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Environmental and economic analysis for grid-connected hybrid photovoltaic-wind power system in a hot arid environment

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Abstract— In recent years, increased concern about global warming, acid rain and air pollution has revitalized interest in the hybrid renewable energy (HRE) system. In this paper, an investigation is made on small-scale operations of 100kWh per day HRE system as a grid-assisted power generation consisting of solar (photovoltaic) and wind energy. A comparison is drawn between a grid-connected HRE system operation and a standard grid operation focusing on environmental and economic impacts. Emissions and the renewable energy generation fraction (RF) of total energy consumption are calculated as the main environmental indicator. Costs including net present cost (NPC) and cost of energy (COE) are calculated for economic evaluation. To simulate long-term continuous implementation of the HRE system, the hourly mean global solar radiation and wind speed data of 2007, from Alice Spring $(23.70°S, 133.88°E)$ of Australia, are used as an example of a typical hot arid climate. The monthly solar exposure between 13.31 and 21.3 $MJ/m^2/\text{day}$ and mean wind speed of 7.13 m/s in 2007 is considered for simulation The Micropower Optimization Model software HOMER developed by the National Renewable Energy Laboratory, USA is used for simulation. It is found that, for Alice Spring arid climates, the optimum results of HRE system show a 64.3% reduction of emissions including CO_2, SO_2 and NO_x. The RF of the optimized system is 54%. It is also found that the HRE system has benefits of cost saving. The reduced NPC and COE are only equal to about 85.3% of energy consumption from standard grid. In addition, through a set of sensitivity analysis, it is found that the wind speed has more effects on the environmental and economic performance of a HRE system under the specific climate.

Keywords— environment; economy; hot arid region; hybrid renewable energy system;

1 INTRODUCTION

In industrialized nations there is rapid escalation in use of fossil fuels, particularly petroleum and its by-products. In recent years increased concern about global warming, acid rain and air pollution has revitalized interest in the application of renewable energy resource[1]. Renewable energy is going to play an important role in economy due to its advantages like less emission, less waste, less energy resource use and etc. A hybrid renewable energy system making most efficient use of the different renewable resource is used to ensure stable and reliable power generation [2].

In hot arid region, renewable energies have been used and are expected to improve the corresponding technical levels. [4-6]. Solar and wind energy are the main renewable energy applications. Healthcote [3] wrote that the UNESCO Arid Land Research Programme introduced a 15 m diameter rotor working in an average 20 km/h wind could provide $104,000\ kWh/yr$ power, which would support for lighting, water heating, pumping and refrigeration for a village of 100 families. Undoubtedly, future research will discover more efficient and useful ways of using wind energy in arid region. As to solar energy, various systems have been constructed to produce electricity power by massive arrays of photovoltaic cells or reflectors focusing the solar irradiation on to the cells setting on power towers [3]. The use of solar radiation in arid lands is also seen as extensive and likely to increase in the future [4]. Some literatures investigated the efficient ways to evaluating renewable energies and reported that there is abundant amount of solar and wind energies available in different arid land. For example, Sabziparvar [5] and Sabziparvar and Shetaee [6] determined a method of calculating the global solar irradiation through comparing the different methods and taking an example of the data in Iran. It is estimated that Atacama Desert could receive in one year the equivalent of all the fossil fuels used in the world in the mid-1960s [7].

For ensuring stable and continuous power, a hybrid renewable energy system including more than one type of energy component, is often used [8]. Some researchers have studied the feasibility of using a hybrid renewable energy system in hot arid region [9-12]. Mahmoudi *et al.* [13] investigated the weather data (hourly wind speed and solar radiation) for hybrid renewable energy system arid coastal countries. They assessed the feasibility of using HRE system (wind + solar) in the Arabian Gulf country of Oman. However, one of the problems of HRE system's application is that there is no normal, effective and achievable method to assess the environmental and economic performance of a HRE system. This study aims to discuss the environmental and economic factors of evaluating a HRE system. Nevertheless, this paper analyzed the environmental and economic benefits of HRE system used in hot arid environment. Alice Spring is taken as an example of the

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famous Australian hot arid land. It is the second largest city in the Northern Territory of Australia. The yearly mean rainfall (data of the years 1940 to 2008) is 279.2 mm [14]. In Alice Spring, temperatures can vary by up to 28 °C (82 °F) and rainfall can vary quite dramatically from year to year. In summer, the average maximum temperature is in the high 30s, whereas in winter the average minimum temperature can be 7.5 °C (45.5 °F). The climatic data is used to simulate the long-term implementation of the system.

