Energy resource quality assessment of PV/wind hybrid renewable energy system

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ABSTRACT:

Renewable energy is seen as one of the main solutions of energy crisis and climate change. With the widely application of renewable energy, it shows increasing interests on the sustainability assessment of energy system. Resource quality assessment is an important sub-indicator of sustainability index (SI) for evaluating energy systems. Hybrid renewable energy system (HRES) comprising of number of elements aims to convert any form of primary energy into final form of energy to be used for improving the quality of life. Energy conversion processes of the renewable energy components are characterized by the exergy efficiency. Although solar energy, wind energy and electrical energy are different in nature, exergy theory can be used to evaluate and compare them. The present study develops a method based on the thermodynamical analysis to quantify the resource quality of each type of renewable energy component of a PV/wind HRES. A case study of an optimized PV/wind power system in Central Queensland Region of Australia is presented in this paper. Through exergetic analysis of solar and wind energy resources and investigation on the generated electricity, the numerical results of exergy and exergy efficiency of the given system are discussed. It is found that the total exergy efficiency of renewable energy resources of the system is around twenty three percent. It is also found that wind energy shows greater quality than solar energy for the given HRES.

INTRODUCTION

Hybrid renewable energy system (HRES) comprising of more than one renewable energy components requires complex methodology for evaluating its sustainability. Energy resource quality is seen as a sub-indicator of energy system sustainability index which is closely related to the multi-dimensional space with five different scales: resource quality, economic quality, environment quality, technological quality and social quality (Afgan et al. 2005). The reliability is highly dependent on the climatic conditions which determine the quantity and quality of renewable energy resource.

A photovoltaic/wind HRES is studied in this energy resource quality analysis. In this system, sunlight is directly used by photovoltaic cell array, and wind turbine convert wind energy into electricity. In addition, grid is connected, when there is no sunshine and less wind flow, the grid power works as a backup system (Arribas et al. 2010).

Nomenclature	
A_{PV}	Area of PV array (m^2)
A_{WT}	Rotor's surface area of wind turbine (m^2)
C_p	Power coefficient of wind turbine (dimensionless)
E_k	Wind kinetic energy (kWh)
$\dot{E_k}$	Wind kinetic energy power (kW)
$E_{out.PV}$	Electricity generation of PV array (kWh)
$E_{out.WT}$	Electricity generation of wind turbine (kWh)
Ex_i	Exergy of the i-th component of the HRE system (kWh)
$\dot{Ex_i}$	Exergy ratio of the i-th component of the HRE system (kW)
Ex_{PV}	Exergy of PV array (kWh)
$\dot{Ex}_{PV}$	Exergy ratio of PV array (kW)
Ex_{sys}	Exergy of system (kWh)
Ex_{WT}	Exergy of wind turbine (kWh)
$\dot{m}$	Air mass flow through the rotor of wind turbine (Kg/s)
$\mathrm{N_b}$	Efficiency factor for wind turbine (dimensionless)
N_a	Electric generator efficiency (dimensionless)
$P_{th.WT}$	Theoretical power output of wind turbine (kW)
S_T	Total solar irradiation (W/m^2)
T_{amb}	Ambient temperature (℃)
T_{sun}	Sun temperature (℃)
$t_{r.i}$	Running time of the i-th component of the HRE system (h)
V	Wind speed (m/s)
$\eta_{\mathrm{alternator}}$	Electrical equipment losses (dimensionless)
$\eta_{mechanic}$	Mechanic equipment losses (dimensionless)
ρ	Air density (Kg/m^3)
ψ_{PV}	Exergy efficiency of PV array (dimensionless)
ψ_{WT}	Exergy efficiency of wind turbine (dimensionless)
ψ_{sys}	Exergy efficiency of system (dimensionless)

EXERGETIC ANALYSIS OF RENEWABLE ENERGY RESOURCE

Exergy is a thermodynamic property of a matter (Zeng and Ao 2002). It is an extensive parameter, like enthalpy and entropy (Perrot 1998). It can be destroyed by an irreversible process. Exergy analysis, an important part of thermo-economic analysis, is used widely in energy system analysis (Chai et al. 2009). The issue is that different energy conversion model has different exergy function. In addition, exergetic efficiency is used as a major factor in the present performance evaluating method for a solar cell (Chu and Liu 2009; EI-Sayed 2003; Fujisawa and Tani 1997; Ibrahim Dincer and Rosen 2007) and wind turbine (EI-Sayed 2003; Ozgener and Ozgener 2007). The essence of this evaluation method is to evaluate the renewable energy resource quality.

