Wind Resource Characterization in the Arabian Peninsula

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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.

Keywords: Wind Energy, Variability, Intermittency, Middle East, Resource Assessment, Reanalysis

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 to 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 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

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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 inter-annual 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 and Gunturu [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) × 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

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

where z is the turbine hub height [31]. $u_* = [(\overline{u'w'})^2 + (\overline{v'w'})^2]^{1/4}$ is the friction velocity, defined with the surface kinematic momentum fluxes in x and y directions. $\kappa = 0.41$ is a standard accepted value of the *von Kármán* constant [32]. d is the displacement height that gives the vertical displacement of the entire flow regime over areas densely covered with obstacles. Roughness length z_0 defines the height that the wind speed is assumed to vanish near the ground. The parameter ψ depends on the stability of the boundary layer. A neutral boundary layer is assumed, thus

$\psi = 0$. Neutral stratification assumes negligible effects of external heating on the vertical distribution of temperature. Although neutral stratification is widely assumed in previous studies of wind resource assessment to adjust wind speed to hub height from measurement height, the neutral boundary layer may not occur in the presence of surface heating [33]. Intense surface heating causes warm air near the surface to rise and create turbulence as in the case of an unstable boundary layer. It implies a smaller change in wind speed with height than in a neutral case. WPD is the wind power available per unit swept area of a turbine defined as

$$\text{WPD} = \frac{1}{2} \rho u^3, \quad (2)$$

where ρ is the air density and u is the wind speed [31]. The fields for calculating wind speed and WPD at hub height have been extracted from the MERRA 2D surface turbulent flux diagnostics available at a single level at the top of the surface layer. Specifically, momentum roughness length (Z0M), friction velocity (USTAR), surface air density (RHOA), and displacement height (DISPH) are extracted from the dataset for the computation. Wind speed and WPD have been computed at all hourly time-steps at 50 m, 80 m, and 140 m corresponding to the typical hub heights of the three generations of wind turbines. Most prior studies in the region did not consider terrain and local conditions when adjusting wind speed to hub height (e.g., [34]), where the effects of wind shear were demonstrated to be significant in power generation [35]. The WPD provides a proxy to wind power resource that is independent of a wind energy system's specification. It combines the contributions of both wind speed and air density in illustrating the physical limit of wind power potential.

2.2. Metrics

Prior studies of the wind energy resource in the Arabian Peninsula were mostly concerned with the abundance of the wind resource in terms of average wind speed or annual energy production estimates. Variability and intermittency have not been investigated comprehensively for this region. The understanding of these temporal characteristics is essential for grid integration to pave the way for wind energy to become part of a larger generation network contributing to the generation of base-load electricity. Therefore, we consider three essential metrics in evaluating the wind energy resource: abundance, variability, and intermittency.

Abundance is the amount of wind energy available. It is conventionally measured by time-averaged wind speed ($\bar{u}$) or time-averaged WPD, which takes the form of

$$\bar{x} = \frac{1}{T} \int_0^T x \, dt, \quad (3)$$

where x is the instantaneous wind speed or wind power density, and T is the length of the record period. Time-averaged WPD and wind speed are used to compare with results from prior studies in the region. For each grid cell in the domain, the hourly wind power density field is used to compute the average WPD over the record period.

$$\bar{p} = \frac{1}{n} \sum_{t=1}^n p_t, \quad (4)$$

where p_t is the average WPD at each hour (t) and n is the total number of time-steps in the record period. In addition, we compute the median WPD, p_{med} , which is the value lying at the midpoint of a frequency distribution of the time series at each grid point such that there is an equal probability to be above or below it. The median is a metric robust to extreme samples and hence is a better characterization of central tendency than the mean for skewed distributions such as those of wind speed and WPD. The p_{med} is used to characterize the wind regimes in the further analysis: regime I where $p_{\text{med}} \geq 67 \text{ W m}^{-2}$, regime II where $46 \text{ W m}^{-2} \leq p_{\text{med}} < 67 \text{ W m}^{-2}$, and regime III where $p_{\text{med}} < 46 \text{ W m}^{-2}$. The three regimes correspond to values separated by the 33rd and 67th percentiles of the median WPDs for all grid cells in the domain. This classification gives an indication of the relative spatial abundance of the wind resource in the region.