2 ENVIRONMENTAL AND ECONOMIC ASSESSMENT FOR HRE SYSTEM

Environmental and economic aspects are the two of important aspects of sustainability. To evaluate the sustainable performance of a HRE system, these two impacts should be considered. The indicators of environmental and economic assessment can be determined by the five relevant meta-criteria: purpose; measurability; representativeness; reliability and feasibility; and communicability [15]. In this section, emission and renewable fraction are discussed as environmental indicators, and cost for economic indicator.

2.1 *Emission*

Emission of a HRE system includes carbon dioxide, sulfur dioxide and nitrogen oxides. Based on the Tokyo Protocol, CO_2 and NO_x are two types of the six main greenhouse gases [16]. SO_2 is one of the most important reasons for acid rain [17].Emission is measured as yearly emissions of the emitted gases in $Kg/year$ and emissions per capita in Kg/Kwh. Air emission of different HRE system can be estimated by the software HOMER [18].

Emission has representativeness for environmental assessment. The limitations of emission as a comprehensive measure of environmental assessment of a HRE system are from the problems associated with capturing and distinguishing all relevant negative impacts on the other aspects of environment, such as water, land and biomass diversity. In addition, emission levels do not embody information of the level of connotative impacts on long-term sustainability and health of life. However, emission is the most important reason for environmental pollution, and it is linked to the main environmental problems as greenhouse effect and acid rain. Thus, emission is used as viable headline assessment for the environmental domain. The calculated result of emission can be reliable and feasible, due to the solar radiation and wind speed data used in the simulation are reliable. They are collected from the local weather station of Bureau of Meteorology, Australia. The estimating method is based on the User Manual of the software HOMER [19], and its feasibility is confirmed by many literatures mentioned before.

Emission is widely accepted and understood as an environmental index. Gaseous emission has many important influences in terms of the choices, integration, and access to energy resources that make up other aspects of long-term sustainability (e.g., energy flow, material flow, and economic efficiency). In this study, the yearly emission of the hybrid renewable energy system is simulated.

2.2 *Renewable fraction*

Renewable fraction of a HRE system means the proportion of renewable energy generated divided by total energy generated. It means the extent of renewable energy in a HRE system. A greater value of this fraction presents a more renewable energy resource used. HOMER has the functions to calculate those two values and calculate the fraction directly.

Renewable fraction has representativeness for environmental assessment. It can be in turn divided into components fraction such as PV fraction (f_{PV}) and wind fraction (f_{WG}). In the study of Celik [20], the two fractions are calculated by the following equations,

$$f_{PV} = \frac{E_{PV}}{E_{TOT}} \quad (1)$$

$$f_{WG} = \frac{E_{WG}}{E_{TOT}} \quad (2)$$

where E_{PV} , E_{WG} and E_{TOT} are respectively the energy generation by photovoltaic, energy generation by wind generator and total energy generation.

2.3 *Cost*

The HOMER software can simulate the net present cost (NPC) and cost of energy (COE) of a hybrid energy system. The simulation input contains the initial capital, replacement cost, and operating and maintenance cost of each component of a HRE system. NPC means the present value of the costs of investment and operation of a system over its lifetime. NPC is used as a main economic indicator to compare an energy system [21]. COE ($\$/kWh$) is the average cost per capita of useful electricity produced by the system [21]. Smaller values of NPC and COE mean a less payment to match the same electricity load. For achieving a sustainable economic efficiency, it is to minimize these two types of cost.