In order to further understand exergy, exergetic analysis and their significance, Koroneos and Katopodi simply highlighted three points as following (C. Koroneos and Katopodi 2006): i. a system which is completely balance with the environment does not contain exergy; ii. a system which is not balance with the environment includes exergy; iii. when energy quality reduces, exergy is destructed.

Exergy theory is used to assess various renewable energy systems, such as solar energy, wind energy, geothermal energy, and biomass (Chen and Chen 2007; Hepbasli 2008; Joshi et al. 2009; Koroneos et al. 2003). The present paper focuses on a PV/wind hybrid system, so just solar and wind energy resource are considered in the study.

The photovoltaic technology has its unique advantages due to the environmental benefits and free resource (Petela 2003). The exergetic analysis of its application has been studied from approximately 50 years ago. Petela proposed the formulae of exergy of thermal radiation (Petela 1961). Then, approximate function for direct solar radiation exergy is derived by Spanner (Spanner 1964). About two decades later, Jeter used Carnot efficiency to conclude the exergy of heat radiation. Petela claimed that no new concept on the exergy formula of heat radiation has been worked out. In fact, this say is judicial only in thermodynamic field. In quantum physics, the exergy and entropy constant of photon are concluded in the newest studies (Chen et al. 2008; Liu 2009).

In the past decades, there were a large number of literatures concerning the application of wind energy resource assessment and its application in various regions (Al-Abbadi 2005; Alawaji et al. 1996; Alawaji 1996; Connors 1996; Elhadidy and Shaahid 2007). Ozgener constructed a test facility to study the exergy analysis wind turbine and developed a experimental method to measure exergy efficiency based on the historical local wind energy resource (wind speed in m/s and temperature in ℃) (Ozgener and Ozgener 2007). Koroneos and Katopodi also claimed that the exergy efficiency of wind turbine depends on its type, rotor diameter and wind speed, and gave the exergy loss according to these three factors (C. Koroneos and Katopodi 2006; Koroneos et al. 2003). Moreover, Xydis et al. (Xydis et al. 2009) proposed a novel methodology for spatial correlation and exergy evaluation for assessing the wind energy resource for a wind farm. This exergy evaluation is based on the electrical losses method which is from Vogastad's thesis (Vogstad 2002).

METHODOLOGY

It is believed that the main advantage of exergy analysis is to build the relationship between the real output and the theoretical one. This study uses exergy efficiency to indicate the renewable energy resources quality of the HRE system. In this section, the configuration of the system is introduced; and the method of exergy calculation and exergy efficiency calculation of solar and wind renewable energy resources are discussed. The total exergy efficiency of the whole system is introduced to represent the resources quality of HRES.

System description

A hybrid renewable energy system generally comprises more than one primary renewable energy component working in parallel with a secondary non-renewable component as a backup system (Liu et al. 2009). The system involved in this study, consists of two renewable energy components: a solar energy component (photovoltaic) and a wind energy component (wind turbine). Fig. 1 shows the configuration of the system. The grid is existed as a backup system working when the renewable energy product is not enough to deal with the electricity load.

Exergetic analysis of solar energy

The exergy analysis of solar energy is closed relative to the concept of exergy analysis of thermal radiation. In this study, the Petela's exergy calculation model as shown in Eq. (1)

of solar radiation is used (Joshi et al. 2009; Petela 2003):

$$\dot{Ex}_{PV} = \left[1 + \frac{1}{3}\left(\frac{T_{amb}}{T_{sun}}\right)^4 - \frac{4}{3}\left(\frac{T_{amb}}{T_{sun}}\right)\right] S_T A_{PV} \tag{1}$$

In this study, the exergy efficiency of photovoltaic component can be given by Eq. (2):

$$\psi_{PV} = \frac{E_{out,PV}}{Ex_{PV}} = \frac{E_{out,PV}}{\dot{Ex}_{PV} \cdot 366} \tag{2}$$

By substituting (1) to (2), the exergy efficiency of PV system is given by Eq. (3):

$$\psi_{PV} = \frac{E_{out,PV}}{\left[1 + \frac{1}{3}\left(\frac{T_{amb}}{T_{sun}}\right)^4 - \frac{4}{3}\left(\frac{T_{amb}}{T_{sun}}\right)\right] \cdot S_T A_{PV} \cdot 366} \tag{3}$$

As seen from Eq. (3), the exergy efficiency of the photovoltaic component, ψ_{PV}, is a function of three ambient variables: ambient temperature, T_{amb}; sun temperature, T_{sun}; and total solar irradiation, S_T. These variables are measurable.

