Arab J Sci Eng (2014) 39:3827–3839
DOI 10.1007/s13369-014-0945-6

RESEARCH ARTICLE - ELECTRICAL ENGINEERING

Economic Modeling of Hybrid Renewable Energy System: A Case Study in Saudi Arabia

Ali M. Eltamaly · Khaled E. Addoweesh · Umar Bawa · Mohamed A. Mohamed

Received: 24 October 2012 / Accepted: 15 February 2013 / Published online: 8 February 2014

Abstract Renewable energy has great potential as an alternative source to supply electricity to the growing communities of modern world. However, the intermittent availability of renewable resources requires the use of hybrid systems so that the resources complement each other. This paper addresses the economic sizing of hybrid renewable energy using three sites of Saudi Arabia as a case study. A methodology is developed to determine the best wind turbine, WT type out of 140 wind turbines from different manufacturers and the best-fit WT for a site to maximize energy production. Similarly, the best-fit WT is matched with the best-fit PV arrays in a determined penetration ratio to meet the load requirements of the sites under study. A detailed economic methodology to obtain the price of kWh has been introduced. A new computer program has been introduced to handle the calculation of the whole system, and to select the best option for installing the hybrid renewable energy system.

Keywords Hybrid PV/wind/battery energy system design · Matching between site and hybrid renewable energy system · Cost of energy · New software for hybrid renewable energy system

A. M. Eltamaly (✉)
Sustainable Energy Technologies Center, King Saud University, P.O. Box 800, Riyadh 11421, Saudi Arabia
e-mail: eltamaly@ksu.edu.sa

K. E. Addoweesh · U. Bawa · M. A. Mohamed
Electrical Engineering Department, King Saud University, P.O. Box 800, Riyadh 11421, Saudi Arabia
e-mail: khaled@ksu.edu.sa

U. Bawa
e-mail: baumar@ksu.edu.sa

M. A. Mohamed
e-mail: dabdelaziz@ksu.edu.sa

الخلاصة

ان الطاقة المتجددة لديها امكانات كبيرة كمصدر بديل لتوليد الكهرباء للمجتمعات الناشئة في العالم الحديث. ومع ذلك ، فإن توافر الموارد المتجددة يتطلب استخدام نظم الهجين بحيث يكمل الموارد كل منها الآخر. فهذه الورقة تتناول حساب الحجم الاقتصادي الأمثل لأنظمة الطاقة المتجددة الهجينة وتطبيق ذلك على ثلاثة مواقع من المملكة العربية السعودية .فقد تم تطوير طريقة لتحديد أفضل توربينة رياح من 140 توربينة رياح من شركات مختلفة. وبالمثل ، تم اختيار أفضل نوع خلايا كهروضوئية لتعظيم إنتاج الطاقة. ثم تمت دراسة أفضل نسب قدرة بين طاقة الرياح والخلايا الكهروضوئية لتغذية الحمل المفترض لتلبية متطلبات الحمل في المواقع قيد الدراسة. وقد تم تقديم منهجية اقتصادية مفصلة للحصول على سعر كيلو وات ساعة. وكذلك تم تقديم برنامج كمبيوتر جديد للتعامل مع حساب للنظام بأكمله لإختيار أفضل حجم وأفضل أنوع التوربينات الهوائية والخلايا الكهروضوئية لكل موقع فى النظام الهجين بحيث تعطي أفضل سعر للطاقة المولده.

1 Introduction

Most of the remote areas in the vast land of Saudi Arabia depend on conventional electric energy sources such as diesel generators for their electric power supply. However, this conventional option depends on the availability of fossil fuel that is usually quite expensive. Besides that, the engines usually operate at low efficiency due to the typical loads in remote areas that vary considerably during the day and night. Therefore, using renewable energy that does not need fuel or does not affect the environment can be considered as a super solution for this dilemma. Renewable energy system can play an important role in generating the electricity without a need to fuel and to reduce the environment hazard. Usage of many renewable energy sources can increase the system reliability and reduce the price of generated kWh considerably.

In this paper, a methodology for pairing between sites and wind turbines and PV module types is presented. Using

hourly mean wind speed and solar radiation data, average wind turbine prices per kilowatt (kW), and different WTs from different manufacturers; an optimization is made to select the most economic WT and PV module for each site. This approach introduces the best site out of three sites under study and the most economic WT and PV module types for the selected site. A detail approach for computing the energy potential of PV and wind energy system is introduced. This paved the way for calculating the average area of solar cells to feed certain load. A proposed computer program is developed for a hybrid renewable energy electric system consisting of wind, PV and battery systems. The computer program has been built in Visual Fortran. 140 different types of wind turbines from different manufacturers and three different types of photovoltaic arrays have been used as a data for the computer program. Through loops of iterations, optimal system sizing of each component is achieved and the best type of WT and PV modules. The methodology is validated by selecting three sites in Saudi Arabia, namely, Yanbon, Dhahran and Dhulom.