3 HYBRID RENEWABLE ENERGY SYSTEM

A hybrid renewable energy system generally consists of more than one primary renewable energy component working in parallel with a secondary non-renewable component as a backup system. This study focuses on a grid-assisted photovoltaic/wind/battery system. Moreover, the system has a component of current converter. It also includes a battery for power storage when generated electrical energy is in access. Fig. 1 shows a general scheme of the system. HOMER, the micropower optimization model, can simplify do the tasks of evaluating designs of grid-connected power systems for a variety of applications and energy components. Fig. 2 illustrates the proposed scheme as implemented in the HOMER code. The additional information for load, energy components, energy resources and etc, are explained in the following sections.

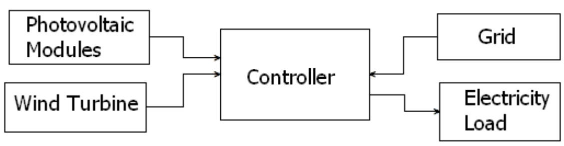


Fig. 1 Configuration of a grid-connected hybrid energy system

3.1 *Electrical load*

Load is an important element of a HRE system and any other power generating system. Air conditioner which is a main electricity consumer is used more frequently in summer. Fig. 3 shows the seasonal profile for an assumed load, an average value of 200 kWh/d. It is seen that there is peak of monthly mean load in December and January. As daily profile, the peak happens between 13:00 and 17:00 hours.

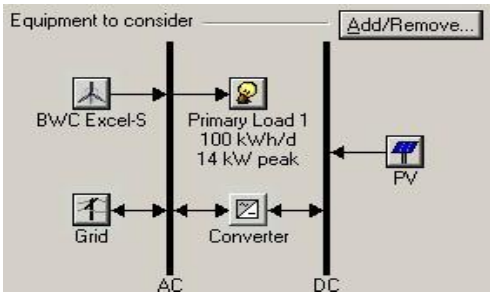


Fig. 2 Scheme of the hybrid system in HOMER code

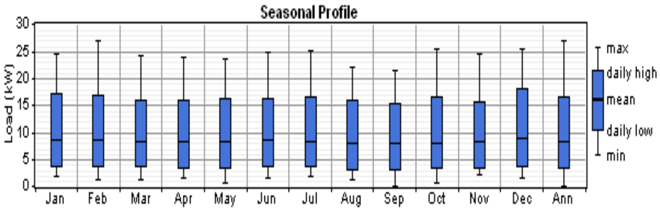


Fig. 3 Average daily load profile for a year

3.2 *Renewable energy resources*

3.2.1 Solar energy resources

Total daily global solar exposure derived from satellite data (MJ/m^2 per day) of the Alice Spring weather station ($23.3753°S, 150.4775°E$) for the year 2007 was collected from the Australian Bureau of Meteorology. The data shows that the exposure duration is longer than 4516 hours per year. Scaling was done on this data to consider the long-term average annual resource ($5.93\ kWh/m^2$ per day) for Alice Spring. HOMER introduces the clearness index from the location (latitude and longitude) information of the site under investigation. Fig. 4 demonstrates the daily radiation in kWh/m^2 per day and the clearness index curve over the period of the whole year. The monthly mean solar radiation is between 3.70 and 7.74 $MJ/m^2\ per\ day$. The maximum value was seen in December while the minimum one was in July. As seen from the Fig., Alice Spring region has more solar resource in summer than winter. Considering the annually variations, the sensitivity analysis is done with three values around the mean, which are: 4.5, 5, 5.5, 5.93, 6.5, 7, 8, 10 $kWh/m^2\ per\ day$.