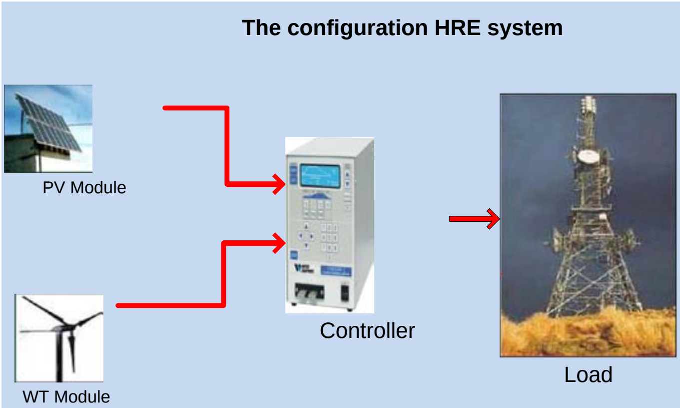


Fig. 1 The configuration of the PV/wind hybrid renewable energy system

Exergetic analysis of wind energy

When the wind goes through the rotor surface of a wind turbine, the wind energy (kinetic) is given by Eq. (4):

$$\dot{E}_k = \frac{1}{2}\dot{m}V^2 = \frac{1}{2}\rho A_{WT} V^3 \tag{4}$$

The theoretical power output, P_{th}, of wind turbine is given by Eq. (5) (Burton et al. 2001):

$$P_{th} = \frac{1}{2} C_p \rho A_{WT} V^3 \tag{5}$$

Where, C_p is the power coefficient. It presents the fraction of the maximum energy in the wind that may be converted by the wind turbine into mechanical work. The theoretical maximum value is limited by Betz law, up to 0.593 (16/27). Realistically, a wind turbine is unable to exploit the 59.3% of wind energy. Koroneos and Katopodi highlighted the two more efficiency factors (C. Koroneos and Katopodi 2006):

- N_g: Electric generator efficiency for inductive generators connected to the grid.
- N_b: The efficiency factor for wind turbine which converts wind energy into electricity.

Similarly, in Ozgener's study (Ozgener and Ozgener 2007), these two efficiency factors were determined as electrical equipment losses ($\eta_{alternator}$) and mechanic equipment losses ($\eta_{mechanic}$); and were respectively $\eta_{alternator} = 0.98$ and $\eta_{mechanic} = 0.97$. According to the idea of the present authors, the electrical equipment losses and mechanic equipment losses is described by: $(1 - \eta_{alternator})$ and $(1 - \eta_{mechanic})$ respectively.

Therefore, the exergy efficiency can be give by Eq. (6):

$$\psi_{WT} = \frac{E_{out,WT}}{E_k} = \frac{E_{out,WT}}{\dot{E_k} \cdot 8760} = \frac{E_{out,WT}}{\frac{1}{2}\rho A_{WT} V^3 \cdot 8760} \tag{6}$$

Obviously, the exergy efficiency, ψ_{WT}, embodies the meanings of the three partly factors: C_p, N_g and N_b.

Total exergy analysis

The exergy efficiency of the hybrid renewable system should reflect the exergy balance of the whole system, including all the renewable energy components. Therefore, the total exergy the system can be given by Eq.(7):

$$Ex_{sys} = \sum_{i=1}^{n} Ex_i = \sum_{i=1}^{n} \dot{Ex_i} \cdot t_{r,i} \tag{7}$$

In the present study, the system comprises of two renewable energy components: photovoltaic and wind energy. Therefore, the Eq. (7) can be written as Eq. (8):

$$Ex_{sys} = Ex_{PV} + Ex_{WT} \tag{8}$$

The exergy efficiency of the system is given by Eq. (9):

$$\psi_{sys} = \frac{E_{out,sys}}{Ex_{sys}} = \frac{E_{out,PV} + E_{out,WT}}{Ex_{PV} + Ex_{WT}} \tag{9}$$

Systematically looking into the present hybrid renewable energy system, the exergy flow through it can be analyzed by Eq. (9), which shows the ratio of exergy inflow by outflow. The total exergy efficiency ψ_{sys} is used as the criterion of resource quality assessment.

