

# Wind Energy Map of Arabian Gulf

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## Abstract

Wind power is not only pollution free and renewable but is becoming more economical with technology development. The countries around the Arabian Gulf region are investing for wind powers both the land and in their marine space. A detailed study on wind power resource in the Arabian Gulf is not available. This paper is on the wind energy resource availability over Arabian Gulf waters, covering 2300 grid points. The data available with Coastal Information System data base at Kuwait Institute for Scientific Research, Kuwait, from 1979 to 2015 is used. The probability density and power density were derived from these data source. Weibull probability density function has been fitted to the wind speed data and the wind power density was evaluated. The study is carried out at 10 m, 30 m and 50 m elevations. The central location of the Arabian Gulf has higher annual average wind speed, ranging from 6 to 8 m/s at 10 m elevation, 7 to 8 m/s at 30 m elevation and 8 to 9 m/s at 50 m elevation. The scale parameter “c” at central location of Arabian Gulf is found to range from 6 - 8 m/s for 10 m elevation, 7 - 8 m/s for 30 m elevation and 8 - 9 m/s for 50 m above sea level. The Weibull shape parameter k varies from 2.5 to 3 at the north and central of the Arabian Gulf. The annual mean wind power density over Arabian Gulf Waters is the highest in the central region of the Gulf. The power density at 10 m, 30 m and 50 m hub height varies between 200 to 300 w/m<sup>2</sup>, 200 to 300 w/m<sup>2</sup> and more than 300 w/m<sup>2</sup> respectively. It is attractive to install large scale wind power generation at the central region of the Arabian Gulf and at elevations of 30 m or 50 m, since this region lies in Class 2 category of the Wind Energy Resource Atlas of the United States. The wind power density is attractive especially in summer season around the central region location in Arabian Gulf (Saudi Arabia, Bahrain and Qatar), since high rate of power is used for air conditioning systems in summer.

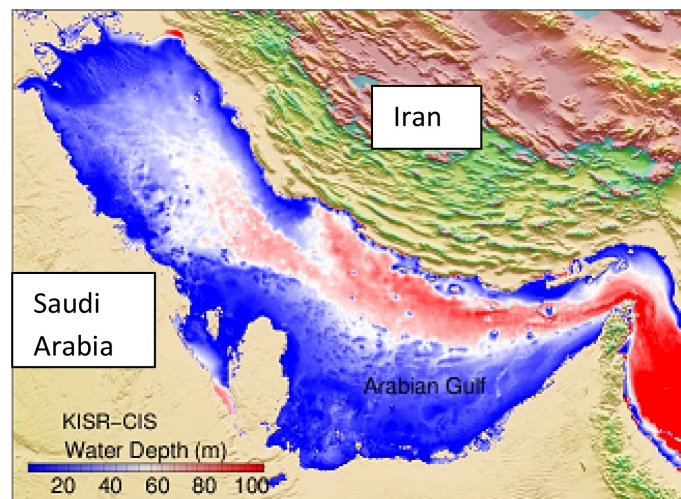
## Keywords

Wind Energy, Arabian Gulf, Weibull Distribution, Gulf Cooperation Council, Kuwait

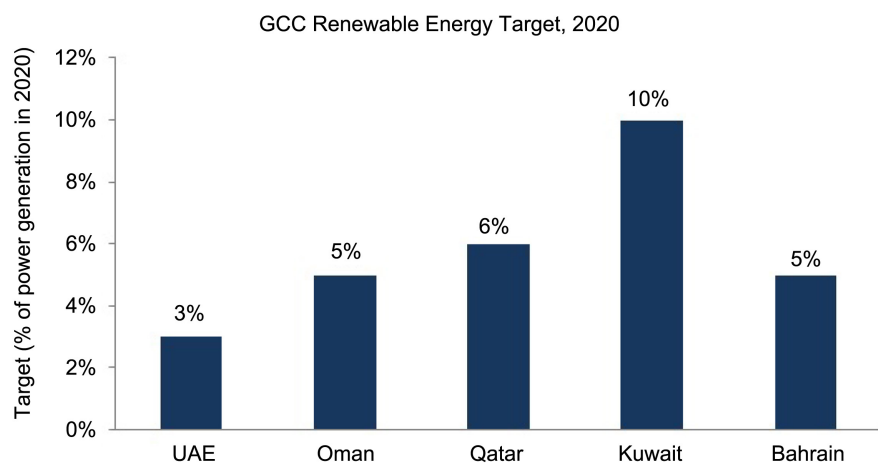
## 1. Introduction

Arabian Gulf is one of the promising seas in the Middle East and is located in between Saudi Arabia on its west and Iran on its east (**Figure 1**). The Arabian Gulf is surrounded by Oman, Saudi Arabia, UAE, Qatar, Bahrain, Kuwait, Iraq and Iran. The Gulf is known for its rich source of oil and gas, which is being very effectively exploited by most of the countries. The gulf has a few islands and there are a plenty of large developed cities located on its shores. The water depth of the Arabian Gulf is shallow. Water depths of more than 100 m are available only on the Iranian coast.

