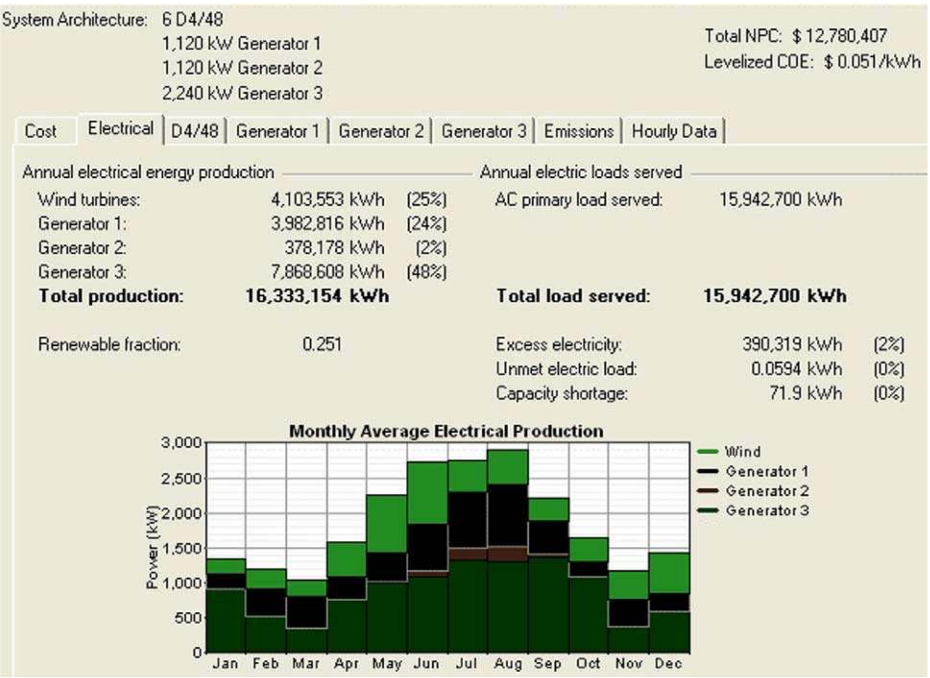


Fig. 12. Energy yield from wind machines and diesel generators.

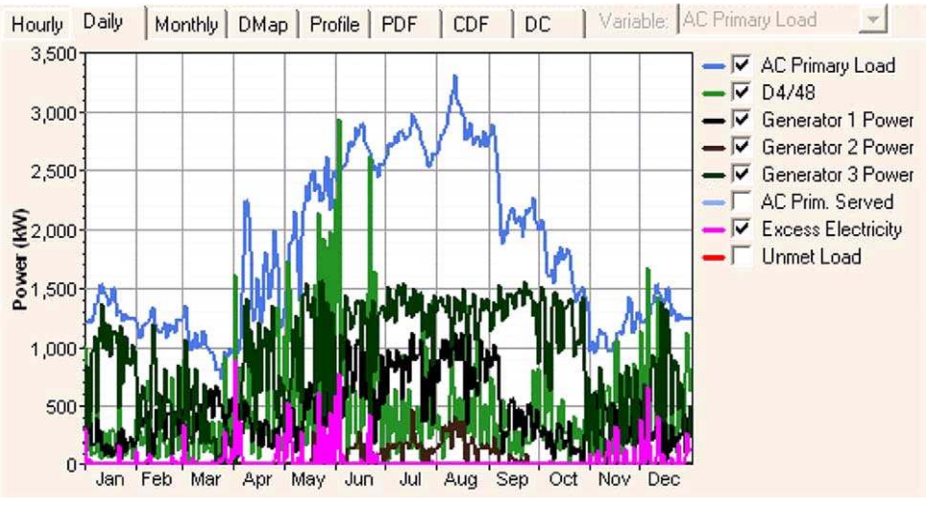


Fig. 13. Daily values of electrical load and energy supplied by wind and diesel generators.

during the year. The excess of energy and still capacity shortage may be accounted for larger sizes of the wind machines and the diesel generators and relatively higher wind speed in some months. The daily values of electricity requirement of the village and energy supplied by hybrid power system are shown in Fig. 13. The hybrid system with 25% wind energy penetration completely met the load of the village with negligible unmet load. Moreover, the wind diesel hybrid system produced 2% excess energy.

