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Original article

Improving the reliability of photovoltaic-based hybrid power system with battery storage in low wind locations

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ABSTRACT

The optimum configurations of photovoltaic-micro wind hybrid power systems with battery storage are determined for 12 low windy locations in the Indian western Himalayas which will provide inputs to formulate a policy for the renewable energy based hybrid systems in the region. The objective is to utilize the available wind resource to supplement the solar resource for improving reliability and minimizing energy storage requirements of hybrid systems. In the analysis 7 micro turbines ranging from 1 kW_p to 5 kW_p are considered. The solar and wind resource assessment of the region shows good solar resource of 4.11–5.24 kWh/m^2/day but low wind resource with wind speeds ranging from 2 to 3.6 m/s. However, wind speeds more than 5 m/s are also available for about 1000 h annually indicating potential for small wind power generation. The feasibility analysis is carried out for 12 locations using measured data for one location and NASA satellite data for other 11 locations. A 1 kW_p micro-wind turbine with cut in speed of 2 m/s is found to generate maximum energy annually for these locations for a typical load. The methodology can be used for identifying optimum micro-wind PV hybrid systems for low wind locations worldwide.

Introduction

There is an increase in energy demand in India due to economic growth, rapid industrialization and fast growing population. India is fourth in per capita energy consumption after China, USA and Russia in [1].The greenhouse gas emissions, climate change issues and fast depletion of fossil fuels have stimulated the country's efforts to utilize renewable energy sources for power generation in recent years to reduce the dependence on conventional and fossil fuel based electricity demand. The total installed electricity capacity in India was 275.912 GW as on 31 July 2015 out of which renewable power generation constitutes 28% of the total installed capacity [2] thus having fifth position in world wide renewable power generation. Although government policies have steadily encouraged renewable power generation, yet there is a need to explore the renewable energy potential of the country in unexplored regions.

With about 300 clear sunny days in a year, India's theoretical solar power potential, on its land area alone is about 5000 trillion kilowatt-hours (kWh) per year. Therefore solar energy available in a year exceeds all fossil fuel energy reserves in India [3]. India has a total 4364.9 MW (both on grid and off grid) installed solar photovoltaic power generation capacity and 23864.9 MW installed wind power generation capacity as on 31st July 2015 [4]. The large scale wind power generation is mainly focused in coastal or remote areas where significant wind speeds are available throughout the year. However, there is new interest towards utilizing even the low to medium wind resources using micro-wind turbines or wind based hybrid energy systems, for which, analysis of wind characteristics is essential for a particular location of interest [5,6] .

Building sector is one of the potential areas for micro wind turbine based systems to reduce the conventional electricity consumption and improve reliability of solar based hybrid systems. The roof mounted wind turbines are at higher elevation, thus are exposed to higher wind regime as compared to ground based ones. Thus, wind based hybrid systems have the potential to make a significant impact on rooftop electricity generation which needs to be explored [7–10]. The integration of more than one renewable energy sources in a hybrid system not only improves the reliability and efficiency but also minimizes the energy storage requirement [11–14]. With the widespread adoption of hybrid energy systems, a number of research studies have been carried out for sizing, optimization, performance analysis etc. with PV and wind as main components of a hybrid system worldwide [15–23]. In the last

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Nomenclature

A_i	anisotropy index
COE	cost of Energy
$C_{ann,tot}$	total annualized cost [$/yr]
CRF	capital recovery factor
$C_{ann,tot}$	total annualized cost of the system [$/yr]
$E_{prim,AC}$	AC primary load served [kWh/yr]
f	factor used to account for 'horizon brightening' = $\sqrt{\frac{G_b}{G}}$
f_{pv}	PV derating factor [%]
G_b	beam radiation [kW/m^2]
G_d	diffuse radiation [kW/m^2]
G	global horizontal radiation on the earth's surface averaged over the time step [kW/m^2]
G_0	extraterrestrial horizontal radiation averaged over the time step [kW/m^2]
G_T	solar radiation incident on the PV array [kW/m^2]
$G_{T,STC}$	incident radiation at standard test conditions [1 kW/m^2]
i	interest rate (%)
N	number of years
R_b	ratio of beam radiation on the tilted surface to beam radiation on the horizontal surface
R_{proj}	project lifetime (yr)
T_c	PV cell temperature in the current time step [°C]
$T_{c,STC}$	PV cell temperature under standard test conditions [25 °C]
Y_{pv}	rated capacity of the PV array, meaning its power output under standard test conditions [kW]
θ	angle of incidence [°]
α_p	temperature coefficient of power [%/°C]
θ_z	zenith angle [°]
β	slope of the surface [°]
ρ_g	ground reflectance, which is also called the albedo [%]

few years, research is also focused on developing various types of micro wind turbines [24–31], however, no serious effort is done to exploit low to medium wind potential for power generation as yet.