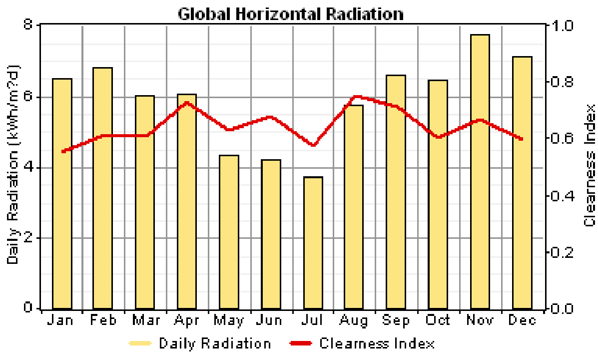


Fig. 4 Average daily global solar radiation data of Alice Spring Airport Weather Station, 2007

3.2.2 Wind energy resources

A three hourly mean wind speed dataset (m/s) of the Alice Spring Airport Weather Station which is 1 m height above ground surface, is collected from the Australian Bureau of Meteorology. Fig. 5 shows the monthly mean wind speed between 5.72 and 8.56 m/s. Similar to solar resource, wind resource also show more affluence in summer than winter.

The rotors of the modern wind machines are placed at heights varying between 50-100 meters, so this data was calculated at 100 meters hub height using boundary layer low [22]:

$$\frac{\bar{U}(z)}{\bar{U}(H)} = \frac{\log_e \frac{z}{z_0}}{\log_e \frac{H}{z_0}} \qquad (3)$$

Where z_0 is surface roughness lengths defined in Table 1.

Table 1 Typical Surface Roughness Lengths [22]

Type of terrain	Roughness length z_0 (m)
Cities, forests	0.7
Suburbs, wooded countryside	0.3
Villages, countryside with trees and hedges	0.1
Open farmland, few trees and buildings	0.03
Flat grassy plains	0.01
Flat desert, rough sea	0.001

At 100 meters height, the average wind speed became 7.13 m/s while at 10 meters it was only 3.82 m/s. Fig. 6 demonstrates that the wind speed mainly distributes between 4 m/s and 8 m/s. As seen from Fig. 5, the wind has shortage during June, July and August. Fig. 6 demonstrates wind speed data fitting a Weibull distribution with a scale parameter $k = 1.79$ and a shape parameter $c = 7.95\ m/s$.

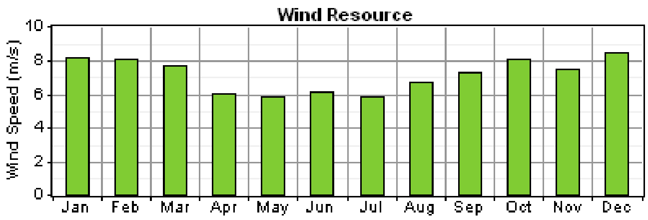


Fig. 5 Average monthly wind speed data of Alice Spring Airport Weather Station, 2007

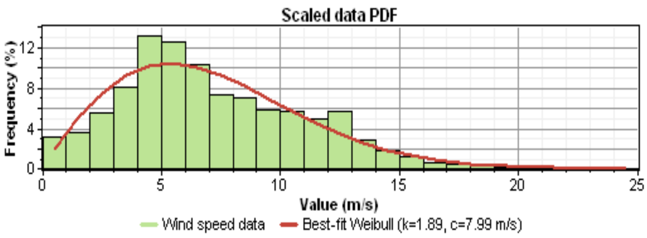


Fig. 6 Wind speed probability distribution function

To sum up, according to the data in the year 2007, renewable energy resource (including solar and wind energy) in Alice Spring is abundant in summer but relatively less in winter. It can be forecasted that the hybrid renewable energy system needs more grid electricity as complementarities.

3.3 *Hybrid system components*

The energy system components are photovoltaic modules, wind turbine, grid, battery, and power converter. This study develops a suitable assembly of the key parameters such as photovoltaic array power, wind turbine power curve, battery storage and converter capacity to match the predefined load. For economic analysis, the cost including the initial capital, replacement cost, and operating and maintenance cost are considered as simulating conditions. All the parameters are shown in Table 2.

3.3.1 *Photovoltaic arrays*

The initial cost of photovoltaic arrays may vary from $\$4.00$ to $\$5.00$ per watt [23, 24]. Considering a more optimistic system, the costs of installation, replacement and maintenance of a $1\,kW$ solar energy system are taken as $\$5000$ and $\$4000$. Sizes of the photovoltaic arrays are varied 0, 1, 2, 3, 4, 5, 6 and 7 kW.