OPTIMIZED CASE STUDY

The local hybrid system running under the specific climatic conditions is optimized by HOMER software (Liu et al. 2009, 2010). Environmental and economic benefits are maximized by the optimized system. The system details and energy resource data are introduced in this section.

System details

The technical characters of the optimized system are shown in Tab. 1. The system includes 1 PV array (1 kW), 1 wind turbine (BWC Excel-R), one converter (2 kW) and electricity load (100kW/day). Fig. 2 shows the power curve of BWC (Bergey Windpower Co.) Excel-R wind turbine (Bergey 2010). The relationship between wind speed and the generated power is clarified. To explain the implementation details of the system, the electrical production of each component is shown in Fig. 3. The PV array generates $765\ kWh/year$ accounting for 2%, and the wind turbine generates $21,266\ kWh/year$ accounting for 44% of the total electricity. The left part of electricity (54%) is from the grid component.

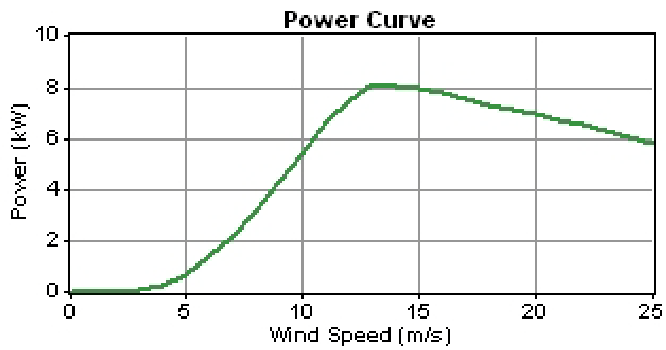


Fig. 2 The power curve of BWC Excel-R wind turbine

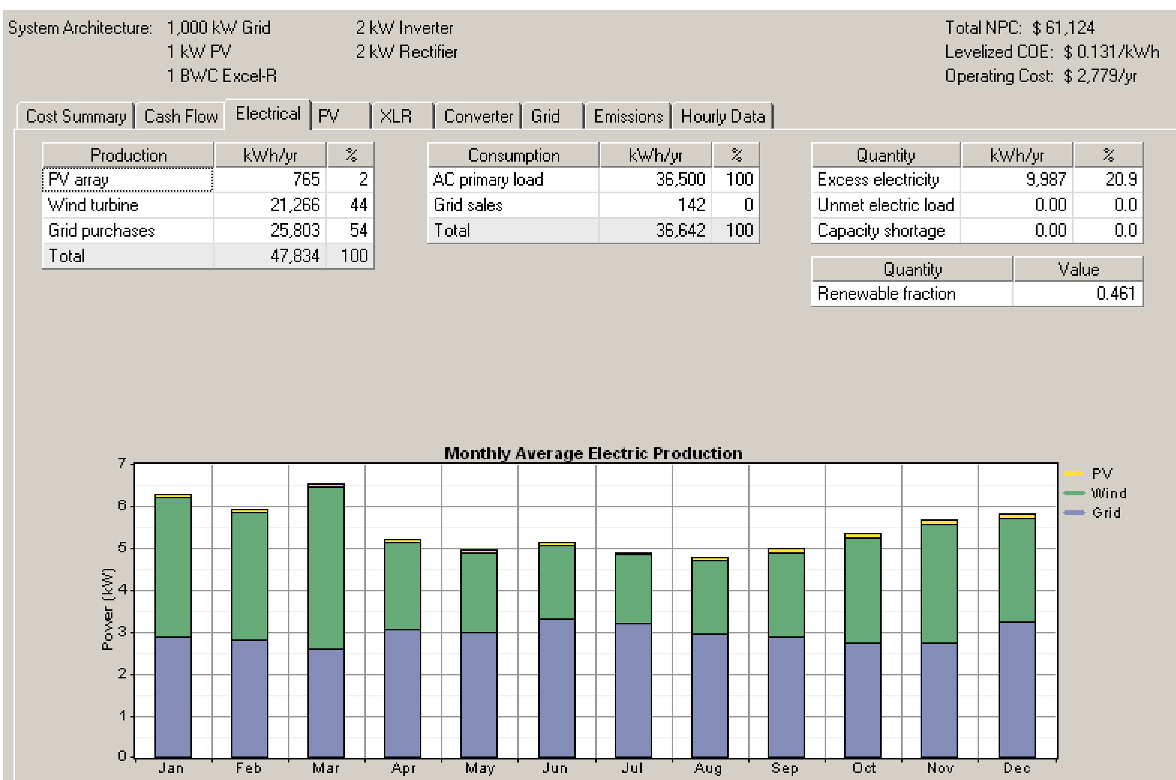


Fig. 3 The electrical production of each component of the optimized HRES

Tab. 1 Technical characters of the system including PV, wind turbine, grid and converter.

Description	**Value/Information**
PV	
Size	1kW