The countries surrounding the Arabian Gulf generate power mainly from hydrocarbons like oil and gas. Though hydrocarbon-based fuel can provide the needed energy in the future, the Gulf Cooperation Council (GCC) Countries have proposed targets for renewable energy (**Figure 2**).



**Figure 1.** Arabian gulf and its bathymetry.



**Figure 2.** Renewable energy target in GCC countries by the year 2020 (Source: <https://www.e-marmore.com/Blog/Infrastructure/March-2015/Alternative-Energy-in-Fossil-Fuel-Rich-GCC-Countries>).

A study by apricum group ([https://www.apricum-group.com/gcc-countries-rising-stars-solar-wind/#\\_ftn1](https://www.apricum-group.com/gcc-countries-rising-stars-solar-wind/#_ftn1)) reveals that wind power may be cheaper than oil based power, if the real export cost is considered for oil. For example, apricum group revealed that solar and wind power can effectively complement the existing conventional capacity and provide electricity at low cost of below 10 USD cent/kWh—about half the cost of oil-fired power generation at market prices. In fact, the most recent tender in Dubai has resulted in the remarkable tariff of 6 USD cent/kWh (unsubsidized). So, particularly oil-rich countries such as Saudi Arabia, Kuwait or the United Arab Emirates (UAE) are better off exporting oil instead of burning it domestically for power generation.

In general, GCC countries have an abundant source of oil and gas and hence at the beginning, the interest on renewable energy was feeble. However, the increase in the level of air pollution and environmental degradation of fossil fuel burning has created more interest on renewable energy investments (Doukas *et al.* [1]). Electricity consumption in GCC countries increased rapidly during the last three decades not only in absolute terms, but also in terms of its share in total energy demand. The continued growth in electricity demand will require significant investments over the coming period and will put further strains on government budgets (Al-Faris, [2]). Due to the vast growth of development in the infrastructure and investment in energy, the electricity consumption in the GCC countries had increased at a fast rate (Al-Naser and Al-Naser [3]); 12.4% from 2005 to 2009 (3.15%, annually). This rate is much larger than the world average, which is 2.2% for the same period, or USA (0.5%). In 2005, the average Watt per person in the GCC countries was 1149 which is much higher than the world average (297 W per person) or the European Union (700 W/person)—but less than USA (1460 W/person). The GCC countries need to increase its electrical capacity by 60,000 MW, which represents 80% of the current installed capacity, to meet demand in 2015. This means that there is a need to build 50 more gas fired power generator plant turbine (each rated 1400 MW). Al-Naser and Al-Naser [3] has also worked out the cost of power production in GCC countries from wind power plants. The cost of 1 kWh from wind electricity in the GCC countries may be from US ¢10 (large turbine  $\approx$  2 MW at 80 m height with good wind speed) to US ¢ 15 (for large turbine  $\approx$  2 MW at 80 m height with modest wind speed) while the cost of kWh from grid connected Wind farm plant (20 MW)—with a cost of USD 38.6 million and energy—is US ¢ 6.7/kWh to US ¢ 8.8/kWh, depending on the location of wind farm. This makes it very challenging for investor, government (Feed-in-Tariff) and citizens because each citizen in GCC countries pays only US cent 1 for each kWh, for consumption less than 3000 kWh, or even nothing for citizens-like in Qatar. Institutes and researchers have carried out studies on feasibility/economics/environmental impacts/policies related to wind power plants in different GCC and MENA countries. Masdar Institute in Abu Dhabi has carried out many studies on the feasi-

bility of different types of renewable energies in this region (Nader [4]; Reiche [5] and Janajreh *et al.* [6]).

Rehman *et al.* [7] has studied on the wind power cost at twenty locations in Saudi Arabia. Rehman and Ahmad [8] have studied the wind energy potential in the coastal areas of Saudi Arabia. Yanbo and Dhahran are identified as the best location. Further detailed studies for Yanbo location was carried out by Rehman [9]. The wind speed at this location is found to be more than 3.5 m/s for 69% of the time in a year.