3.3.2 *Wind turbine*

Energy generation form wind turbine depends on wind speed variations. The wind turbine rated power should be greater than average electrical load. Therefore, according to the load data discussed above, the average load is around $40\,kW$. Therefore, a BWC Excel-R turbine manufactured by Bergey Windpower is used. It's rated power is 7.5 kW DC.

3.3.3 *Grid*

Grid exists as a backup power component in this HRE system. When the renewable energy resource is not enough to meet the load, the electricity from grid is consumed. Moreover, grid has the functions as a storage system, so a grid-assisted power system does not need a battery [24].

3.3.4 *Power converter*

A converter is required for systems in which DC conponents serve an AD load or vice-versa. The HOMER software considers a converter as inverter (DC to AC), rectifier (AC to DC), or both. For an $1kW$ system the installation and relacement costs are taken as $800 and $750 respectively [25]. Seven different sizes of converter (0, 2, 4, 6, 8, 12 and 16 kW) are taken in the model lifetime of a unit is considered to be 25 years with an efficiency of 90%.

Table 2 Technical data and study assumptions of photovoltaic, wind turbine, grid, battery and converter

Description	**Value/Information**
PV	
Capital cost	$4000.00/kW
Life time	20 years
Operation & maintenance cost	$3200.00/kW
Size	0,1,2,3,4,5,6,7 kW
Wind Turbine	
Model of wind turbine	BWC Excel-R
Hub height	100 m
Capital cost	$27500
Life time	30 years
Operation & maintenance cost	$25000
Size	0,1,2
Grid	
Electricity Price	0.3 $/kWh
Emission factors (CO_2)	632 g/kWh
Emission factors (NO_x)	2.74 g/kWh
Emission factors (SO_2)	1.34 g/kWh
Converter	
Capital cost	$ 800/kW
Life time	25 years
Operation & maintenance cost	$ 750/kW
Size	0, 2,4,8,12,16 kW

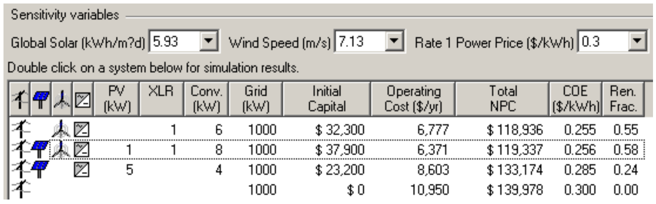
4 RESULTS AND DISCUSSIONS

The software HOMER provides the results in terms of optimal systems and the sensitivity analysis. Considering the electricity price fixed at $\$0.3/kWh$, the PV-wind grid-connected system can be varied to identify an optimal system type for Alice Spring region. In this software the optimization and sensitivity results will be presented in the forth coming paragraphs.

4.1 *Optimization results*

The optimization results for specific wind speed ($7.13\,m/s$), solar irradiation ($5.93\ kWh/m^2\ per\ day$) and grid electricity price ($\$0.3/kWh$) are summarized in Fig. 7. In this case, a wind power system seems to be most feasible economically with a minimum total net present cost (NPC) of $114,130 and a minimum cost of energy (COE) of $\$0.255/kWh$. This is due to the abundant wind energy resource in Alice Spring. In addition, the COE of wind turbine generator is more economical than solar array modules.

Fig. 7 shows that when renewable fraction was 58% the NPC was $119,337 and the COE was $0.256/kWh. This reveals that the economic performance of a PV-wind system is quite similar to the wind-grid system. The reduced NPC and COE are just equal to 85.3% of a standard grid power system. This PV-wind-grid case has greater renewable fraction (0.576) which means the bigger proportion of renewable energy power generations.


Sensitivity variables
Global Solar (kWh/m?d) 5.93 Wind Speed (m/s) 7.13 Rate 1 Power Price ($/kWh) 0.3
Double click on a system below for simulation results.