Wind Turbine	
Model of wind turbine	BWC Excel-R
Size	1
Grid	
Statement	Included
Load	100kW/day
Converter	
Size	2kW

Energy resource data

To sum up, solar irradiation and wind speed are the critical factors of respectively solar energy resource and wind energy resource. Therefore, the solar irradiation data and wind speed data are collected from the Bureau of Meteorology (BOM) of Australia (BOM 2010a). In this study, Queensland is a northeastern state of Australia, and Rockhampton is a major regional center of Central Queensland (Rockhampton 2010). The climate is classified as Subtropical (BOM 2010b). It lies within the southeast trade wind belt, too far south to experience regular northwest monsoonal influence, and too far north to gain much benefit from higher latitude cold fronts. Fig. 4 shows the solar irradiation map of Queensland region. The yearly solar irradiation for Rockhampton is between 15 and 18 MJ/m^2. In order to have an intuitive understanding of the general conditions of solar and wind energy, Fig. 5 shows the wind frequency analysis. The highest frequency of wind at 9 a.m. is southwestern and more than 30 km/h, while the west wind at 3 a.m. is about 25 km/h.

Fig. 4 Historical average daily solar exposure of Rockhampton between 1990 and 2008(BOM 2010a).

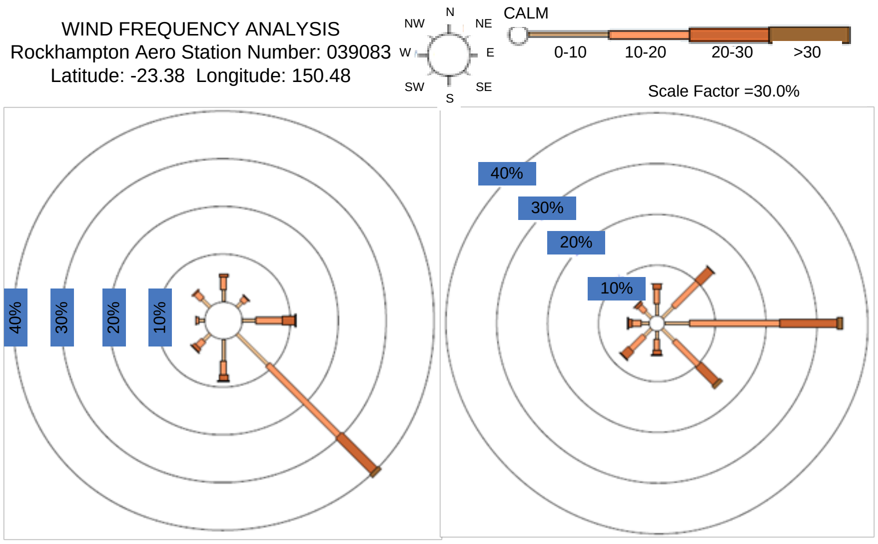
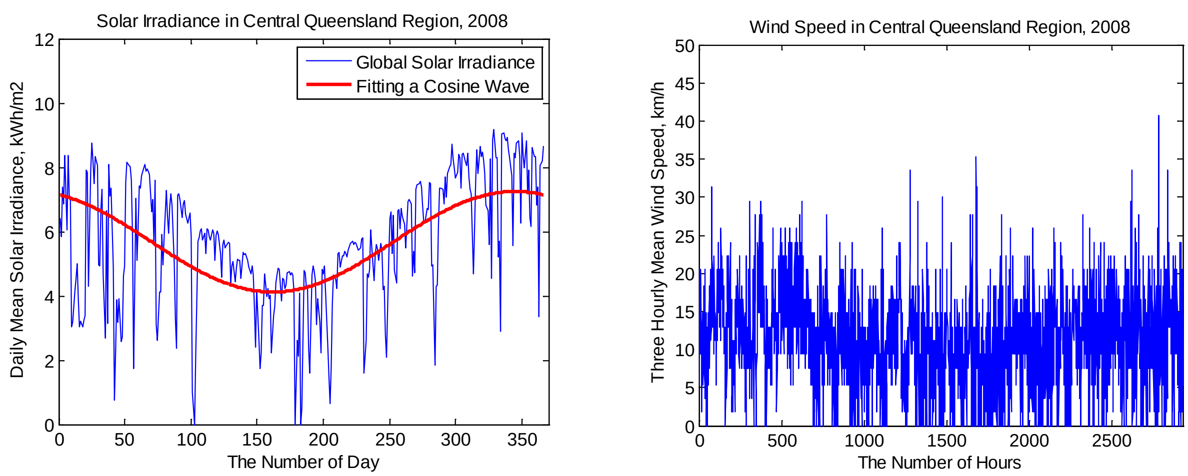