5.2. Sensitivity results

The HOMER software simulates all the systems in their respective search space for each of the sensitivity values. An hourly time series simulation is performed for one complete year. A feasible system is defined as the hybrid system which meets the required load. The software eliminates all infeasible systems and presents the results in ascending order of NPC. In the present case wind speed (4, 4.95, 6, 7 and 8), diesel price (0.025, 0.05, 0.075, 0.1, 0.125 and 0.15 $/L), wind energy operating reserve (0, 10, 20 and 30%), maximum annual capacity shortage (0, 3, 5, 7 and 10%) and minimum renewable energy fraction (0, 5, 10, 15, 20 and 25%) were used as sensitivity variables. A total of 3600 sensitivity cases were tried for each system configuration. Overall 248 systems were simulated for 3600 sensitivities which mean a total of 892,800 combinations were tried. The total simulation time was 7 h 59 min and 56 s on a Pentium IV Dell personnel computer having Intel Processor of 2.66 GHz and a RAM of 512 MB.

The optimization results are shown in terms of wind speed and diesel price in Figs. 14–16 for 0, 3 and 10% maximum annual capacity shortages, respectively. This type graphical representation of optimal system type provides information that a particular system will be optimal at certain wind speed and a certain fuel cost. Furthermore, the wind speed and diesel cost are usually site dependent so one can conclude that at a particular wind speed and fuel cost the system will be optimal for a particular place or location. The system

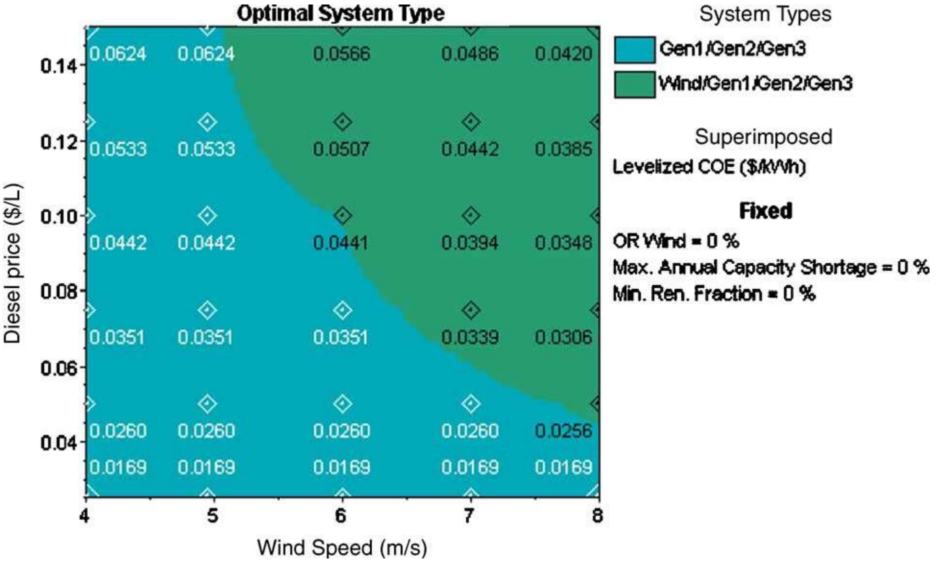


Fig. 14. Optimized wind diesel hybrid system for WOR = 0%, MACS = 0% and MRF = 0%.

