Renewable Energy 91 (2016) 374–385

Contents lists available at ScienceDirect

Renewable Energy

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

Techno-economic energy analysis of wind/solar hybrid system: Case study for western coastal area of Saudi Arabia

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ARTICLE INFO

Article history:
Received 20 April 2015
Received in revised form
27 December 2015
Accepted 24 January 2016
Available online xxx

Keywords:
Techno-economic analysis
Hybrid wind/solar system
Excess electricity
Energy cost

ABSTRACT

The potential of hybrid wind/solar energy system in the west coast area of Saudi Arabia is analyzed in this paper. The investigation puts emphasis on the energy production and cost of energy from both wind turbine and photovoltaic (PV) in the hybrid system. Unmet electric load and excess electricity are taken into consideration. The annual average solar irradiation and wind speed considered in this study are 5.95 kWh/m^2/day and 3.53 m/s, respectively. MATLAB and HOMER software are used to perform the technical and economic analyses of the hybrid system. As indicated from the simulation results, the PV array shares more electricity production than the wind turbine generator if both wind turbine and PV array are utilized in the wind/solar hybrid system with the same sizes. The wind levelized cost of energy is $0.149/kWh, which is more expensive than the solar energy of $0.0637/kWh. The energy cost of the hybrid system is dominated by battery and wind turbine expenses.

1. Introduction

The world is still injecting a considerable amount of investment in renewable energy resources. This trend has been driven by the continuous changes in the climate resulting in global warming. In recent years, many efforts have been made to increase the implementation of renewable sources of energy through researches and application, not only in the developed countries but also in the developing countries [1]. The increased exploitation is aimed at reducing carbon emission from energy generation and improving the reliability/security of energy supply [2].

Increase in fossil fuel consumption for electric power generation has forced the kingdom of Saudi Arabia to pay more attention on renewable energy generation. The kingdom now recognizes that reducing dependency on fossil fuel for domestic consumption will give positive impact on national economic growth and environmental issues. Generating some electricity from renewable resources instead of using fossil fuel will increase the revenue for the kingdom from petroleum. Moreover, it is predicted that CO_2 emission from fossil power generation system will increase for about 20% of the current global energy-related CO_2 emissions in 2030 [3]. This level of predicted CO_2 emission will be reduced if renewable energy resources are implemented for the power generation. However, the renewable energy cost is more expensive than the electricity cost from conventional energy in Saudi Arabia as reported in Ref. [4]. The gradual decrease in energy cost since several years ago and the need for environmental sustainability have led to the economic viability of renewable energy resources like solar and wind. The cost of renewable energy is proved to be less than that of conventional energy generation in Saudi Arabia if the indirect costs of fossil fuel are included, such as environmental and health costs [5]. Therefore, Saudi Arabia is also looking towards the development of renewable energy in the coming time [6]. Optimal management of renewable energy resources is a key necessity to ensure that maximum amount of energy is extracted from these resources. Several efforts have been done to optimize size of grid-connected photovoltaic (PV) energy system [7,8].

Saudi Arabia has some potential locations for renewable power generations. Solar and wind energy are the most important renewable energy source in Saudi Arabia [9]. Solar energy appears to be a promising candidate for electricity generation, while wind energy takes second place of renewable energy source in Saudi Arabia [4]. This is due to the viable wind speed potential of about 5.7 m/s [10,11] and the high solar radiation of around 2200 kWh/m^2

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http://dx.doi.org/10.1016/j.renene.2016.01.071
0960-1481/

[12,13]. Saudi Arabia, especially on coastal areas, has relatively large wind and solar energy which can be harvested.

Wind and solar energy are intermittent resources and are dependent on geographical and weather conditions. Standalone wind or solar energy systems will not generate accessible energy for noticeable time portion of the year [14] and they seem to be uneconomically. Hybridization of wind/solar energy systems for electricity are usually more reliable and less expensive compared to standalone wind or solar energy systems, as reported in Refs. [15–18].

In order to simplify the analysis of wind and solar hybrid systems, geographic and weather conditions can be omitted, as reported in Refs. [19]. However, for obtaining accurate results, the environmental site conditions have to be taken into consideration. The environmental factors are very specific and dependent on locations. Renewable energy such as wind and solar also vary with time of the day, season and type of terrain, all of which have impact on electric energy production and cost of energy [20,21].

