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Wind resource characterization in the Arabian Peninsula

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HIGHLIGHTS

- The wind field is reconstructed with consistent space–time resolution for 35 years.
- Areas with wind power potential not previously found are identified in this study.
- Wind variability and intermittency are for the first time addressed in this region.

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ABSTRACT

Wind energy is expected to contribute to alleviating the rise in energy demand in the Middle East that is driven by population growth and industrial development. However, variability and intermittency in the wind resource present significant challenges to grid integration of wind energy systems. These issues are rarely addressed in the literature of wind resource assessment in the Middle East due to sparse meteorological observations with varying record lengths. In this study, the wind field with consistent space–time resolution for over three decades at three hub heights (50 m, 80 m, 140 m) over the whole Arabian Peninsula is constructed using the Modern Era Retrospective-Analysis for Research and Applications (MERRA) dataset. The wind resource is assessed at a higher spatial resolution with metrics of temporal variations in the wind than in prior studies. Previously unrecognized locations of interest with high wind abundance and low variability and intermittency have been identified in this study and confirmed by recent on-site observations. In particular, the western mountains of Saudi Arabia experience more abundant wind resource than most Red Sea coastal areas. The wind resource is more variable in coastal areas along the Arabian Gulf than their Red Sea counterparts at a similar latitude. Persistent wind is found along the coast of the Arabian Gulf.

1. Introduction

The potential adverse impacts of climate change and energy insecurity have encouraged countries worldwide towards adopting renewable energy as an integral part of their future energy mix. Near-surface wind energy has the potential to power the world; it allows extracting energy at a rate of at least 400 TW [1]. It is suggested that following a moderate wind energy deployment plan by 2050 would delay the crossing of the 2 °C threshold for 1–6 years [2]. Wind energy provides a viable alternative energy source to energy intensive countries such as China, where it is estimated to be sufficient to replace 23% of the electricity generated from coal [3]. In the Middle East and North Africa (MENA), population growth has led to increases in demand for fuel and electricity for air-conditioning and desalination. Regional annual Total Primary Energy Supply (TPES) increased by 14.9% to 800 millions Mtoe (million tonnes of oil equivalent) in 2010 compared to the TPES of 2007 [4]. These steady increases in domestic consumption of energy drive the latest expansion of the renewable energy market [5]. Among net oil importers such as Jordan, energy insecurity and dependence on expensive oil imports have led to an expansion of the renewable energy program. Renewable energy has grown from 0.4 TW h in 2008 to 1.2 TW h in 2011 among net oil importers [4]. In the net oil exporting countries, renewable energy has grown from 0.8 TW h in 2008 to 1.6 TW h in 2011 [4]. This growth has been the result of rising opportunity cost of oil and gas accompanied by an increase in urbanization and a rapid rise in domestic demand for energy. These expansions are evident in the countries' recent large-scale procurement of renewable energy systems to fulfill national renewable targets [5]. The surging interest in renewable energy calls for a better understanding of the spatial and temporal characteristics of the resource. This paper focuses

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on the wind energy resource, the most variable and intermittent source of renewable energy in the Arabian Peninsula.

There are two key challenges in assessing the wind resource in the Arabian Peninsula. Most of the observations available are sparse in space and inconsistent in time: spatially scattered observations with varying record lengths come from meteorological stations that are located mainly in clustered coastal and inland settlements. Hourly wind speeds were collected by 293 weather stations in the Peninsula during our period of study from 1979 to 2013. Among the stations, 42 collected data for at least half of the time. Only 17 stations have observations available for more than 80% of the record length [6]. Despite these challenges, Ansari et al. [7] constructed the Saudi Arabian Wind Energy Atlas in 1986 using hourly observations from 20 airport weather stations from 1970 to 1982. They described diurnal and seasonal variations of wind speed at measurement height at these locations and mapped prevailing wind directions. Rehman and Halawani [8] described diurnal, monthly, and interannual wind speed variations at 10 weather stations. Most of the studies focused on prominent sites of assessment that are mainly coastal. A similar tendency is observed for the MENA region [9–11], with the exception of Ohunakin et al. [12] where the focus was inland. These analyses concentrated on wind speed time series from meteorological stations with different record periods. The wind resource is frequently characterized by average wind speed or wind power density (WPD) that is at measurement height or is adjusted to hub height. Recent works have attempted to study the spatial variation of the wind resource. Jervase and Al-Lawati [13] performed an areal analysis of wind resource abundance in Oman using the NASA Surface Meteorology and Solar Energy (SSE) Release 6.0 dataset with a spatial resolution of $1^\circ \times 1^\circ$. Al-Yahyai and Charabi assessed wind resource in Oman using a nested ensemble numerical weather prediction (NWP) approach, where two global models were used as boundary conditions to drive two local area models. The wind abundance has been assessed at the scale of a country [14] and a city [15]. Moreover, Charabi et al. [16] demonstrated that NWP models at 7 km are effective in resolving finer structures such as the sea breezes in this region. However, without well-formulated boundary conditions based on a long-term and spatially and temporally consistent dataset, an NWP model would not capture the impact of large-scale circulations such as the El Niño. Since these circulations are of low frequency, they have higher spectral power and, therefore, have a significant impact on the wind resource. Existing meteorological observations contain missing data due to handling errors or malfunctioning of the instrument. These observations are spatially sparse, for instance, located mainly at airports and urban areas. These factors led to some potentially resource-rich regions being overlooked, which prevented prior studies in developing a comprehensive characterization of the wind resource for the entire Arabian Peninsula.