PV (kW)	XLR	Conv. (kW)	Grid (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.
	1	6	1000	$ 32,300	6,777	$ 118,936	0.255	0.55
1	1	8	1000	$ 37,900	6,371	$ 119,337	0.256	0.58
5		4	1000	$ 23,200	8,603	$ 133,174	0.285	0.24
			1000	$ 0	10,950	$ 139,978	0.300	0.00

Fig. 7 The optimization results of the HOMER simulation

The cost of the standard grid and the optimized PV-wind-grid system, are compared in Table 3. Obviously, the PV-wind-grid system is more economical, while the NPC and COE of the standard grid system are $139,978 and $0.3 /kWh. Table 4 shows the emission of the standard grid system and the optimized system. As the main greenhouse gas, the emission of carbon dioxide from standard grid is $23{,}068\ kg/year$, while the optimized system exhausts only $8{,}230\ kg/year$ which means 64.3% reduction. Meanwhile, the sulfur dioxide and nitrogen oxide emissions of the PV-wind-grid system are equal to less than 36% of a standard grid system. Fig. 8 shows that the cost summary of each components of PV-wind-grid system. The most costs are for the wind turbine.

Table 3 Cost comparison between standard grid and PV-wind-grid system

Types of Costs	*Standard grid*	*PV-wind-grid system*
NPC ($/year)	*139,978*	*119,337*
COE ($/Kwh)	*0.3*	*0.256*

Table 4 Emissions comparison between

Pollutant ($kg/year$)	*Standard grid*	*PV-wind-grid system*
CO_2	*23,068*	*8,230*
SO_2	*100*	*35.7*
NO_x	*48.9*	*17.5*

In the optimized PV-wind-grid system, the grid component costs the most money ($69,749), while the PV-gird system just costs $3,876. This is caused by the renewable energy components do not need any more cost for energy resource, but the grid component does. The wind component and the converter cost of $39,313 and $6,400 respectively.

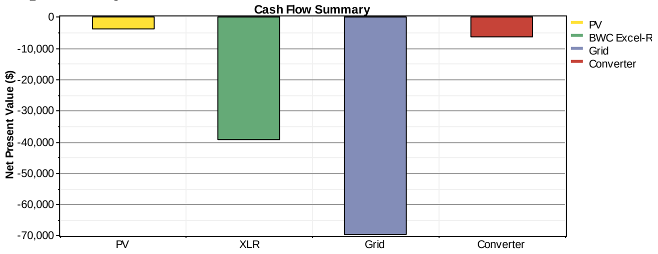


Fig. 8 Cost summary of the PV-wind-grid system

The monthly energy yield of each component of the PV-wind-grid system is shown in Fig. 9. Implementing under the specific electricity load ($100\ kWh/day$), the PV array produces 1,811 $kWh/year$ ($f_{PV}=4\%$). The wind turbine component produces almost 54% (24,275 $kWh/year$) of the system total energy production (45,306 $kWh/year$). In another word, the wind generation fraction f_{WG} of this system is 54%. In this system, the grid purchases share of 42% (19,220 $kWh/year$) of the total energy production.

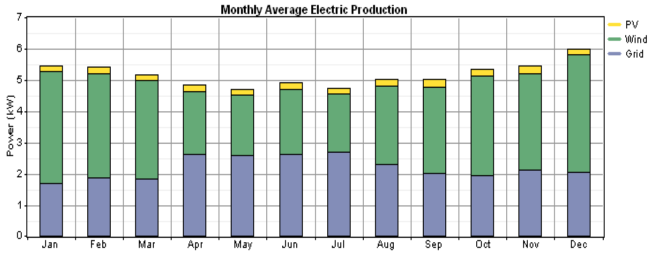


Fig. 9 Monthly average electric production of the PV-wind system

4.2 *Sensitivity results*

In this study, sensitivity analysis was done to study the effects of variation in the solar irradiation and wind speed. The simulation software simulates the long-term implementation of the hybrid system based on their respective search size for the predefined sensitivity values of the components. The emissions, renewable fraction, NPC and COE are simulated based on the three sensitivity variables: wind speed (m/s), solar irradiation ($kWh/m^2\ per\ day$), and grid electricity price ($\$/kWh$). For all of the sensitivity values HOMER simulates all the systems in their respective predefined search space. A long-term simulation for every possible system combination and configuration was done for one year period (from Jan 1st 2007 to Dec 31st 2007).