In Iran, Mostafaeipour [10] studied on the feasibility for offshore wind turbine installation compared to world. The investigation was carried out to harness wind power in the Arabian Gulf, Caspian Sea, Urmia Lake and Gulf of Oman. Development of renewable energy is one of priority research goals in Iran. There are many installed wind turbines in suitable regions like Manjil and Binalood in Iran, but there has not been any offshore wind installation yet in Iran. It is suggested that policy makers to invest and pay more attentions toward harnessing renewable energy sources like offshore wind in Arabian Gulf and Gulf of Oman in southern parts of Iran. Mostafaeipour *et al.* [11] has carried out detailed feasibility study for wind energy for the city of Shahrabak in Iran. Similar study was carried out for the capital city, Tehran by Keyhani *et al.* [12]. Marafia and Ashour [13] have investigated on the economics of offshore and onshore wind energy systems in Qatar. The study result indicates the suitability of utilizing small to medium-size wind turbine generators, efficiently in the offshore since the average wind speed was more than 6.0 m/s. Oman also has carried out many investigations on the status and future prospectus of renewable energy (Kazem [14] and on wind power for a new city (Albadi *et al.* [15]). It is clear that most of the GCC countries have good offshore wind energy potential and there are tendencies to invest for commercial offshore wind mills.

It is clear from these studies that the countries around the Arabian Gulf have significant interest in exploiting the wind energy on the land and over the Arabian Gulf. However, a detailed knowledge of the wind power resource over the Arabian Gulf is missing. This is the main motivation for the present study. The results of this study will help the governments of different GCC countries for planning and implementation of wind power plants in their respective territorial waters in the Arabian Gulf.

A thorough knowledge of the statistical properties of the wind speed is essential for predicting the energy output of a wind energy conversion system. Because of the high variability in space and time of wind energy, it is important to verify that the analyzing method used for the wind data will yield the estimated energy of the wind speed distribution. The wind variation for a typical site is usually described using the so-called Weibull distribution. In this study, attention is given to the Weibull two parameter ( $k$ , the shape parameter, and  $c$ , the scale parameter) functions because it has been found to fit a wide collection of wind speed data around the world. The main objectives of this study are to come up with wind energy map of Arabian Gulf based on statistical analysis of long

term data. It is strongly hoped that this new wind energy map will have many potential uses including identification of the best location in the Arabian Gulf for installing offshore wind energy farms.

## 2. Methodology and Analysis

**1) Wind Power density function:** It is well known that the power of the wind at speed  $v$  through a wind turbines blade sweep area ( $A$ ) increases as the cube of its velocity and can be calculated as follows (Ahmed [16], Al-Naser [17]):

$$P(v) = \frac{1}{2} \rho A v^3 \quad (1)$$

where  $\rho$  is the mean air density (1.225 kg/m<sup>3</sup> at average atmospheric pressure at sea level and at 15°C). However, as a consequence of the cubic dependence of power with wind velocity, the mean speed remains an unsuitable measure when assessing the available wind power density.

It is also well known that the statistical behavior of the wind can be approximated by the Weibull distribution function (Weibull [18], Ramrez [19] and Celik [20]), which describes the probability,  $P(w)$ , for a certain wind speed,  $v$ , depending on the scale parameter,  $c$ , and the shape parameter,  $k$ . The expected monthly or annual wind power density per unit area of a site based on a Weibull probability density function can be expressed as follows:

$$P_w = \frac{1}{2} \rho c^3 \Gamma\left[1 + \frac{3}{k}\right] \quad (2)$$

To following equation is used to calculate the Weibull shape parameter or factor ( $k$ ) by iteration method (maximum likelihood method):

$$k = \left( \frac{\sum_1^n v^k \ln(v)}{\sum_1^n v^k} - \frac{\sum_1^n \ln(v)}{n} \right)^{-1}$$

where  $c$  is the Weibull scale parameter (m/s), and is given by:

$$c = \frac{v_m}{\Gamma\left(1 + \frac{1}{k}\right)} \quad (3)$$

where  $\Gamma$  the gamma function and “ $n$ ” is *is the* total wind data record. Then, Weibull scale parameter is calculated as

$$c = \left( \frac{\sum_1^n v^k}{n} \right)^{\frac{1}{k}}$$

The two significant parameters  $k$  and  $c$  are closely related to the mean value of the wind speed  $v_m$  (Celik [21]). By extracting  $c$  from Equation [3] and  $k$ , the power density for the Rayleigh model can be found by (Al-Mohamad [22]):

$$P_R = \frac{3}{\pi} \rho c^3 \left( \frac{\pi}{4} \right)^{\frac{3}{2}} \quad (4)$$

Errors in calculating the power densities using the distributions in comparison to values of the probability density distributions derived from measured wind speed values can be found by the following Equation:

$$\text{Error}(\%) = \frac{P_{W,R} - P_{m,R}}{P_{m,R}} \quad (5)$$

where  $P_{W,R}$  is the mean power density calculated from either the Weibull or Rayleigh function used in the calculation of the error and  $P_{m,R}$  is the wind power density assessed from the probability density distribution, derived from the measured wind speed values which serves as the reference mean power density.

