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Surface measured solar radiation data and solar energy resource assessment of Pakistan: A review

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ABSTRACT

Over the past decade, Pakistan has been facing a shortage of between 3000 MW and 6000 MW in the supply and demand of electricity, leading to several hours of power cut. Sixty-three percent of current electricity generation is based on fossil fuels, leading to cost vulnerability, whereas only one percent is based on renewable resources (non-hydroelectric). The geographical location and climatic conditions of the country offer a high solar energy potential, which signifies the need for solar resource assessment for the planning of solar energy projects. The article provides an overview of the solar resource assessment based on surface measured data and satellite data carried out by researchers. Various researchers have developed solar energy potential maps for the country based on solar insolation data measured by Pakistan Meteorological Department (PMD). The data measured by PMD reported in the previous literature have been compared with the long-term data from the World Radiation Data Centre (WRDC), and both data show good agreement. The approximate annual mean daily global horizontal insolation for the whole country, based on surface measured data by WRDC, is 5.30 kW h/m^2 (19.0 MJ/m^2 or 221 W/m^2). The government of Pakistan sought to exploit the solar and wind energy potential during the last decade with the help of international agencies. Based on satellite data, the solar resource assessment was done by National Renewable Energy Laboratory, USA (NREL) in 2007, and the Energy Sector Management Assistance Program (ESMAP) of the World Bank in 2015. The solar atlas prepared by NREL was not validated by the surface measured data, whereas the solar atlas prepared under ESMAP is to be validated in 2017. A comparison of NREL estimated data and WRDC data shows that NREL's atlas overestimates solar insolation up to 25% in some regions. The annual mean daily solar global horizontal insolation estimated under ESMAP is 5.67 kW h/m^2.

1. Introduction

Pakistan has been facing severe electricity crisis since 2007 due to the enormous difference in demand and supply leading to load shedding of several hours daily across the country. The installed generation capacity of the country is about 23,600 MW, and the power shortage is approximately 3000 MW to 6000 MW during peak hours [1–3]. The energy shortage becomes worse during the summer, leading to prolonged load shedding of between eight and eighteen hours, which varies significantly between urban and rural areas [1–3]. The country's energy mix is based on 63% of fossil fuels, out of which 37% is fuel oil, which means the cost of generation is expensive and highly dependent on oil price changes, leading to cost vulnerability. The energy produced by renewable sources (other than large hydroelectric) contributes less than 1% of the current energy mix [1,4]. The Alternative Energy Development Board (AEDB) Pakistan, reports that 28 solar power projects with a capacity of 956.8 MW are under development within the framework of the AEDB policies and procedures [5]. The solar market in the country is at a nascent stage, and the country has tremendous potential to meet its power needs from solar energy resources. According to AEDB [6] the wind energy has commissioned project capacity of 308.2 MW, under construction project capacity of

Abbreviations: AEDB, Alternative Energy Development Board Pakistan; CSR, NREL's Climatological Solar Radiation; DHI, Diffused Horizontal Irradiation; DNI, Direct Normal Irradiation; ESMAP, Energy Sector Management Assistance Program; GHI, Global Horizontal Irradiation or Insolation; GOES, Geostationary Operational Environmental Satellite; GTI, Global Solar Irradiation on Flat Plate Tilted at Latitude; IEA, International Energy Agency; kW h, Kilowatt Hour; MAPE, Mean Absolute Percentage Error; MBE, Mean Bias Error; MJ, Mega Joule; MPE, Mean Percentage Error; MW h, Megawatt Hour; NASA, National Aeronautics and Space Administration; NREL, National Renewable Energy Laboratory, USA; NWFP, North-West Frontier Province of Pakistan (now Khyber Pakhtunkhwa); PMD, Pakistan Meteorological Department; RMSE, Root Mean Square Error; SARI/E, South Asia Regional Initiative for Energy Cooperation; SSE, Solar Meteorology and Solar Energy service; SUNY, State University of New York at Albany; TW h, Terawatt Hour; UNDP, United Nations Development Program; USAID, U.S. Agency for International Development; WMO, World Meteorological Organization; WRDC, Mean Absolute Percentage Error

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477 MW and projects of 663 MW capacity are in the pipeline. The energy production for wind has been demonstrating a viable market for non-hydro renewable energy in the country.

The first ever solar power plant was inaugurated in Islamabad on May 29, 2012, under the project titled 'Introduction of Clean Energy by Solar Electricity Generation System', which is a special funding from the Japan International Cooperation Agency (JICA) under the Cool Earth Partnership. Two photovoltaic power (PV) plants each of 178 kW capacity were installed at the premises of the Pakistan Engineering Council and the Planning Commission of Pakistan under this project [7]. Quaid-e-Azam Solar Park, the first ever photovoltaic power station in Pakistan of 1000 MW capacity is under construction in Bahawalpur [8]. The solar power plants are under development in Punjab, Sindh, Balochistan and Kashmir under a development program by the International Renewable Energy Agency with the cooperation of China and private sector energy companies in Pakistan [7].

The utilisation of solar energy began in Pakistan in the 1980s. Pallet and Brabben [9] reported the installation and operation of twenty solar powered micro-irrigation units (solar water pumps) at research and private agriculture farms throughout the country with the support of the Pakistan Agriculture Research Council (PARC) and Agriculture Development Bank of Pakistan (ADBP). The Directorate General of Energy Resources, Ministry of Petroleum and Natural Resources started a program of solar villages, and the first solar energy system was installed in 1981; this solar village had a power capacity of 5 kW and the electric power was utilised for domestic purposes and water pumping [10].

In Pakistan, PMD started measuring solar radiation data for five meteorological stations and sunshine duration data for 37 stations from 1957. WRDC centrally collects and archives the global solar radiation data, which is the only reliable source to access long-term measured solar radiation data for Pakistan; the other source is PMD. The solar radiation data for Pakistan measured by PMD have been reported by many researchers [11–22] to estimate the solar energy potential of Pakistan. The solar energy potential maps (monthly and annual) for the country were first developed by Raja and Twidell [13,14] using surface measured data of global solar insolation and sunshine duration of 30 years, the annual mean daily solar irradiation (GHI) in the major parts of the country was estimated from 4.4 to 6.0 kW h/m^2 with mean of 5.3 kW h/m^2. Ahmad et al. [20] developed monthly maps of solar radiation (GHI) and reported that the annual mean daily solar insolation for the whole country is 5.5 kW h/m^2. The minimum annual mean daily solar radiation (4.3 kW h/m^2) of Pakistan is higher than the global annual mean daily (3.6 kW h/m^2), which reflects the excellent solar energy potential of the country [21].

The research work performed to estimate the solar resource assessment of Pakistan based on satellite data is limited [23–25] and not a single attempt has been made at the national level to estimate solar resource potential of the whole country using long-term satellite data. The National Renewable Energy Laboratory, USA (NREL), developed solar resource maps for Pakistan under the South Asia Regional Initiative for Energy Cooperation (SARI/E) program of the U.S. Agency for International Development (USAID), but these maps were not validated against surface measured data. The Energy Sector Management Assistance Program (ESMAP) of the World Bank developed maps for the solar resource estimate for Pakistan in the year 2015 under a three-year project, which will complete in 2017. The SolarGIS [26] is a geographical information system designed to meet the needs of the solar energy industry; it provides worldwide maps for solar global horizontal irradiation, direct normal irritation and diffused horizontal irradiation. The world maps of global horizontal irradiation and direct normal irradiation (daily mean and annual sum) are presented in the Fig. 1(a) and (b) respectively [26] to show the solar potential of Pakistan compared to the world. The solar potential of Pakistan (especially Sindh and Baluchistan provinces) is among the second highest around the world.

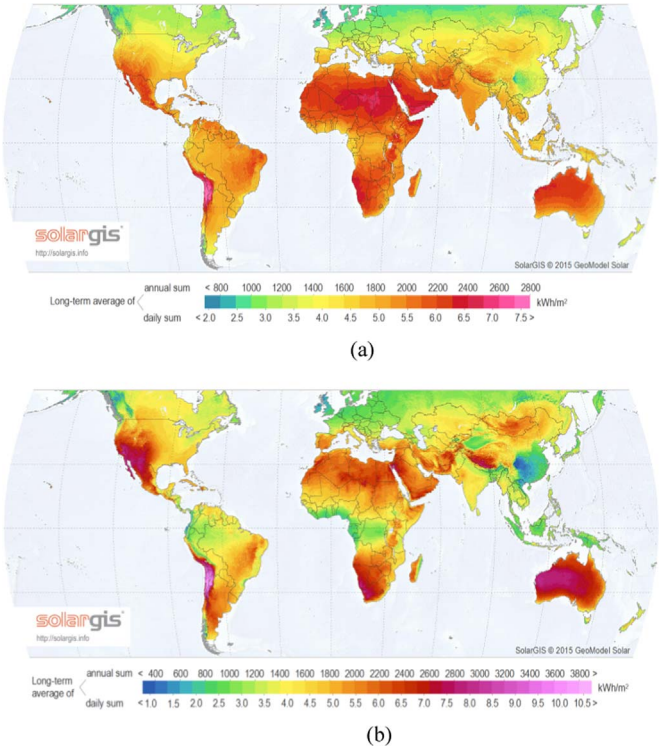

Fig. 1. (a) World map of global horizontal irradiation (kW h/m^2) [26] (b) World map of direct normal irradiation (kW h/m^2) [26].

This article presents the review of the surface measured data of solar radiation for Pakistan, and the solar energy potential assessment based on surface measured data and satellite data. The articles related to renewable energy for Pakistan, especially solar energy, from internationally recognised peer-reviewed journals to date were collected initially, and articles containing measured solar radiation and solar energy potential especially were selected. The articles were divided into three main sections:

- Articles related to surface measured data of solar insolation, estimation of solar insolation based on measured solar insolation and sunshine duration, estimation of solar radiation based on empirical relationships, and solar insolation maps.
- Articles related to the estimation of solar insolation based on satellite data and solar insolation maps, including solar resource assessment performed by NREL and ESMAP.
- Articles related to the description of the solar energy potential, including solar energy and the solar energy potential of the country reported by different sources are compared, validated and presented.

The long-term solar radiation data from the WRDC for five meteorological stations of Pakistan was analysed to obtain monthly mean daily values. The monthly mean daily data measured by PMD and reported by researchers for the different duration for five meteorological stations were compared with the WRDC data. The monthly mean daily solar insolation from NREL's CSR model, NREL's SUNY model and NASA-SSE was also compared with the long-term surface measured data. The solar energy potential of the country reported in the previous literature was analysed and critically reviewed. The annual mean daily global horizontal irradiation from the literature was analysed, and the solar resource potential for the whole country was calculated.