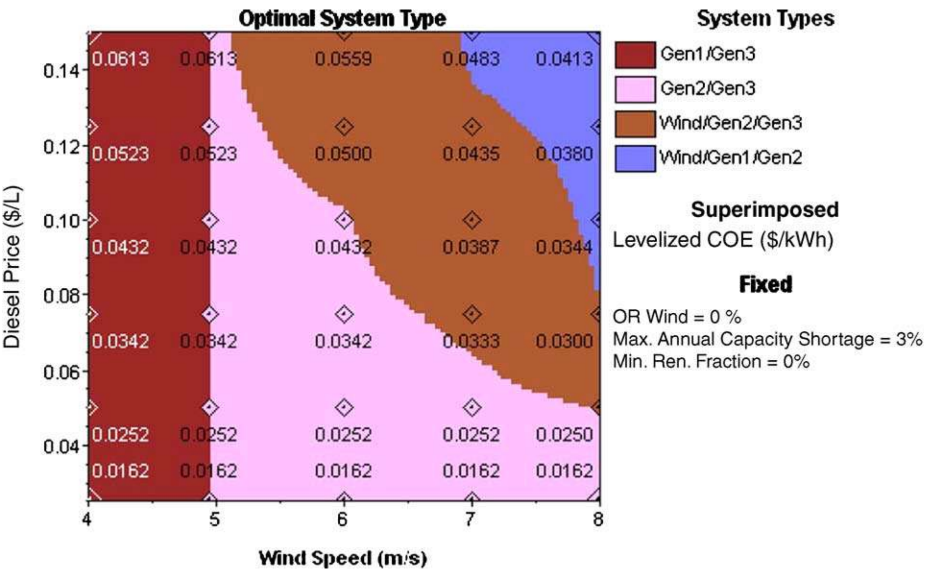


Fig. 15. Optimized wind diesel hybrid system for WOR = 0%, MACS = 3% and MRF = 0%.

shown in Fig. 14 reflects that for wind speed less than 5.0 m/s the diesel system is feasible over whole range of fuel costs for the village. At 6.0 m/s wind speed or more and diesel price of 0.1 $/L or more, the wind diesel hybrid system becomes economically feasible. The cost of energy of such a system was 0.0441 $/kWh.

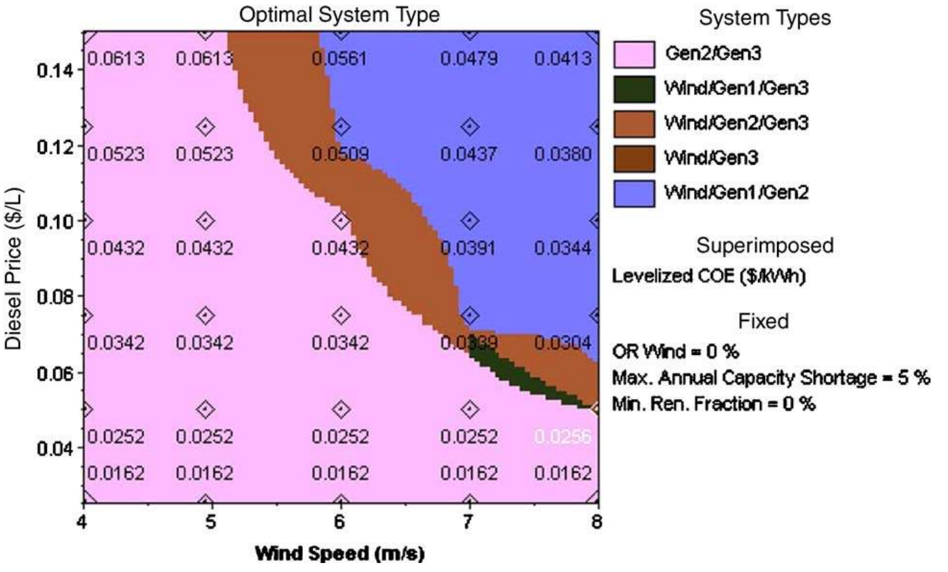


Fig. 16. Optimized wind diesel hybrid system for WOR = 0%, MACS = 5% and MRF = 0%.

With a minimal compromise on maximum annual capacity shortage (MACS) of 3%, the diesel system is the economical solution for wind speed less than or equal to 5.0 m/s and over entire range of fuel costs used in the present case, as shown in Fig. 15. The wind diesel hybrid system becomes economically acceptable only at wind speeds of 6.0 m/s or more and fuel price above 0.1 $/L. For a MACS of 5%, the wind diesel hybrid system becomes feasible only above 6.0 m/s wind speed and a fuel cost of 0.1 $/L or more like previous two cases, as can be seen from Fig. 16. The effect of MACS is not noticeable because of large load and larger sizes of the wind machines and diesel generators.