Moreover, previous resource characterizations have focused on average wind abundance and annual energy production estimates. Wind power variability and intermittency present significant challenges to grid integration of wind energy systems, as identified by wind integration studies in the United States [17]. Variability and intermittency have been considered, most commonly using tower measurements where data are limited in the spatial and temporal dimensions [18–20]. Rehman and Halawani [8] provided a wind persistence measure via auto-correlation and auto-regression for ten weather stations. Rehman and Ahmad [21] presented a wind availability analysis for 5 coastal locations in Saudi Arabia in terms of frequency of wind speed within a specified interval. Wind speed time series from meteorological stations were fitted by Weibull distributions to investigate the monthly variation of wind speed and their changes with hub height in Saudi Arabia [22,23] and Bahrain [24]. Ouarda et al. [25] fitted multiple distributions and assessed their goodness-of-fit with wind speed measurements in the United Arab Emirates (UAE). However, the variability and intermittency of the wind resource have not been studied in the entire Peninsular region.

The primary goal of this study is to overcome the limitation of sparse station observations with varying record lengths by constructing the wind field using a gridded reanalysis dataset with a multi-decadal record period to arrive at a characterization of wind variability and intermittency. We characterize the wind resource using metrics proposed in Gunturu and Schlosser [26] (United States), Cosseron et al. [27] (Europe), Fant et al. [28] (South Africa), and Hallgren et al. [29] (Australia).

This work aims to answer the following questions:

- What methodology can be used to assess the wind energy resource in a region where observational data are sparse and non-concurrent? (Section 2)
- Where are the areas with wind power potential that were not previously located due to lack of observations? (Section 3.1)
- How do wind variability and intermittency differ in spatial distributions from conventional metrics of resource abundance? (Sections 3.2 and 3.3)

In the following sections, we explore regional wind resource and compare our results with results from prior studies. We first describe wind resource abundance as characterized by the median WPD. Our wind field reconstruction shows a qualitative agreement with previous studies. We then describe the regional wind resource using metrics of variability and intermittency.

2. Material and methods

2.1. Data

The spatial domain of interest spans the Arabian Peninsula bounded between 10°N and 35°N in latitude and 35°E and 60°E in longitude. This spatial extent allows investigation of the Red Sea, the Gulf of Aden, the Arabian Gulf, and part of the Arabian Sea along with inland areas.

The WPD field is reconstructed using the Modern Era Retrospective-Analysis for Research and Applications (MERRA) dataset. MERRA is a reanalysis conducted by the Global Modeling and Assimilation Office (GMAO) at NASA using the Goddard Earth Observing System Version 5 (GEOS-5). GEOS-5 is a general circulation model (GCM) used within a data assimilation system where satellite and surface observations are utilized [30]. The dataset has a spatial resolution of 0.5° (latitude) $\times$ 0.67° (longitude) and hourly output is available. For this study, a record period from January 1, 1979 midnight (UTC) to January 1, 2014 midnight (UTC) is chosen. This temporal range enables studying of wind variation over different time scales from hours to decades. The spatial coverage of the dataset provides an opportunity to understand the regional wind patterns, those that coarse observations cannot address.

Wind speed and WPD are two primary variables in wind resource assessments. Wind speed at the turbine hub height is calculated using the similarity theory for the surface layer in which the turbine submerges [31]. Wind speed is computed as

$$u(z) = \frac{u_*}{\kappa} ln \frac{z-d}{z_0} - \psi, \tag{1}$$

where z is the turbine hub height [31]. $u_* = \left[(\overline{u'w'})^2 + (\overline{v'w'})^2 \right]^{1/4}$ is the friction velocity, defined with the surface kinematic momentum