The main objective of the study is to utilize the available wind resource to supplement the good solar resource for improving the reliability and efficiency to minimize the energy storage requirements of roof top hybrid systems. Thus in the present study focus is on identifying optimum configurations of photovoltaic based micro wind hybrid power systems in a complex hilly terrain with good solar but low wind regime. The techno-economic feasibility and annual power generation analysis of optimum configurations are carried out for 12 urban locations in the western Himalayan state of Himachal Pradesh (H.P) namely Bilaspur, Chamba, Hamirpur, Kangra, Kinnaur, Kullu, Lahaul & Spiti, Mandi, Shimla, Sirmour, Solan and Una.

The state is located in north-western Himalayas between latitudes 30.38°-33.21° North and longitudes: 75.77°–79.07° East, covering a geographical area of 55 673 km^2 [32,33]. The altitude ranges from 250 m to 6795 m which extends from Shivalik hill range to Dhauladhar mountain range and Great Himalayan range. This state having population of 6.856 million, more than 60% of which lives in rural and difficult remote areas. The state is known as hydro-power state of India [34–36], but focus is on exploring other renewable energy sources to meet the future power demand. A few research studies has been carried out to identify solar and wind resource of the state by a number of researchers [37–47].

The main focus of the present study is to identify suitability of solar- micro wind hybrid systems for 12 locations based on meteorological resource of the region. These locations are not explored as yet for PV-wind power generation as such the present study will not only provide inputs for decentralized power generation applications but also help in formulating a policy for the promotion of renewable energy based hybrid systems in the region.

The paper is organized as follows: detailed meteorological resource analysis is given in Section 2; Section 3 presents methodology; PV-micro wind based hybrid system is described in Section 4; Section 5 presents Results and discussion followed by Conclusions in Section 6.

Solar and wind resource assessment

The meteorological data for the location of interest are important for efficient utilization of PV and wind systems. The monthly averaged data for four meteorological periods (July-2011 to June-2015) are used in the present study for 12 locations are collected from two different sources as reliable measured data are available only for Hamirpur at present, whereas for remaining eleven locations measured data are not available. To overcome this problem in this study data used are obtained from National Aeronautics and Space Administration's (NASA) website [48] for rest of 11 locations. NASA has long supported satellite systems and research base to provide data like long-term estimates of meteorological quantities for the study of climate processes. These satellite and model-based predicted data can be used for sizing and designing of PV-wind based systems for preliminary feasibility analysis for regions where real time ground measured data are not available for a particular or nearby location. However, the accuracy of using such data has to be determined which will certainly be not as in case of using reliable measured data,. In this context the comparison of NASA data with measured data is also shown in the present study so as to have an idea about the accuracy of using such data.

This study used near real-time meteorological data coverage on ½° latitude by ½° longitude grid.The first data set used are the 1 min average measured data of Hamirpur location from the automatic weather monitoring station installed at CEEE, NIT-H (Lat. 31.68^{0}N, Long. 76.52^{0}E, elevation 875 m above mean sea level. The weather monitoring station is equipped with Young's propeller type anemometer with wind vane at 10 m height, pyranometer, rain fall, temperature, pressure, and relative humidity sensors with a C-1000 Campbell data acquisition system (Fig. 1).The detailed specifications of measuring instruments and sensors are given in Table 1.

Solar radiation, wind speed and temperature are the main parameters which affect the functioning of a hybrid power generation system as these parameters vary from location to location. In order to utilize wind and solar energy efficiently in a hybrid system, the analysis of these three parameters has to be made for the particular study location prior to designing a system. In this section two types of data inputs for 12 locations are used for solar radiation, wind speed and temperature for a four year period.

Solar resource

The two types of input solar radiation data used are: measured global horizontal radiation data (for Hamirpur) and NASA data of solar radiation for other 11 locations.