**2) Wind speed variation with height:** Since the wind speed data are available at 1 height of 10 m from the ground or mean water level, it is necessary to assess the wind speed at the center of turbine hub, which varies from 30 m to 50 m depends on its capacity. This requires an equation that predicts the wind speed at one height in terms of the measured speed at another height. The most common expression for the variation of wind speed with height is the power law (Perez [23]) having the following form:

$$\frac{v_2}{v_1} = \left[ \frac{h_2}{h_1} \right]^\infty \quad (6)$$

where  $v_1$  and  $v_2$  are the mean wind speeds at heights  $h_1$  and  $h_2$ , respectively. The exponent  $\infty$  depends on factors such as surface roughness and atmospheric stability as shown in **Table 1**.

Numerically, it lies in the range 0.0 - 0.5, with the most frequently adopted roughness value being 0.5 with roughness length of 0.0024.

The Equation (6) can be written as follows:

$$\frac{v_2}{v_1} = \frac{\ln\left(\frac{h_2}{r}\right)}{\ln\left(\frac{h_1}{r}\right)} \quad (7)$$

where  $r$  is Roughness Length (m),  $v_2$  wind speeds at selected elevation from ground level  $h_2$ .

The wind speed at a certain height above ground level is

$$v_2 = v_1 \left[ \frac{\ln\left(\frac{h_2}{r}\right)}{\ln\left(\frac{h_1}{r}\right)} \right] \quad (8)$$

The fact that the wind profile is twisted towards a lower speed as we move closer to ground level is usually called wind shear. Wind shear may also be important when designing wind turbines.

The information provided in this methodology section is used for assessing the Weibull parameters over the Arabian Gulf and its probability distribution.

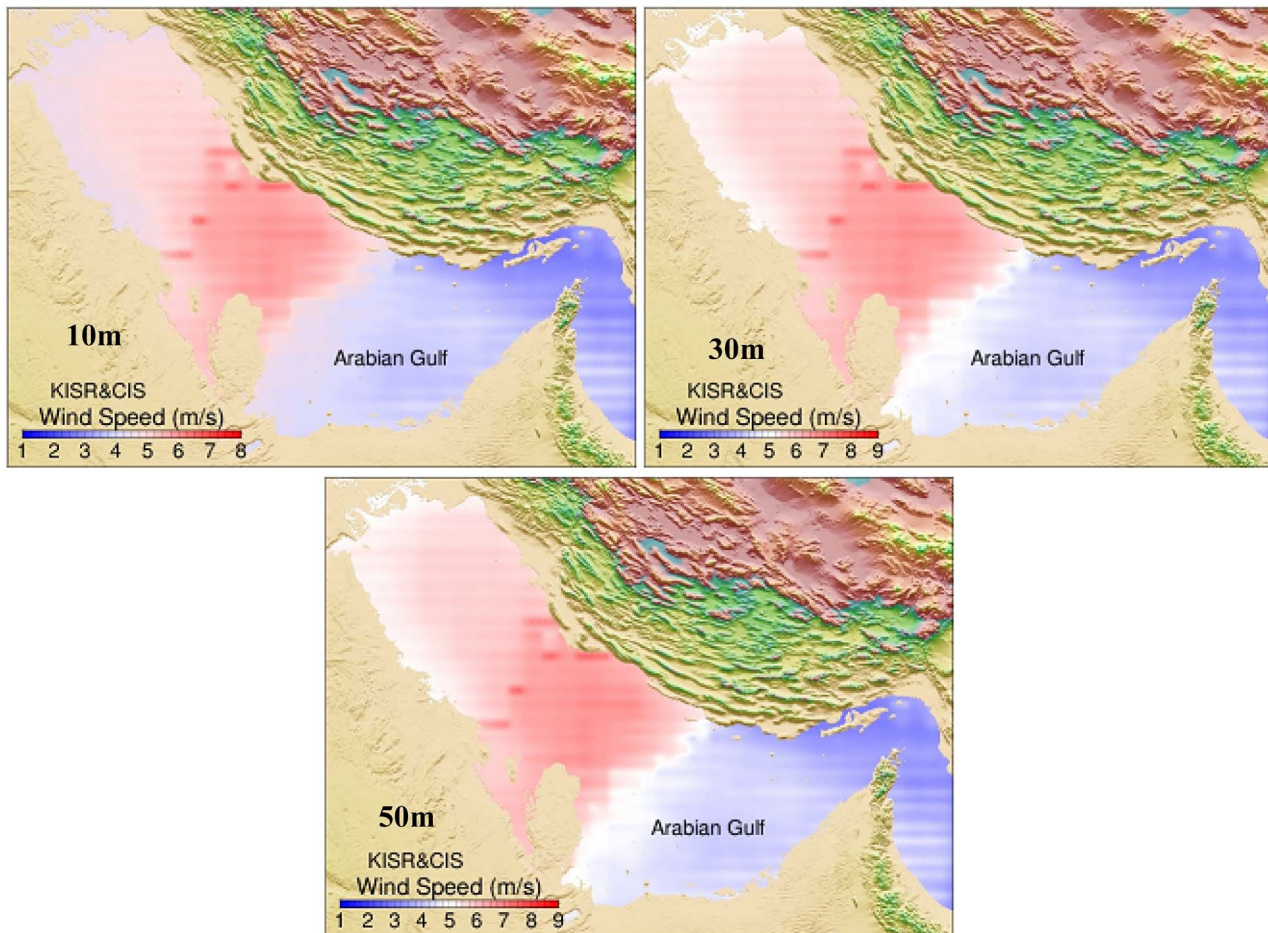
**Table 1.** Roughness classes and roughness length (Source: definitions according to the European Wind Atlas, WASP).