Fig. 5 Wind frequency of the Rockhampton between 1939 and 2004. (a). Wind frequency of Rockhampton at 9 a.m.; (b). Wind frequency of Rockhampton at 3 P.m. (BOM 2010a).

This study used the daily global solar irradiation data and three hourly mean wind speed of Central Queensland Region of Australia. Fig. 6 shows the collected data and supplies the details of the two sets of data.



(a) (b)

Fig. 6 Renewable energy resource data in Central Queensland Region in the year 2008.
Weather station name: Rockhampton Aero; Coordinator (latitude/longitude): (-23.3753, 150.4775); Height of the weather station: 10 meters; Number: 039083; WMO (World Meteorological Organisation) Index Number: 94374; Period: 1/Jan/2008 - 31/Dec/2008; (a) Daily solar irradiation and the fitted cosine function: $S_T = 1.564\cos\left(\frac{2\pi D}{366} + 0.3674\right) + 5.6873$, where S_T is the irradiation in kW/m^2 and D is time in day; (b) Three-hourly wind speed data in m/s. Considering of the height of the wind turbine is above on the weather station, the wind speed data set is processed by boundary layer law (Burton et al. 2001): $\overline{U}(z) = \overline{U}(H)\frac{\ln(z/z_0)}{\ln(H/z_0)}$.

Given the Eq. (1) and (5), the ambient temperature and air density are important parameter for exergy calculation. Therefore, the monthly average temperature of the year 2008 is collected from BOM of Australia (Fig. 7). Moreover, the standard conditions air density ($1.29\ Kg/m^3$) is used in this study.