5.3. Green house gases (GHG) reduction

The GHG pollute the environment (air, water and soil) which ultimately adversely affect the life of human beings. An indirect or hidden cost, which is not taken into consideration while using fossil fuels, is paid by the human beings. The diesel power system being used at the village adds a total of 15,676,257 kg of pollutants into the local atmosphere of the village every year. The wind diesel hybrid system with 25% wind energy penetration, if used, can bring down the quantity of the pollutants to 12,410,395 kg per year. This shows a reduction of 3,265862 kg (approximately 21%) of pollutants every year. The concentrations of various constituents of pollutants like CO_2, CO, Nitrogen, etc. for diesel and hybrid system with 25% wind energy penetration are summarized in Figs. 17 and 18, respectively.

6. Conclusions

The study performed the economical feasibility for adding wind energy into the existing diesel systems to meet the load of the village. Under the existing wind speed scenario of the village and the range of fuel price used in the simulation, the existing diesel system was

Pollutant	Emissions	
Carbon dioxide:	15,264,700	kg/yr
Carbon monoxide:	37,679	kg/yr
Unburned hydrocarbons:	4,174	kg/yr
Particulate matter:	2,840	kg/yr
Sulfur dioxide:	30,654	kg/yr
Nitrogen oxides:	336,210	kg/yr

Fig. 17. GHG for diesel system.

Pollutant	Emissions	
Carbon dioxide:	12,084,576	kg/yr
Carbon monoxide:	29,829	kg/yr
Unburned hydrocarbons:	3,304	kg/yr
Particulate matter:	2,249	kg/yr
Sulfur dioxide:	24,268	kg/yr
Nitrogen oxides:	266,167	kg/yr

Fig. 18. GHG for WDH system.

found to be the feasible solution. The hybrid system becomes feasible when wind speed is $\geqslant$6.0 m/s and the fuel price is $\geqslant$0.1 $/L. The maximum annual capacity shortage did not have any impact on the system optimization. It may be accounted partially for larger sizes of the wind machines, the diesel generators and lower intensities of the wind speed. Since the wind data was not available for the village, so it was taken from a near by airport and used for simulation purpose. The study recommends collecting wind speed data at the actual site at three different heights using a wind mast of 40 m for at least one complete year. This data then must be used for final feasibility of the hybrid system.

Acknowledgements

The author wishes to acknowledge the support of The Research Institute of King Fahd University of Petroleum and Minerals, Dhahran, Saudi Arabia.

References

[1] Liu W, Gu S, Qiu D, Techno-economic assessment for off-grid hybrid generation systems and the application prospects in China, http://www.worldenergy.org/wec-geis/publications/default/tech_papers/17th_congress/3_2_17.asp