Roughness	Roughness Length m	Energy Index %	Landscape Type
0	0.0002	100	Water surface
0.5	0.0024	73	Completely open terrain with a smooth surface, e.g. concrete runways in airports, mowed grass, etc.
1	0.03	52	Open agricultural area without fences and hedgerows and very scattered buildings. Only softly rounded hills
1.5	0.055	45	Agricultural land with some houses and 8 meter tall sheltering hedgerows with a distance of approx. 1250 meters
2	0.1	39	Agricultural land with some houses and 8 meter tall sheltering hedgerows with a distance of approx. 500 meters
2.5	0.2	31	Agricultural land with many houses, shrubs and plants, or 8 meter tall sheltering hedgerows with a distance of approx. 250 meters
3	0.4	24	Villages, small towns, agricultural land with many or tall sheltering hedgerows, forests and very rough and uneven terrain
3.5	0.8	18	Larger cities with tall buildings

### 3. Results and Discussions

Data for wind speed used in the present calculations were obtained for the period 1979-2015 from the Coastal Information System Database at KISR (Al-Salem [24] [25] and Rakha [26]). The wind data used were numerically predicted and are validated with the instrumentally measured wind speed data from Kuwait International Airport data (Al-Salem [27]). All the locations in the study were positioned over Arabian Gulf waters in open spaces free of obstacles at a height of 10 m above the ground. Wind speeds stored and averaged over one hour in the database. The wind speed changes with height because air pressure is low at higher elevations and the air which gets heated from the surface of earth also moves to higher altitude. This air provides energy to the air speed at higher elevation. In this study, 3 different heights at 10, 30 and 50 m from the sea level are used to calculate the mean wind speed maps over Arabian Gulf waters for a period of 1979-2015 as shown in **Figure 3**. The results obtained from the wind speed study can be summarized as follows:

- The central area of Arabian Gulf has higher wind speed ranging from 6 - 8 m/s at 10 m elevation, 7 - 8 m/s for 30 m elevation and 8 - 9 m/s for 50 m elevation.
- The northern area of Arabian Gulf has moderate wind speed ranging from 3 - 4 at 10 m elevation, 4 - 5 m/s for 30 m elevation and 5 - 6 m/s for 50 m elevation.



**Figure 3.** Mean wind speed (m/s) at 10, 30 and 50 m above sea level over Arabian Gulf waters for periods of 1979-2015.