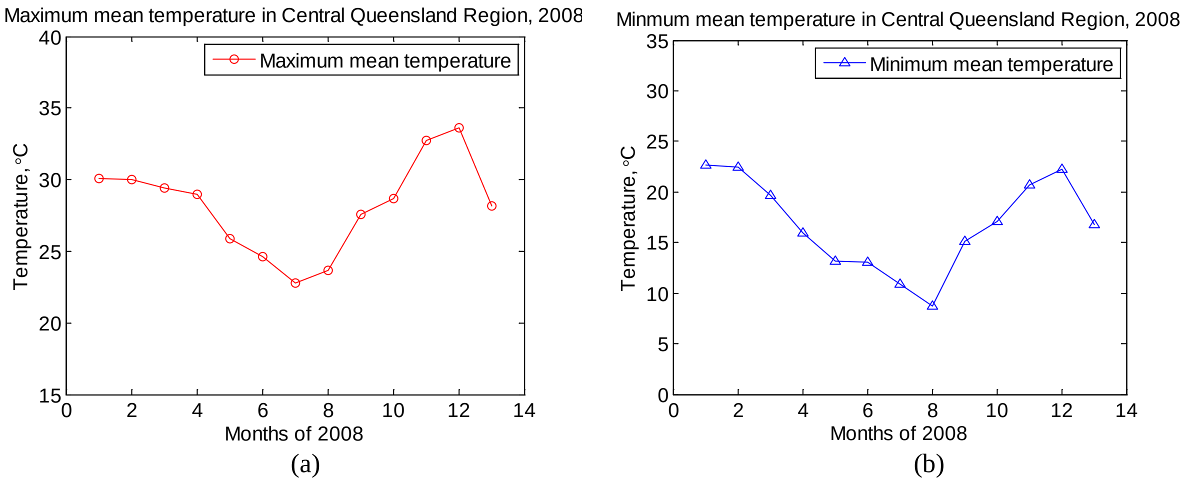


Fig. 7 Monthly mean temperature of Central Queensland Region of Australia, 2008. (a). Monthly maximum mean temperature, ℃; (b). Monthly minimum mean temperature, ℃.

Results and discussion

From the 1st January 2008 until 31st December 2008, the optimized PV/wind HRE system of Rockhampton region generated electricity $22,031\ kWh$, including $765\ kWh$ from the PV module and $21,266\ kWh$ from the wind turbine component as shown in Tab.2. The maximum available solar energy and wind energy for the system are respectively $14,554\ kWh/year$ and $79,969\ kWh/year$. Consequently, the annual exergy efficiency of the system is 23.3%, which is lower than the usage efficiency of conventional energy. The PV component has an exergy efficiency of 5.3%, while 26.6% for wind component.

The monthly exergy of the given system is calculated and shown in Fig. 8. The left column of this figure reflects the exergy of renewable energy resource of each month of 2008, and the right column demonstrates the electricity generation from January to December of the year. Solar energy is relatively abundant in summer (from October to March), and December has most solar energy of $1,705\ kWh$. Wind energy has the same profile to solar energy, and there is most wind energy about $1.145 \times 10^4\ kWh$ in March. Totally, the system also has more energy resource in the same period of one year. In March, it is seen that there is most exergy of $1.164 \times 10^4\ kWh$. Similarly, the corresponding electricity generator and the whole system have the same profile of exergy during different periods.

Tab. 2 The annual electricity generation and exergy of the renewable energy resources for the system

Components	PV array	Wind turbine	Total
Electricity Output, kWh	765	21266	22031
Exergy, kWh	14535	79969	94504
Exergy Efficiency, %	5.3%	26.6%	23.3%