[2] Bagul AD, Salameh ZM, Borowy B. Sizing of a stand-alone hybrid wind-photovoltaic system using a three event probability density approximation. Solar Energy 1996;56(4):323–35.
[3] Markvart T. Sizing of hybrid photovoltaic–wind energy systems. Solar Energy 1996;57(4):277–81.
[4] Beyer HG, Langer C. A method for the identification of configurations of PV/Wind hybrid systems for the reliable supply of small loads. Solar Energy 1996;57(4):277–81.
[5] Protogeropoulos C, Marshall RH, Brinkworth BJ. Techno-economic optimization of autonomous wind/ photovoltaic renewable energy systems with battery storage. Proc 12th Eur Commun Photovolt solar energy Conf 1994;721–4.
[6] Fortunato B, Mummolo G, Cavallera G. Economic optimization of a wind power plant for isolated locations. Solar Energy 1997;60(6):347–58.
[7] Lundsager P, Bindner H. A simple, robust & reliable wind diesel concept for remote power supply. Renew Energy 1994;5(Part I):626–30.
[8] Hongyin Z, et al. The Development and review of wind/diesel systems of the world. New Energy (Chongqing, China) 1996;18(6):1–8.
[9] Azmi Bin Awi Wind-diesel Hybrid Power System for Off Grid-application in alaysia, C019.
[10] Shen Dechang, The Application of Small Size Windmills in Rural C022.
[11] Manwell JF, McGowan JG. Development of wind energy systems for new england islands. Renew. Energy 2004;29:1707–20.
[12] Barley CD, Lawrence TF, Benavidez PJ, Abergas RL, Barruela RB. Feasibility of Hybrid retrofits to Off-Grid Diesel Power Plants in The Philippines. Golden, CO: National Renewable Energy Laboratory; 1988.
[13] Khan MJ, Iqbal MT. Pre_Feasibility Study of Stand-Alone Hybrid Energy Systems for Applications in Newfoundland. Renew. Energy 2005;31:835–54.
[14] Ansari J, Madni IK, Bakhsh H. Saudi Arabian Wind Energy Atlas, KACST, Riyadh, Saudi Arabia; 1986. p. 1–27.
[15] Rehman S. Prospects of Wind Farm Development in Saudi Arabia. Renew. Energy 2004;30(3):447–63.
[16] Rehman S. Wind Energy Resource Assessment for Yanbo, Saudi Arabia. Energy Conversion and Management 2004;45(13–14):2019–32.
[17] Rehman S, Aftab A. Assessment of wind energy potential for coastal locations of the Kingdom Saudi Arabia. Energy—The International Journal 2004;29:1105–15.
[18] Rehman S, Halawnai TO, Mohandes M. Wind power cost assessment at twenty locations in the Kingdom of Saudi. Renew. Energy 2003;28:573–83.
[19] Mohandes M, Rehman S, Halawani TO. A neural networks approach for wind speed prediction. Renew. Energy 1998;13(3):345–54.
[20] Mohandes M, Halawani TO, Rehman S. Support vector machines for wind speed prediction. Renew. Energy 2004;29(6):939–47.
[21] Rehman S, Halawani TO. Statistical characteristics of wind in Saudi Arabia. Renewable Energy 1994;4(8):949–56.
[22] Rehman S, Halawani TO, Husain T. Weibull parameters for wind speed distribution in Saudi Arabia. Solar Energy 1994;53(6):473–9.
[23] El-Amin I, Shaahid SM, Rehman S, Al-Shehri A, Bakashwain J, Ahmad F. Performance and economic analysis of stand-alone hybrid wind-diesel power system for remote area applications of Saudi Arabia, European Wind Energy Conference (EWEC), 22–25 November; 2004, UK.
[24] Rehman S. Wind energy availability and capacity factor analysis. In: Proceedings of the 2nd BSME-ASME International Conference on Thermal Engineering, BUET, Dhaka, Bangladesh, January 02 to 04, vol. 2, 2004. p. 900–5.
[25] Rehman S, Ahmad A. Assessment of wind energy and capacity factor calculations for two locations of Saudi Arabia. In: Assessment of wind energy and capacity factor calculations for two locations of Saudi Arabia, vol. 2, 2004. p. 906–11.
[26] Rehman S, El-Amin I, Al-Shehri A, Bakhashwain J, Ahmad F, Shaahid SM. Utilization of wind-diesel systems to provide power requirements of remote settlements in Saudi Arabia, Fourth International Workshop on Large-Scale Integration of Wind Power and Transmission Networks for Offshore Wind Farms, Royal Institute of Technology, Electric Power Systems, 20–21 October; 2003, Denmark.
[27] Siddiqui AH, Khan S, Rehman S. Wavelet based computer simulation for wind speed in Saudi Arabia. In: Proceedings of the First Saudi Science Conference, King Fahd University of Petroleum and Minerals, Dhahran, Saudi Arabia, vol. 3, 2001. p. 3.

[28] Rehman S. Renewable energy education—its need and global status. Dhahran, Saudi Arabia: King Fahd University of Petroleum and Minerals; 2000.
[29] HOMER 2.14, National Renewable Energy Laboratory (NREL), 617 Cole Boulevard, Golden, CO 80401-3393, URL: http://www.nrel.gov/homer.
[30] DeWind, Publication, D4/48 600 kW wind machine technical description, http://www.dewind.de/en/downloads/D4-600-100-eng.pdf.