In the present case, solar irradiation is set as sensitivity variables: $G = 4.5, 5, 5.5, 5.93, 6.5, 7, 8, 10\ kWh/m^2/\text{day}$, while wind speed are: $v = 6, 6.5, 7, 7.13, 7.5, 8\ m/s$. Moreover, the grid electricity price is also defined as a sensitivity variable ($P = 0.15, 0.2, 0.3, 0.4\ \$/kWh$). A total of 192 sensitivity cases were tried for each system configuration. The simulation time was 17 minutes and 11 seconds on personnel computer with Intel CORE Duo Processor of 2.97GHz and a RAM of 4 GB.

The sensitivity results in terms of solar irradiation, wind speed and grid electricity price analyze the feasibility of each system. Here the feasibility of hybrid renewable energy system is analyzed based on emission reduction and cost saving. This type of sensitivity analysis of the systems provides information that a particular system would be optimal at certain sensitivity variables [26]. The PV-wind system is feasible when the grid electricity price more than $0.3/kWh. Under this condition, the RF can be between 0.55 and 0.65. A PV-wind system is feasible when global solar irradiation is more than $5\,\text{kWh/m}^2$ per day and the grid electricity price is more expansive than $0.3/kWh. Its RF can reach between 0.59 and 0.63. When the grid electricity price is constant at $0.3/kWh, the PV-wind system is feasible when the global solar irradiation is more than $5\,\text{kWh/m}^2$ per day and the wind speed is between $6.0-6.75\,\text{m/s}$. RF varies around 0.55.

Based on the optimization results, wind energy production shows a bigger proportion of energy generation than solar. While the solar power occupies less than 5% of the total energy generation, wind power occupies approximately half. Therefore, the wind energy resource has more impacts on the implementation. Fig.s 10-13 reflect the cost, renewable fraction and emissions variation dependent on the sensitivity variable wind speed. The NPC and COE of the hybrid power system (the configuration is undefined here) reduces when the wind speed increase from 6.0 m/s to 8.0 m/s. Simultaneously, as seen in Fig. 11, renewable fraction rise sharply from 0.24 to 0.48 (when wind speed increases from 6.00 to 6.5 m/s), and then steadily increases to 0.63 at slower rate. In addition, as shown in Fig.s 12 and 13, the main emissions of carbon dioxide, sulfur dioxide and nitrogen oxide persistently decrease 63%.