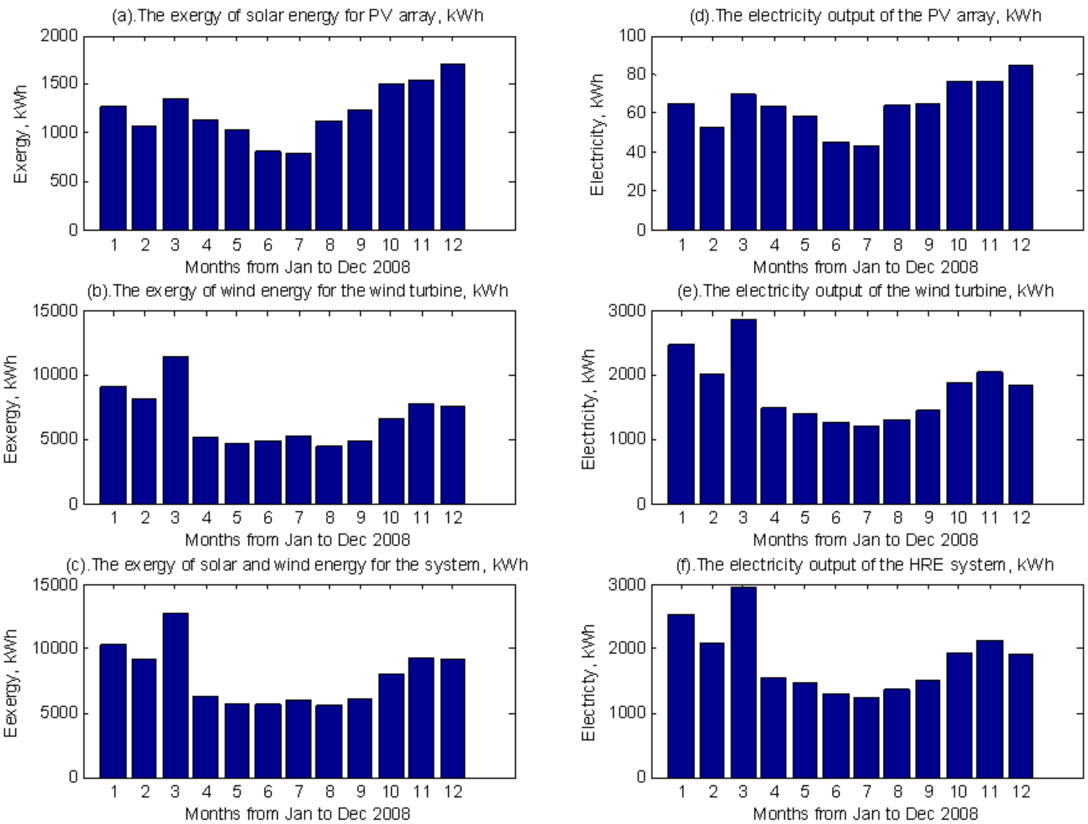


Fig. 8 Monthly exergy and electricity generation of PV, wind turbine and the renewable energy system

The monthly exergy efficiency of the components and the system are shown in Fig. 9. Because of the greater proportion of wind turbine in the system, the curve of the system efficiency has a similar profile to the wind turbine exergy efficiency in the year. Compared the three curves of exergy efficiency of PV, wind turbine and whole system, the PV module has lower exergy efficiency around 5%. Wind turbine has relative higher efficiency varying between 23 and 29.7 per cent. The monthly exergy efficiency of the whole system is between 20 and 25 per cent. The efficiency of the system arrives at the peak of 25.4% in May of 2008, while the lowest efficiency is 20.7% in July.

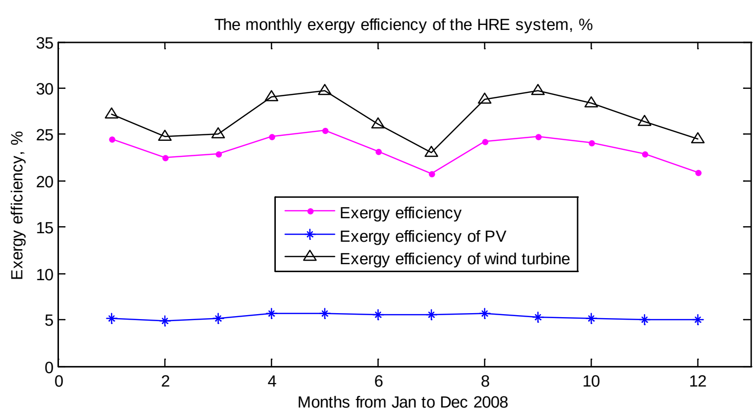


Fig. 9 Monthly exergy efficienty of the HRE system

CONCLUSION

This study focuses on the energy resource quality assessment which is one of sustainability indicators of HRES. The applied methodology for renewable energy resource quality assessment is based on exergy analysis and exergy efficiency calculation. Aiming at the optimized system including PV and wind turbine, the exergy and exergy efficiency calculating methods of solar and wind energy are discussed. Based on the local climatic data including solar irradiations and wind speed, the renewable energy resources quality of the PV/wind HRES case in Central Queensland Region was evaluated by the investigated exergy and exergy efficiency analysis method.

It was found that exergy analysis is an effective method for renewable energy resources quality assessment. It was also found that exergy efficiency is a practical parameter of indicating the renewable energy resources quality of HRES. For the case of the given HRES in Central Queensland Region under the climatic condition of 2008, the computed result of exergy efficiency is 23.3% which percentage is lower than the efficiency of conventional energies like coal. This exergy efficiency of renewable energy resources can be promoted by progressing exploitation technologies of renewable energies.

In such case, it is revealed that wind energy resource is playing a more important role in the given HRES, because wind energy has a bigger exergy efficiency of 26.6% while solar just shows 5.5% efficiency. Conventionally, although solar energy is primarily considered as renewable energy application in Queensland where is seen as the solar state of Australia, wind energy shows better quantity and efficiency for a HRES in the Central Queensland Region actually.

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