Variability characterizes the fluctuations of the wind energy resource at a given location. It is measured by the robust coefficient of variation (rCV) of WPD [26], computed as follows for each cell:

$$\text{rCV} = \frac{\text{median}(|p - p_{\text{med}}|)}{p_{\text{med}}}. \quad (5)$$

The rCV provides a dimensionless measure of variability across the spatial domain. High rCV indicates highly variable wind resource, thus less desirable for operation.

Intermittency is defined by availability and persistence of the wind resource. Availability is the fraction of time over a time series when the WPD exceeds a threshold

of 200 W m^{-2} . The threshold has been chosen keeping in mind the 300 W m^{-2} threshold (Wind Class 3) in filtering sites for commercial scale power production in the Regional Energy Deployment System (ReEDS) model of the National Renewable Energy Laboratory (NREL) [36]. A lower threshold of 200 W m^{-2} (Wind Class 2) is chosen in light of recent developments in low-wind turbines which render conventionally low-wind areas viable for energy applications. Availability (A) is computed following [26],

$$A = \frac{1}{n} \sum_{t=1}^n \tau(p_t), \quad (6)$$

$$\tau(p_t) = \begin{cases} 1, & p_t > 200 \text{ W m}^{-2} \\ 0, & \text{otherwise} \end{cases}$$

$\tau(p_t)$ records the events when p_t is greater than the threshold. Persistence reflects the steadiness over time in wind power generation above a given threshold. Episode length is defined as the duration of consecutive time steps when p_t is above the threshold.

Persistence is measured by the median episode length (MEL). The median length of wind episodes is the median length of all recorded continuous periods when WPD is above the threshold [26],

$$\text{MEL} = \text{median}[\tau(p_t)]. \quad (7)$$

It should be noted that intermittency concerns the statistics of threshold-crossing of the WPD while variability measures the fluctuation of the WPD in magnitude. This distinction was elaborated in Gunturu and Schlosser [26].

The present study aims at identifying regional features of wind resource while finer local characteristics and circulations could not be represented. Our analysis identifies regions for further down-scaling and micro-siting assessment where models with finer resolutions in space and time are appropriate. Dynamical down-scaling in the mountainous regions of the Arabian Peninsula would benefit from the use of Kalman filters, as it has shown improvements in NWP wind speed forecast in complex terrain [37]. Sub-hourly data would be needed to characterize wind intermittency at scales relevant to grid integration of individual wind farms, as illustrated in the Wind Integration National Dataset (WIND) Toolkit by NREL [38]. Prevalence of intense surface heating in the region requires proper parameterization of the stability of the boundary layer to better estimate the variation of wind speed with height during day-time. It is also important to validate

model results with current *in situ* measurements at different hub heights, such as the measurements taken by K.A.CARE in Saudi Arabia [39].

3. Results

Figure 1: Median WPD (W m^{-2}) computed at 50 m AGL using the wind fields reconstructed from the MERRA data. The color scale is uniform except for values beyond 100 W m^{-2} and below 30 W m^{-2} . Large extreme values beyond the 98-percentile in the spatial domain are masked in grey. Selected locations of prior studies (table A.1) are shown.

3.1. Abundance

Near-surface wind resource over the Arabian Peninsula varies due to its diverse topographical features. We discuss the wind resource over this vast area by categorizing the spatial domain into three regimes based on the median WPD (fig. 1). The three wind regimes are illustrated in fig. 2.

3.1.1. Regime I (relatively abundant)

The Arabian Peninsula shows a varied abundance of the near-surface wind resource spatially. Regime I shows the most abundant wind resource in the region with median WPD above 67 W m^{-2} . Offshore regions have the most abundant wind resource. Among the onshore locations, the Hejaz Mountains east of Jeddah in Saudi Arabia, the southern coast of Oman, and eastern Yemen show a relatively high abundance of wind resource. The mountainous coastline along the Gulf of Aqaba and central Jordan also have moderately abundant wind resource. These regions show a comparable spatial distribution of average and median WPD and the average WPD is about twice the

Figure 2: Categorized median WPD (fig. 1) at 50 m AGL into three regimes: regime I where median WPD is above 67 W m^{-2} , regime II where median WPD is from 46 W m^{-2} to 67 W m^{-2} , and regime III where median WPD is below 46 W m^{-2} . Elevation contours at 400 m intervals are drawn using elevation data from MERRA. Selected locations of prior studies (table A.1) are shown.