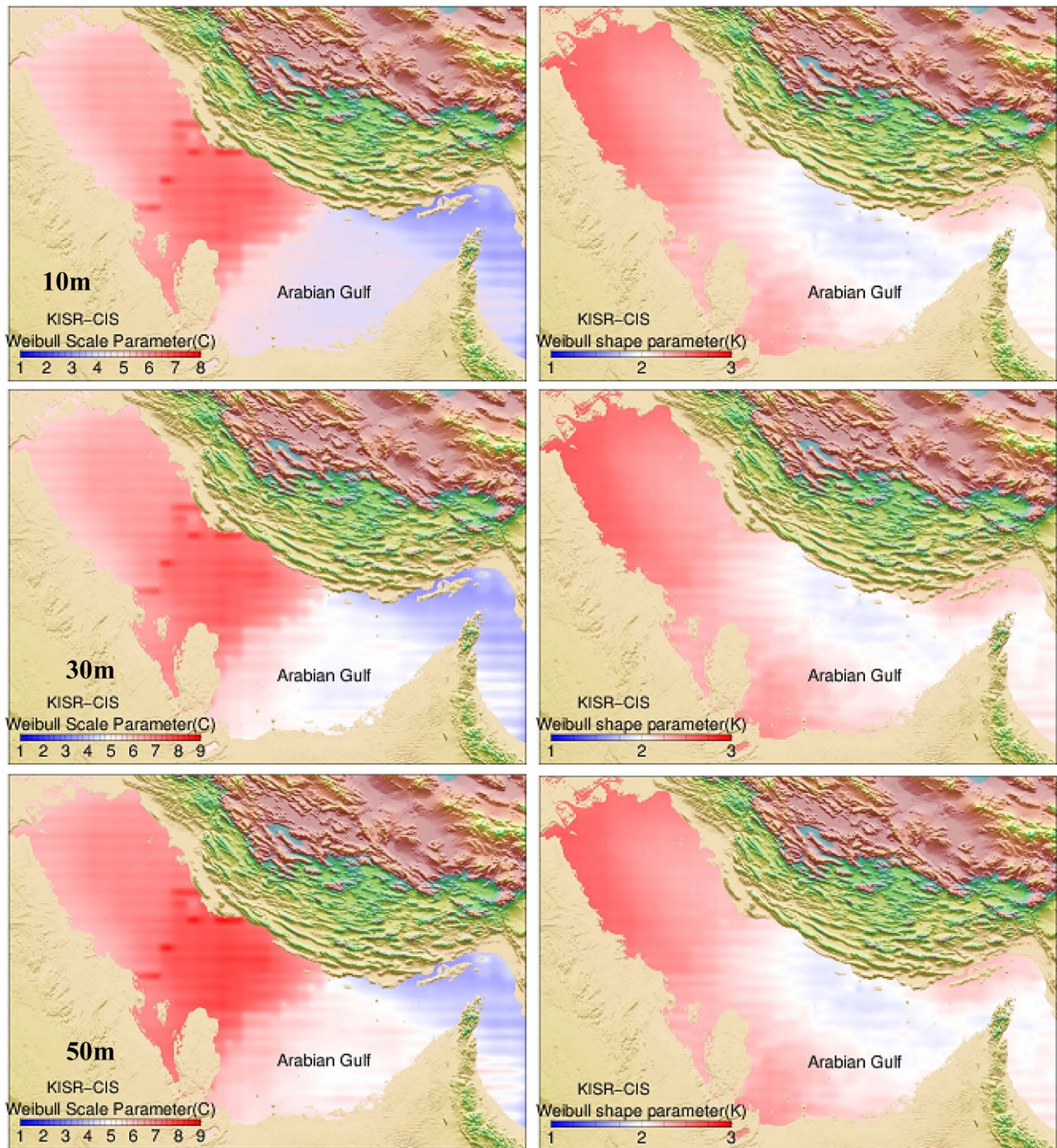
- The southern area of Arabian Gulf has low wind speed ranging from 2.5 - 3.0 m/s for 10 m elevation, 3 - 4 m/s for 30 m elevation and 4 - 4.5 m/s for 50 m elevation.

Hence it is clear that the central area of the Arabian Gulf is attractive for extracting wind energy.

The variation of wind velocity is often described by using the Weibull two-parameter density function. As described earlier, the Weibull shape function  $k$  and scale factor  $c$  are calculated analytically from the available data and are presented as a maps of mean values in **Figure 4** for sea level elevations at 10, 30 and 50 m over Arabian Gulf waters. At the central area of Arabian Gulf, the scale parameter  $c$  has higher prediction value and is ranging from 6 - 8 m/s for 10 m elevation, 7 - 8 m/s for 30 m elevation and 8 - 9 m/s for 50 m above sea level. The Weibull shape parameter  $k$  is found to vary from 2.5 - 3 at the north and central area of the Arabian Gulf. This shows the Weibull distribution function has a good wind speed predicted comparing to the mean wind speed shown in **Figure 3** for all elevation selected.