2 Modeling of Hybrid Renewable Energy System Components

2.1 Design of the Wind Energy System

Wind energy is a form of solar energy produced by uneven heating of the earth's surface. Unlike any conventional power source, wind power is less predictable. Although, wind power source is less predictable than the solar power, it is typically available for more hours in a given day. Choosing of wind energy site based on the wind speed data is very important. Many literatures have been done to choose the best possible site from many available sites [1–6]. The power from the wind can be defined as:

$$P_{\mathrm{w}} = \frac{1}{2}\rho A_i u^3 \tag{1}$$

The actual wind turbine output power can be calculated from the following equation:

$$P_{\mathrm{W}}(u) = \left\{ \begin{array}{cc} 0 & u \le U_{\mathrm{C}} \\ P_{\mathrm{R}} * \frac{u-U_{\mathrm{C}}}{U_{\mathrm{R}}-U_{\mathrm{C}}}, & U_{\mathrm{C}} \le u \le U_{\mathrm{R}} \\ P_{\mathrm{R}} & u \ge U_{\mathrm{R}} \\ 0 & u \ge U_{\mathrm{F}} \end{array} \right\} \tag{2}$$

Using the above equation, the power output of a turbine can be modeled if the cut-in (U_{C}), cut-out (U_{F}) and rated wind speed (U_{R}) and the rated power (P_{R}) are known.

The speed of the wind is continuously changing, making it desirable to describe the wind by statistical methods. Weibull distribution will be used in the analysis of this paper. Weibull distribution uses scale, c and shape, k parameters. An accurate statistical method for obtaining Weibull parameters has been used in analysis [1–6]. The final results for the Weibull parameters are:

$$k = a$$
$$c = \exp(-b/k) \tag{3}$$

where

$$a = \left(\sum_{i=1}^{w}(x_i - \bar{x})\sum_{i=1}^{w}(y_i - \bar{y})\right) / \left(\sum_{i=1}^{w}(x_i - \bar{x})^2\right) \tag{4}$$

$$b = \bar{y}_i - a\bar{x}_i = \frac{1}{w}\sum_{i=1}^{w} y_i - \frac{a}{w}\sum_{i=1}^{w} x_i \tag{5}$$

and
$$\begin{aligned} y_i &= \ln(-\ln(1 - F(u_i))), \\ x_i &= \ln(u_i) \end{aligned} \tag{6}$$

The capacity factor of the wind turbine in certain site can be obtained from the following equation:

$$C_{\mathrm{F}} = \frac{\exp\left[-(U_{\mathrm{C}}/c)^k\right] - \exp\left[-(U_{\mathrm{R}}/c)^k\right]}{(U_{\mathrm{R}}/c)^k - (U_{\mathrm{C}}/c)^k} - \exp\left[-(U_{\mathrm{F}}/c)^k\right] \tag{7}$$

$$P_{\mathrm{W,av}} = C_{\mathrm{F}} * P_{\mathrm{R}} \tag{8}$$

The average number of wind turbines ANWT is given by the following equation:

$$\mathrm{ANWT} = \frac{P_{\mathrm{LW,av}}}{P_{\mathrm{W,av}}} \tag{9}$$

where $P_{\mathrm{LW,av}}$ is the average required load from wind turbine, $P_{\mathrm{W,av}}$ is the average electric power generated from each wind turbine.

2.2 Modeling of PV Energy System Generator

The orientation of the PV array against the movement of the sun determines the intensity of the sunlight failing on the modules surface, and therefore it will affect the system power output. The orientation will be facing south in the case of Saudi Arabia due to its location in the northern of the equator. The PV array surface should be positioned in a way that it is aimed directly perpendicular to the sun's rays. This will capture the maximum amount of sunlight to be converted into electricity. This can be easily achieved using a tracking system that follows the sun's trajectory at a particular time and day. However, a tracking system is costly and requires high maintenance. Therefore, various studies have been conducted on the optimum tilt and orientation angle for fixed surfaces. However, the optimum monthly tilt angle provides maximum power output from the system during the month. The tilt angle can be fixed at a certain angle all year round, seasonally, or monthly changed. In this paper, PV array is assumed to be