Figure 3: Average WPD (W m^{-2}) computed at 50 m AGL using the wind fields reconstructed from the MERRA data. The color scale is uniform except for values beyond 200 W m^{-2} and below 60 W m^{-2} . Large extreme values beyond the 98-percentile in the spatial domain are masked in grey. Selected locations of prior studies (table A.1) are shown.

median, illustrating a positively skewed distribution (fig. A.2). One exception is along the coast of the Gulf of Aqaba, where the average and median WPD are close, leading to a less skewed distribution.

The abundance of the wind resource is illustrated in average WPD (fig. 3). A map of average wind speed is also included for reference and comparison with prior studies where WPD is not available (fig. A.3). The East of the Hejaz and Asir mountains in Saudi Arabia has average WPD of 143 W m^{-2} . This is confirmed by recent meteorological measurements from 1998 to 2002 at Dhulum with average WPD of 186 W m^{-2} at 40 m AGL [40]. Before the use of reanalysis, wind resource assessments relied on data collected at meteorological stations and compared among known locations. The consensus from earlier studies has been that coastal areas possess more abundant wind resources (e.g., [41]). Our discovery of higher wind resources away from the coast points to the need for more *in situ* observations at locations indicated in this study.

Bahrain and Qatar show average WPD (wind speed) of around 119 W m^{-2} (4.63 m s^{-1}) and 139 W m^{-2} (4.71 m s^{-1}) respectively. A prior study [24] shows an average wind speed of 8.65 m s^{-1} at 60 m AGL extrapolated from hourly observations at 10 m AGL at Bahrain International Airport from 2003 to 2005. These observations point to the need for further investigations to better understand the disparity between the median and average WPD shown in Bahrain and Qatar where the ocean strongly influences circulation over the island and the peninsula.

Along the Oman coast, our results show an average WPD of about 197 W m^{-2} for southern coast and 85.8 W m^{-2} near Sur. Meteorological observations reported at Thumrait, Sur, Masirah, and Marmul, show average WPD of 230, 194, 165, and 109 W m^{-2} at 10 m AGL [42]. Further investigations into the long-term time-series would help reveal climatological differences in the two sub-regions.

In eastern Yemen around the Hadramaut Mountains, we find an average WPD (wind speed) of about 110 W m^{-2} . The region surrounding Aden shows an average WPD of about 105 W m^{-2} (4.75 m s^{-1}), where the wind speed decreases further eastward. A prior study [43] using five years of meteorological observations from the airport at Aden shows an average wind speed of 4.5 m s^{-1} at 10 m AGL. The more abundant wind resource appears in the west of Aden, where future *in situ* observations would benefit from further studies into the local resource characteristics.

Along the coast of the Gulf of Aqaba, the average

WPD is around 105 W m^{-2} . In central Jordan, average WPD is found to be 176 W m^{-2} . This finding seems to deviate from prior observations where the wind resource is more abundant in the southwestern area. In particular, Fujaij shows an average WPD of around 91.6 W m^{-2} (4.3 m s^{-1}), where the annual average wind speed of 6.88 m s^{-1} was reported [44].

3.1.2. Regime II (moderately abundant)

Regime II shows areas with a moderately rich wind resource of median WPD between 46 and 67 W m^{-2} . It includes the northern coast of the Red Sea, the coast of the Arabian Gulf, the areas west of Riyadh and along the borders of Saudi Arabia with Yemen and Oman, and northwestern Kuwait.

The northern Arabian coast of the Red Sea has been popular for wind resource studies due to long-standing meteorological measurements at major settlements. Our results show that the surroundings of Yanbu have an average WPD around 106 W m^{-2} , close to the observed 134 W m^{-2} [40]. Our results indicate that a more abundant wind resource is present within 100 km of the meteorological stations. Northwest of Yanbu shows a higher wind average WPD of around 138 W m^{-2} . Comparable wind abundance can also be found in the mountains further north of Yanbu and along the coast of the Red Sea northwest of Yanbu. This analysis identifies coastal sites beyond those discussed and observed in prior studies (i.e., Rehman and Ahmad [21]).

The coast of the Arabian Gulf illustrates a highly positively skewed distribution of WPD where the average value is about three times the median, indicating a potentially high variability in wind power previously not reported in the literature. The average WPD near Dhahran is shown to be around 136 W m^{-2} , close to the observed 154 W m^{-2} [40].