The average annual maps of wind power densities were calculated from CIS wind speed database and from Weibull distribution prediction are shown in

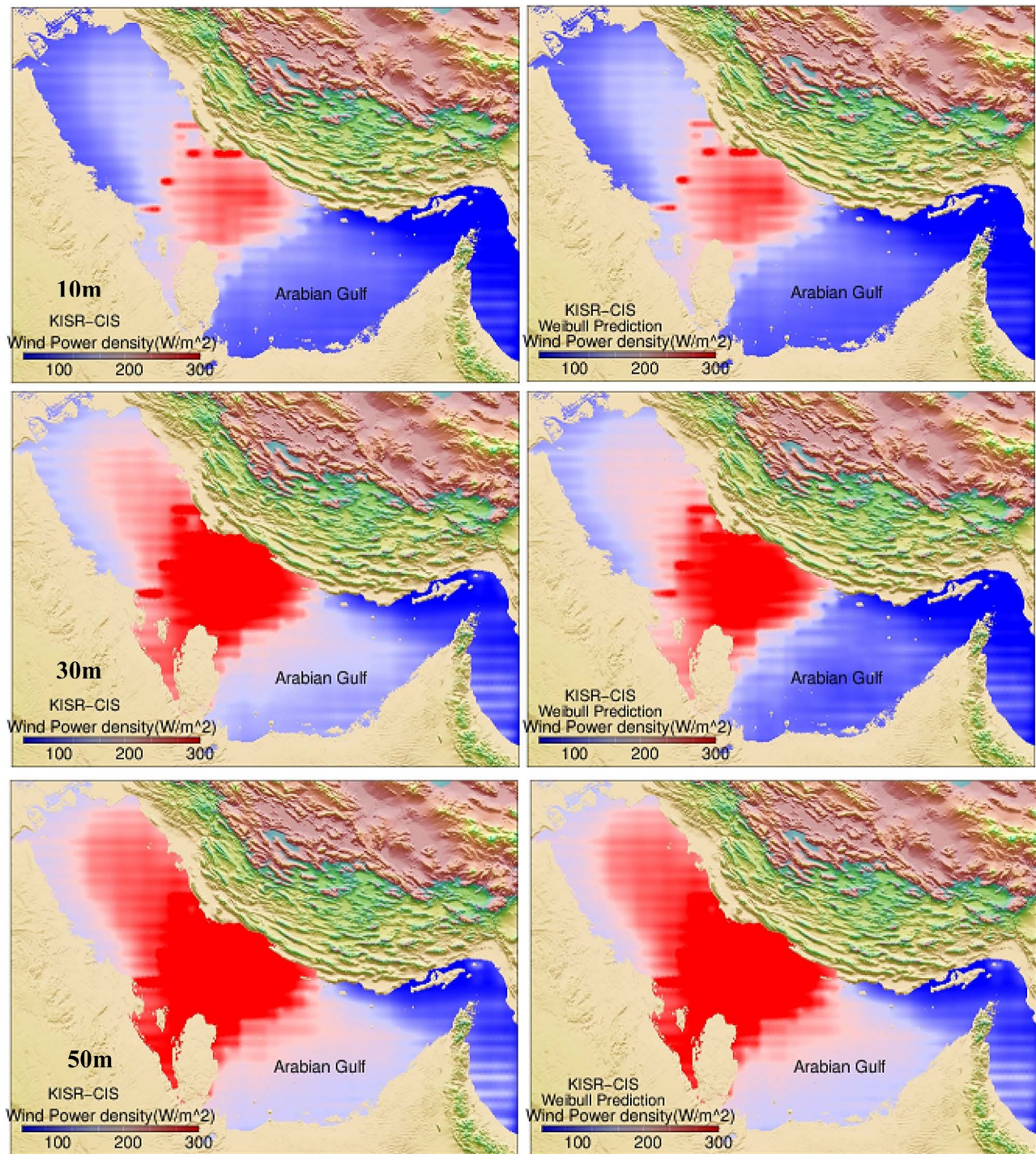




**Figure 4.** Weibull shape function  $k$  and scale factor  $c$  for wind speed data at 10, 30 and 50 m above sea level over Arabian Gulf waters for periods of 1979-2015.

**Figure 5** for elevation 10, 30, 50 m above sea level over Arabian Gulf waters for period of 1979-2015. The information gathered from this figure is as follows:

- The wind power density over Arabian Gulf Waters is the highest in the central region of the Gulf. The power density at 10 m hub height varies between 200 to 300  $w/m^2$ ; at 30 m, it varies between 200 to 300  $w/m^2$  and at 50 m, it is more than 300  $w/m^2$ .



**Figure 5.** Comparison of Weibull predicted and actual distribution of wind power density ( $w/m^2$ ) at 10, 30 and 50 m over Arabian Gulf Waters for periods of (1979-2015).