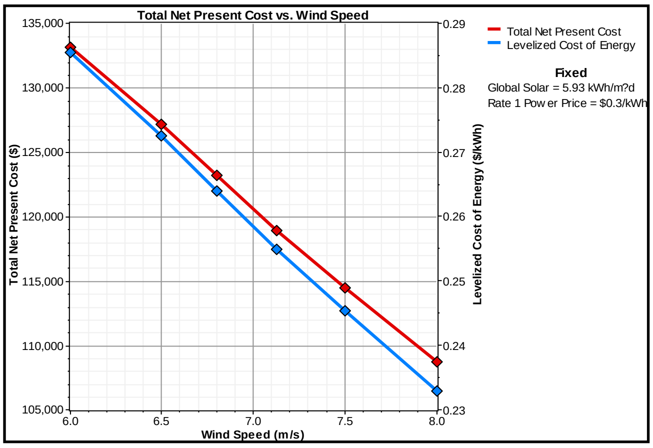


Fig. 10 The relationship between cost and wind speed

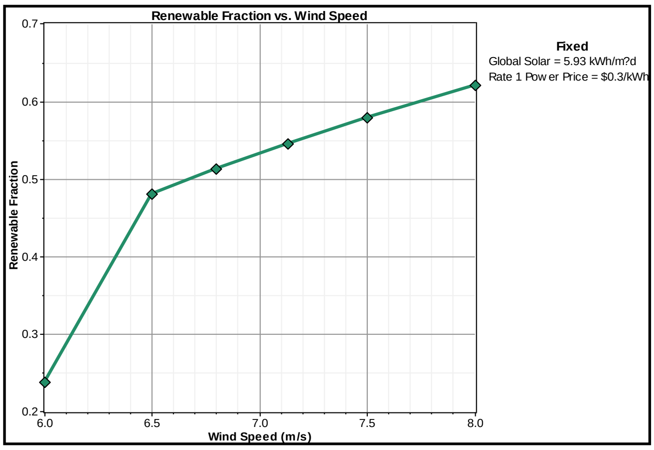


Fig. 11 The relationship between RF and wind speed

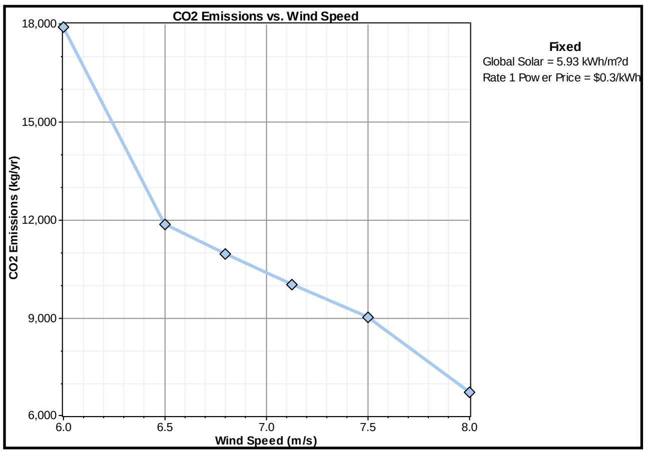


Fig. 12 The relationship between CO_2 emissions and wind speed

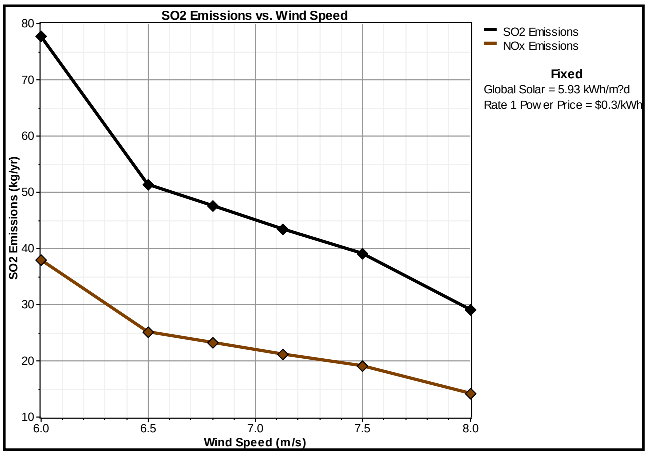


Fig. 13 The relationship between sulfur dioxide (nitrogen oxide) and wind speed

5 CONCLUSION

This study simulates a PV-wind grid-connected hybrid system in hot arid environment. The solar and wind energy resource data are collected from the weather station of Alice Spring which is a typical hot arid region. In 2007, the mean solar irradiation was $G = 5.93\,kWh/m^2$/day and wind speed was $7.13\ m/s$. The electricity load is assumed as $100\,kWh$ per day. The hybrid renewable energy system sizing is done using the software HOMER to meet the requirements of emission reduction and cost saving. The optimized HRE system, including a BWC Excel-R wind turbine and an 1 kW PV module, reduces the COE to \$0.256/kWh, while the standard grid electricity is defined as \$0.3/kWh. In addition, the emissions of CO_2, SO_2 and NO_x decrease to less than 40% of the standard grid power system. The sensitivity analysis indicates that PV-wind HRE system are feasible under the meteorological conditions in Alice Spring region. With the increasing of wind speed, the NPC, COE and emissions of the hybrid renewable energy system reduces, and renewable fraction grows up.

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