Kuwait also shows a highly positively skewed distribution in WPD as illustrated by the difference between the median (fig. 1) and the average WPD (fig. 3). Northwestern Kuwait has an average WPD of around 164 W m^{-2} , where southern Kuwait shows an average WPD of around 147 W m^{-2} . A prior study shows an average WPD at 30 m AGL at Umm Omara (northwest) and Al-Wafra (south) to be 271 W m^{-2} and 273 W m^{-2} respectively. These discrepancies could arise from the choice of a constant exponent of $1/7$ when adjusting the wind speed from 10 m AGL observations to 30 m [45]. The $1/7$ constant exponent has been a popular choice in the wind resource assessment literature in extrapolating wind speed to hub height and deemed inappropriate for domains with

complex surface characteristics [46]. This choice of the exponent in prior studies did not account for surface characteristics, leading to an overestimate of the wind resource.

3.1.3. Regime III (least abundant)

Regime III shows areas with the comparatively least abundant wind resource in the region where median WPD is below 46 W m^{-2} . The area includes the southern Arabian coast of the Red Sea, the southern coastline of Yemen, the east coast of Oman, and Abu Dhabi in the UAE.

The southern Arabian coast of the Red Sea has an average WPD (wind speed) of around 70.4 W m^{-2} (3.57 m s^{-1}), which is confirmed by observations at Jizan, where monthly average wind speed is between 3.8 m s^{-1} and 5.2 m s^{-1} [21]. The southern Yemen coast also shows comparable wind power density, with a similar mountainous terrain along the coastline. Northeastern Oman and the UAE show low average WPD of 80.7 W m^{-2} , consistent with observations [25, 42].

3.1.4. Effects of variation of hub height

Figure 4: Changes of median WPD (fig. 1) and average WPD (fig. 3) at 80 m and 140 m from those at 50 m AGL. Large extreme values beyond the 98-percentile in the spatial domain are masked in grey. The color scale is uniform except for values beyond 45%.

The rate of change of average and median WPD with altitude depends on the roughness length (fig. A.4). Roughness length defines the influence of surface characteristics on wind power resource. Figure 4 shows a general increase of WPD with altitude, much affected

by the varying terrain. Offshore locations show lower increase than onshore sites. These observations are consistent across average and median WPD. With increased hub height, both the magnitude and the frequency of higher wind power resource increase and shift the distribution to higher WPD values, making it less skewed. The rate of increase is proportionally consistent across the average and median WPD at the two altitudes.

3.1.5. Comparison with Vestas' wind map over Saudi Arabia at 100 m AGL

Figure 5: Average wind speed (m s^{-1}) computed at 100 m AGL using the wind fields reconstructed from the MERRA data. The color scale is uniform except for values beyond 6.6 m s^{-1} and below 2.4 m s^{-1} . Selected locations of prior studies (table A.1) are shown.

Figure 5 shows the annual average wind speed at 100 m AGL by our reconstruction and fig. 6 shows its comparison to Vestas' estimation. Vestas' wind speed map was calculated using the output from the Weather Research and Forecasting (WRF) model with a spatial resolution of $3 \text{ km} \times 3 \text{ km}$ and hourly temporal resolutions from 2000 to 2013 [47]. The wind speed estimate is available at the Renewable Resource Atlas at King Abdullah City for Atomic and Renewable Energy (K.A.CARE) in Saudi Arabia [39]. The model was driven by the boundary conditions from the National Center for Environmental Prediction (NCEP) Global Forecast System Analysis of $1^\circ \times 1^\circ$ spatial resolution and 6-hourly temporal resolution. Topography used in the Vestas model was obtained from the Moderate Resolution Imaging Spectroradiometer (MODIS) of $30'' \times 30''$ spatial resolution. Figure 5 indicates relatively high average wind speed at the tip of the Gulf of Aqaba, north of Duba, west of Yanbu, south of Jeddah, and to the east of the Hejaz and Asir Mountains. Figure 6

Figure 6: Differences in the average wind speed (m s^{-1}) at 100 m AGL between our calculation and that from estimation of Vestas (Vestas - MERRA) are illustrated with a color scale that is uniform except for values beyond 2.5 m s^{-1} and below -2.5 m s^{-1} . Selected locations of prior studies (table A.1) are shown. The MERRA dataset is regridded to 1 km resolution by nearest neighbor for illustration.