Numerous researches have been conducted by researchers on the technical and economic analysis of renewable energy systems. Garcia et al. carried out an analysis of hybrid energy system with variable renewable generation and under flexible operation. The dynamical properties and limitations were identified and solutions for managing and mitigating high variability of renewable energy have been recommended [22]. In addition, an analysis of technical and economic feasibility of stand-alone hybrid system was conducted at a location in United Arab Emirates where a 500 kW optimal hybrid renewable energy system for the remote area was modeled and analyzed with 37% reduction in CO_2 emission as compared to the conventional diesel generator [23]. The authors in Ref. [24] evaluated a PV module performance by back surface water cooling under hot climate. Their model predicts various electrical and thermal parameters affecting the performance of the PV system. Murphy et al. analyzed the cost of reliable electricity by analyzing hybrid distributed generation systems, diesel and grid-connected solar in view of an unreliable electric grid in Uganda [25]. It was noted that the improved reliability increases cost, but the increase can be justified for users needing more reliability.

In this work, the techno-economic feasibility study of wind/solar hybrid system is analyzed for Yanbu, Saudi Arabia (Latitude: 24°05′20″ N, Longitude: 38°03′49″ E). Yanbu is located on the Red Sea coast area and has great wind potential [26,27] and good level of solar irradiation. Technical and economic analyses are performed for a wind/solar system with battery storages. MATLAB and HOMER [28] are used as tools that facilitate optimum design of the wind/solar hybrid systems. The analyses of the hybrid power system are performed by simulating system operation for the project lifetime. This simulation requires data on capital expenses, operation and maintenance, as well as replacement costs. For the simulation of the wind/solar hybrid system, the key variables to be examined are wind turbine, PV array, and battery sizes in order to determine which hybrid energy system configuration is optimal based on energy production, cost, unmet electric load, and excess electricity. The unmet electric load is defined as the electrical load that goes unserved because the electrical demand exceeds the supply and deficiency occurs. The excess electricity is the surplus electrical energy produced and must be dumped because it cannot be used to serve electrical load or to charge batteries (batteries are unable to absorb it all).

Moreover, the investigation places emphasis on energy production, served/unserved electricity demand, cost of energy (COE), and cost of wind/solar systems with battery storages. The best size of the combination of PV array and wind turbine for the wind/solar hybrid system is also investigated. The influence of battery storage size on the hybrid system is taken into consideration.

Geographical location of Yanbu is shown in Fig. 1. Weather data used in this work are real data for the location under study. For accurate results, environmental site conditions such as wind shear, site altitude, hub height, ambient temperature, and ground reflectance are included in the computation.

2. Wind and solar resources

2.1. Wind speed, direction, and power

A wind rose diagram provides details of typical wind speed distribution and direction at a specific location. It is commonly illustrated in a circular format and shows the wind blows frequency from particular directions. The spread of wind directions is important to give information on how to choose a wind turbine. The wind turbine with horizontal axis needs to face towards the wind to get the highest efficiency power generation.

Fig. 2 presents a wind rose diagram for Yanbu, based on one year of hourly wind speed data. The spoke length around the circle shows the frequency of time of wind blow for a particular direction. Every concentric circle indicates wind blow in a different frequency, which is zero at the center and larger frequency at the outer circle. This diagram shows that the wind at Yanbu is most often out from the west. There are 3 spokes around the west direction comprising 47.5% of all hourly wind directions. It shows a rare event for the wind to blow from the north or the southeast. The longest spoke or the winds from the west shows that in Yanbu the wind blows from the west at speeds above 5 m/s for about 10% of the time in a year.

The hourly wind speed data at Yanbu is shown in Fig. 3. The data is obtained by measuring wind speed at 10 m anemometer height. The wind speed varies between 0 and 12 m/s and rarely exceeding 12 m/s (0.79%). The annual average wind speed in Yanbu is about 3.53 m/s. The wind speeds of less than or equals 3.0 m/s are about 27.2% of the year. This means that the energy can be exploited for 72.8% of the year with 3.0 m/s cut-in-speed.

The vertical extrapolation of wind speeds at the wind turbine hub height can be done using two wind profile laws: the logarithmic law is defined as

$$u_2 = u_1 \frac{\ln\left(Z_2/Z_0\right)}{\ln\left(Z_1/Z_0\right)} \quad (1)$$

where the wind speed at hub height u_2 (m/s), the wind speed at anemometer height u_1 (m/s), the hub height z_2 (m), the anemometer height z_1(m) and the surface roughness z_0 (m), and the power law is defined as

$$u_2 = u_1 \left(\frac{Z_2}{Z_1}\right)^{\alpha} \quad (2)$$

where α is the wind shear exponent. The IEC standards [29,30] recommend a wind shear exponent value of 0.20 for onshore (normal) wind conditions and 0.11 for onshore (extreme) wind conditions.

Once the hub height wind speed has been specified, the wind turbine power output can be taken from the power curve, which is developed at wind speed under temperature and pressure standard conditions of (STP) as used in Ref. [31]. The expected power output is multiplied by the air density ratio to adjust to the actual power output of wind turbine, as follows: