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Features of fully integrated renewable energy atlas for Pakistan; wind, solar and cooling

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ABSTRACT

A fully integrated renewable energy atlas is presented which provides the wind and solar photo-voltaic (PV) power generation potential as well as cooling demand for Pakistan at a temporal resolution of 1-hr and spatial resolution of 14 × 14 km^2. The proposed atlas uses weather based modelling for calculating renewable power generation time-series and the power-demand modelling is performed using real hourly electrical-load demand, conventional power generation and power consumption data for the year 2016. It has been found that Pakistan has much higher potential for the wind power generation than solar (PV) power generation and very good potential for the concentrated solar power. Furthermore, the optimum wind/solar power mix suggests that 95% of wind power generation and 5% of solar (PV) power generation leads to the least amount of power-shortfall. It is envisioned that the integration of renewable energy with cooling sector can be instrumental in overcoming Pakistan's electrical power-crisis. The current power-shortfall of 38.36 TW h can be resolved by installing rated wind and solar (PV) power generation capacity of 10.4 GW and 882 MW, respectively.

1. Introduction

Pakistan, like many other developing countries is going through power-crisis from more than a decade. Recently, several studies have highlighted the reasons and challenges of current power-crisis. The main reasons for this power-crisis are all interconnected and have been identified as; mismanagement, short-sightedness, negligence in policy planning [1–4], management framework [5], uneconomical power mix [2], security of electrical power supply [6], increase in oil prices, electrical-grid losses, economic and financial instability [7]. Nevertheless, it is unfortunate that this decade long power-crisis is yet to be resolved.

According to recent forecasts, the current average hourly power-shortfall of Pakistan is around 5000 MW and the annual increase in electrical-load demand is around 10% [3,8]. It has been predicted that the electrical-load demand will increase to around 63,000 MW by the year 2020 and Yousuf et al. [9] have called for an immediate installation of around 39,177 MW into the electrical-grid. Several authors have recommended the transition to sustainable energy with global shift towards the sustainability, climate change, greenhouse gas (GHG) emissions and health concerns [10]. Moreover, few authors have discussed sustainable energy as the ultimate option to overcome this severe dilemma of power-crisis and stressed upon utilising vast resources of wind, solar (PV), geothermal and biomass energy. These renewable energy technologies are already mature enough and have proved their cost-effectiveness compared to conventional fossil fuels [11–16]. The world-wide installation of solar (PV) and wind power technology has experienced an increase in growth by more than 55% [17] and 25% [18], respectively.

Recently, the US government and world bank has helped the government of Pakistan with geographical solar energy and wind resource mapping studies [19–22]. The solar energy mapping studies [19,20] performed by the US-National Renewable Energy Laboratory (NREL) and German Aerospace Center institute (DLR) have calculated that, Pakistan has a solar power potential of almost 1600 GW [23] and few western regions have the potential comparable to world's highest MENA region [24]. Stökler et al. [24] presented a high-resolution solar energy map for Pakistan and recommended using measurements from atleast 65 to 70 well-maintained weather stations to out-perform the accuracy of results from the geographical based models. Perez et al. [25] discussed the significance and credibility of geographical satellite models compared to results from the extrapolation and interpolation of measurements from the on-site weather stations. Furthermore, Adnan [26] presented the real data of ground based measurements from 58 weather stations and calculated the solar radiations on horizontal surface for different locations in Pakistan. Rafique et al. [27] discussed the feasibility of a grid-connected PV power system in rural communities and suggested that government grants as well as incentives can significantly

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Nomenclature

I_{sc}	solar constant, average intensity of incoming solar radiations
I	downward-shortwave solar radiations
O	upward-shortwave solar radiations
I_B	beam solar radiations
I_d	diffused solar radiations
t	index representing hour of year
θ	solar incidence angle of solar radiations
Φ	solar zenith angle of solar panel
h	hour angle
δ	declination angle
α	solar altitude
Z_s	solar azimuth angle
β	slope β of solar panel
k	clearness of sky index
ρ	ground reflectance
$I_{B,tilited}$	beam solar radiations upon titled solar panel surface
$I_{D,tilited}$	diffused solar radiations upon titled solar panel surface
$I_{G,tilited}$	ground reflected solar radiations upon titled solar panel surface
T_s	cell temperature under standard testing conditions (STC)
$\tilde{\alpha}$	device dependent temperature coefficient
η_R	reference efficiency
P_{solar}	solar (PV) power generation
v	wind speed
v_{10}	wind speed at 10 m height
v_{80}	wind speed at hub-height i.e. 80 m
Z_o	surface roughness
H	hub-height
c	scale parameter
k	shape parameter
Γ	gamma function
μ_v	mean wind speed
$P_{(v)}$	power curve of wind turbine
$f_{RLH\,(v)}$	wind distribution from Rayleigh distribution function
P_{wind}	wind power generation
Q_{sc}	cooling demand
CDD	cooling degree hours
HDD	heating degree hours
t_{base}	base-temperature, ambient set-point temperature
$t_{base,c}$	base-temperature for cooling demand
$t_{base,h}$	base-temperature for heat demand
T	outside dry-bulb air temperature
p	population data
G	power generation
G_{CON}	conventional power generation
G_{RES}	generation from renewable energy sources
L	electrical-load demand
$\langle . \rangle$	time average of all hours in a year
α^W	wind/solar power mix
Δ	mismatch
P_{ex}	excess-power generation
G_B	power-shortfall

impact the conversion of consumers to solar (PV) technologies in Pakistan. Even-though, these studies are valuable but they do not consider the solar radiations upon tilted solar panel surface and can not provide achievable solar (PV) power generation with parameters for an actual solar panel. The solar radiations striking upon the tilted solar panel surface are comparatively higher than at horizontal ground surface. The intensity of these tilted solar radiations depend upon the beam, diffused and ground reflected solar radiations. Moreover, the achievable solar (PV) power generation depends upon the tilted solar radiations, outside temperature, geographical location and orientation of the solar panel. Hence, the solar energy mapping on horizontal surface alone as calculated in Ref. [24] is not enough for evaluating solar (PV) energy generation potential and remains a gap in knowledge. This elaborates the significance of this solar (PV) atlas for the policy makers, investors and engineers.

Similarly, the US-National Renewable Energy Laboratory (NREL) [19] and Denmark Technical University (DTU) [22] have produced geographical wind power density maps for Pakistan and recommended the utilisation of this huge unused power generation resource. As suggested in Ref. [22], Pakistan has a wind power potential of almost 346 GW [21] and wind turbines with the hub-height of 80 m should be preferred over 100 m, as they will experience less turbulence and provide more power generation due to specific weather conditions of Pakistan. Shami et al. [28] presented the wind measurements for three different provinces and calculated the wind power density. Although, these studies for the wind-speed and wind power density are available, but results for wind power generation potential are not practical and misleading for engineers, as power generation from each wind turbine depends upon specific hub-height, rotor area, cut-in speed and cut-out speed. This cut-in and cut-out speed is the limit below and above which the wind turbine is either stopped or can not generate power. This atlas provides practically achievable wind energy generation potential using specifications of an actual wind turbine.

Furthermore, Rafique et al. [6] discussed that Pakistan has a renewable energy potential of almost 167.7 GW. Valasai et al. [1] recommended the urgent need for developing realistic energy policy to minimise the generation supply-demand gap and transition towards the future resilient power infrastructure for sustainable development. Shakeel et al. [2] discussed that, the existing power mix in Pakistan is dependent on fossil fuel with expensive generation costs and suggested a road-map for renewable energy based sustainable future. However, as indicated by Farooqui et al. in [29] there is limited knowledge available on the practically achievable power generation potential from renewable energy sources with seasonal variations in Pakistan. There are several unanswered questions such as:

- What is the hourly achievable geographical wind and solar (PV) power generation potential after accounting power-losses from wind turbines and solar panels?
- How does the current electrical-load demand, power generation and power-shortfall vary at each hour with seasonal variations throughout the year?
- What is the technically optimum wind and solar (PV) power mix for the integration of renewable energy in Pakistan?
- How much wind and solar (PV) power generation is required for resolving the current power-crisis in Pakistan?

This paper provides answer to these questions and presents a fully integrated renewable energy atlas for Pakistan. This atlas generates the hourly achievable wind and solar (PV) power generation and cooling demand time-series and calculates optimum wind and solar (PV) power mix for the integration of renewable energy in Pakistan. The atlas uses weather based modelling as well as specifications of a particular wind turbine and solar panel for converting meteorological data into hourly solar (PV) and wind power generation time-series. This methodology has been adopted from Refs. [30–32].

The paper proceeds as follow: the preface to current power-crisis scenario from previous studies is given in Section 2. Then, the methodology and several data-sets used in this renewable energy atlas are explained in Section 3. Subsequently, results from the geographical