shows that the wind speed patterns of the two maps are qualitatively similar, with root-mean-square error (RMSE) of 1.15 m s^{-1} . However, at these identified high wind locations the Vestas' map holds higher values than from our reconstructions using MERRA, with the Vestas' average wind speed being 0.424 m s^{-1} higher on average. The area in the north near Arar and Rafha, and in the east near the coast of the Arabian Gulf show similar spatial patterns in wind speed with the Vestas' map, but higher values in general. This qualitative assessment reflects the higher spatial variability that is shown in the model with higher spatial resolution. A converse pattern is shown on the Vestas' map where there is a higher wind speed east of Najran than in the Empty Quarter. There is a higher wind speed shown to the west of the Hejaz Mountains where fine topographical features exist in the Vestas' map. It remains to investigate further these discrepancies and their relation to the models and assimilation schemes.

3.1.6. Comparison with 3TIER's wind speed map at 80 m AGL

The average wind speed at 80 m AGL from our reconstruction using the MERRA dataset is compared with 3TIER's average wind speed map. The 3TIER wind map is available with 5 km spatial resolution hosted at the Global Atlas for Renewable Energy of the International Renewable Energy Agency (IRENA) [48]. The 3TIER's map uses over ten years of hourly data generated from statistical and dynamical downscaling

where surface-atmosphere interactions are accounted for. The 3TIER wind speed estimates were validated with 229 NCEP-ADP stations in the Middle East and Africa, where only around 60 stations are in the Middle East [49]. The RMSE is 1.03 m s^{-1} between the annual average wind speed of station data and those from the model output in Africa and the Middle East. However, the data for the 3TIER map are not retrievable. There is also a lack of publicly available documentation on the creation of the dataset. Hence, the following discussion is not illustrated.

Our wind speed reconstruction and 3TIER's estimates are qualitatively similar. On the coast of the Red Sea, the two maps agree on the lower wind speed between the southern Red Sea and the mountains. Prominent wind patterns agree over the north, the east, and the south of Saudi Arabia, the UAE, Qatar, Kuwait, the eastern and the southern coasts of Oman, and Yemen. Known locations at Yanbu, Jeddah, and Al Qahma appear to show higher wind speed in the 3TIER map than in the MERRA reconstruction.

3.2. Variability

Figure 7: Robust coefficient of variation computed at 50 m AGL using the wind fields reconstructed from the MERRA data. The color scale is uniform except for values beyond 1.45 and below 1.15. Selected locations of prior studies (table A.1) are shown.

The robust coefficient of variation (fig. 7) measures the median deviation as a fraction of median WPD. A higher rCV indicates relatively higher variability at a location in WPD. Low variability reduces the output volatility and is favorable for power generation. Figure 7 indicates that the sea-ward side of elevated areas shows greater variability than other sites in the spatial domain. Within the Regime I area, the inland face of the Hejaz and Asir Mountains shows relatively

low variability. Similarly, the Hadramaut Mountains in Yemen and the Wahiba Sands desert in eastern Oman show relatively low variability in WPD. Along the Gulf of Aqaba, the mountainous region also shows relatively low variability. Within Regime II, both the coastlines of the Red Sea and the Arabian Gulf show higher variability than inland locations. However, the surroundings of Yanbu show only moderate variability. Changes in hub height lead to insignificant changes in variability (fig. A.5).

3.3. Intermittency

Intermittency is characterized by availability and persistence.

3.3.1. Availability

Figure 8: Availability of wind resource computed at 50 m AGL using the wind fields reconstructed from the MERRA data. The color scale is uniform except for values beyond 0.45 and below 0.1. Large extreme values beyond the 98-percentile in the spatial domain are masked in grey. Selected locations of prior studies (table A.1) are shown.

Availability (fig. 8) measures the fraction of time when the wind power resource is above a given threshold (i.e., 200 W m^{-2}). It represents the amount of time with meaningful power generation by a turbine. Most onshore locations have availability between 10% to 30%, except for the low wind abundance areas in Yemen, northeast Oman, and along the southern coast of the Red Sea. Areas with abundant wind resource appear to have high availability. The western mountains in Saudi Arabia, the southern coast of Oman, the tip of the Gulf of Aden, and Kuwait show availability of around 25%.

Figure 9 shows that an increase in hub height contributes to increased availability onshore due to

reduced effect of boundary layer friction on the wind by the surface. Increases in availability with hub height are most significant in regions with low wind abundance, except southern coastal Yemen.

Figure 9: Changes of availability (fig. 8) at 80 m and 140 m from those at 50 m AGL. Large extreme values beyond the 98-percentile in the spatial domain are masked in grey. The color scale is uniform except for values beyond 40% and below 15%.

3.3.2. Persistence

Figure 10: Median length of wind episode (h) computed at 50 m, 80 m, and 140 m AGL using the wind fields reconstructed from the MERRA data. The color scale is uniform except for values beyond 10 h. Selected locations of prior studies (table A.1) are shown.

Median episode length (fig. 10) measures the persistence of the wind resource, which indicates persistent up-time of energy production at a specific location. In Regime I, MEL is eight hours in the western mountains of Saudi Arabia, central Jordan, and the southern coast of Oman. It indicates that the wind resource at these locations is persistent for at least eight consecutive hours during half of the record period. At the tip of Yemen at the Gulf of Aden, the MEL is 14 hours. Moderate MEL above five hours by the coast of the

Gulf of Aqaba is noticed. Areas with moderate wind speed near the Arabian Gulf such as Kuwait and eastern Saudi Arabia show a higher persistence of the wind with the MEL of greater than eight hours. Low wind abundance regions exhibit persistence with the MEL of below five hours. The MEL tends to increase with hub height with almost no exceptions (fig. A.6).

4. Conclusions

This study provides the first regional assessment of the abundance, variability, and intermittency of wind resource over the Arabian Peninsula. Employing the MERRA dataset, the wind field at different hub heights is reconstructed applying similarity theory using the roughness length, friction velocity, and displacement height. The reconstructed wind field spans over three decades with consistent spatial and temporal resolution. The wind power density field enables analysis of various aspects of the large-scale features of the wind energy resources in the Arabian Peninsula. The wind resource is also characterized using metrics of wind variability and persistence. This work improves upon the earlier comprehensive studies in providing an areal overview of the wind resource with higher spatial resolution and metrics of temporal variations in the wind. 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 [40]. 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. More persistent wind is also found along the coast of the Arabian Gulf.

This analysis points to the areas previously not recognized. Studies at finer resolutions for these identified areas are necessary to resolve spatial features and local circulations relevant to wind power generation. Our reconstructed wind field will enable investigations on the impact of large-scale circulations on regional wind resources. Effects of the El Niño Southern Oscillation (ENSO) [50] and the North Atlantic Oscillation (NAO) [51] at various hub heights can be assessed using the reconstructed wind fields at different hub heights. The economic viability of wind energy applications at a regional scale can be conducted with higher spatial and temporal resolution using this dataset to provide greater consistency than in prior studies

[11, 52–54]. Specifically, wind power production in this region can be modeled in a way similar to those performed in Northern Ireland [55], Great Britain [56], and Sweden [57]. In light of an estimated 25 years turbine lifetime [58], sustainable deployment of wind energy systems in the region requires assessments of the effects of climate change on the regional wind resource using developed approach [59]. A measure-correlate-predict (MCP) approach can be used to estimate the long-term wind resources at a target site using our reconstructed wind fields in conjunction with short-term wind measurement campaigns [60]. An investigation into the best pattern for wind power aggregation through region-wide interconnection to mitigate intermittency will be a timely and valuable next step towards an optimal integration of large-scale wind energy systems in the Arabian Peninsula [61].

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A. Appendix

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Figure A.1: Country map in the Middle East

Figure A.2: Illustration of a skewed distribution of WPD at Yanbu

Figure A.3: Average wind speed (ms^{-1}) is computed at 50 m AGL using the wind fields reconstructed from the MERRA data. Selected locations of prior studies (table A.1) are shown.

Figure A.4: Fractional change in WPD at 80 m and 140 m from 50 m over temporal median of roughness lengths

Figure A.5: Distribution of fractional changes in rCV at 80 m and 140 m from 50 m out of 1638 grid cells

Figure A.6: Distribution of differences in MEL at 80 m and 140 m from 50 m out of 1638 grid cells

Mark	Location
Ma	Maan
Y	Yanbu
Ar	Arar
R	Rafha
D	Dhahran
Aq	Aqaba
Sa	Salalah
W	Al Wajh
Jz	Jizan
S	Sur
Do	Doha
M	Manama
A	Abu Dhabi
Ad	Aden
J	Jeddah
K	Kuwait
Dl	Dhulum

Table A.1: Selected locations of prior studies in the region as indicated on the maps.

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