- The wind power density over the southern region of the Arabian Gulf is the lowest. The wind power density at 10 m hub height is found to vary between 100 to 120  $w/m^2$ ; at 30 m, it varies between 120 to 150  $w/m^2$  and at 50 m, it is found to vary between 150 to 200  $w/m^2$ .
- In the northern region of the Arabian Gulf, the wind power density at 10 m,

30 m and 50 m hub heights vary between 100 to 170  $w/m^2$ , 180 to 190  $w/m^2$  and 200 to 220  $w/m^2$  respectively

**Figure 5** is provided to show how the predicted wind power density by Weibull distribution and actually estimated value from the data is comparing. It is found that at elevation of 30 m or 50 m and at central region of the Arabian Gulf, the wind power is attractive and is lying in Class 2 as shown **Table 2** of the Wind Energy Resource Atlas of the United States (Elliott [28]). Wind mills of larger capacities can be installed in this region. Similarly, at elevations of 30 m or 50 m at North or south region of Arabian Gulf waters, small-scale wind power plants can be installed since this regions falls under Class 1 of **Table 2**.

The annual average wind power density maps of the whole Arabian Gulf are displayed at **Figure 4** and **Figure 5**. However, a monthly wind power distribution is needed for monthly power generation estimate. **Figure 6** and **Figure 7** provides the monthly average wind power density maps for January to June and July to December respectively over Arabian Gulf waters at hub height of 30.

It is clear that **Figure 6** and **Figure 7** provides the following vital information of monthly and season distribution of wind power:

- During the winter season (December-February), the wind power is high at central region of Arabian Gulf and moderate at both north and southern region.
- During spring season (March-May), the wind power is high at central region of Arabian Gulf, moderately high at north, but low at southern region.
- During summer season (June-August), the wind power is high at central and northern regions of Arabian Gulf and moderate in the southern region. However, during August, the wind power density becomes low over the whole Arabia Gulf waters.
- During the fall season (September-November), the wind power is low at all the regions over Arabian Gulf waters; but in November the wind power become high at the central.

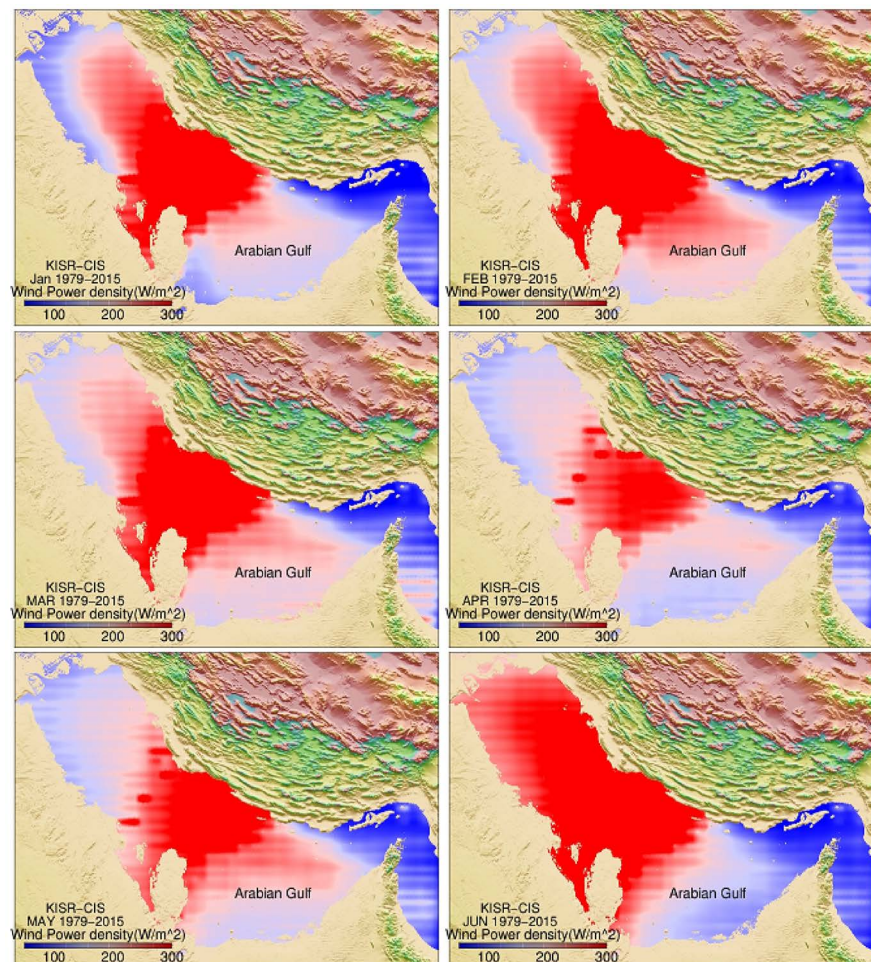
It is to be noted that the power consumption is high during summer due to powering for air conditioning and hence, the high wind power availability at the central and northern Arabian Gulf region is attractive for countries around these regions. **Table 3** shows the mean monthly wind power density at elevation of 30m for a selected location over the Arabian Gulf waters for period of

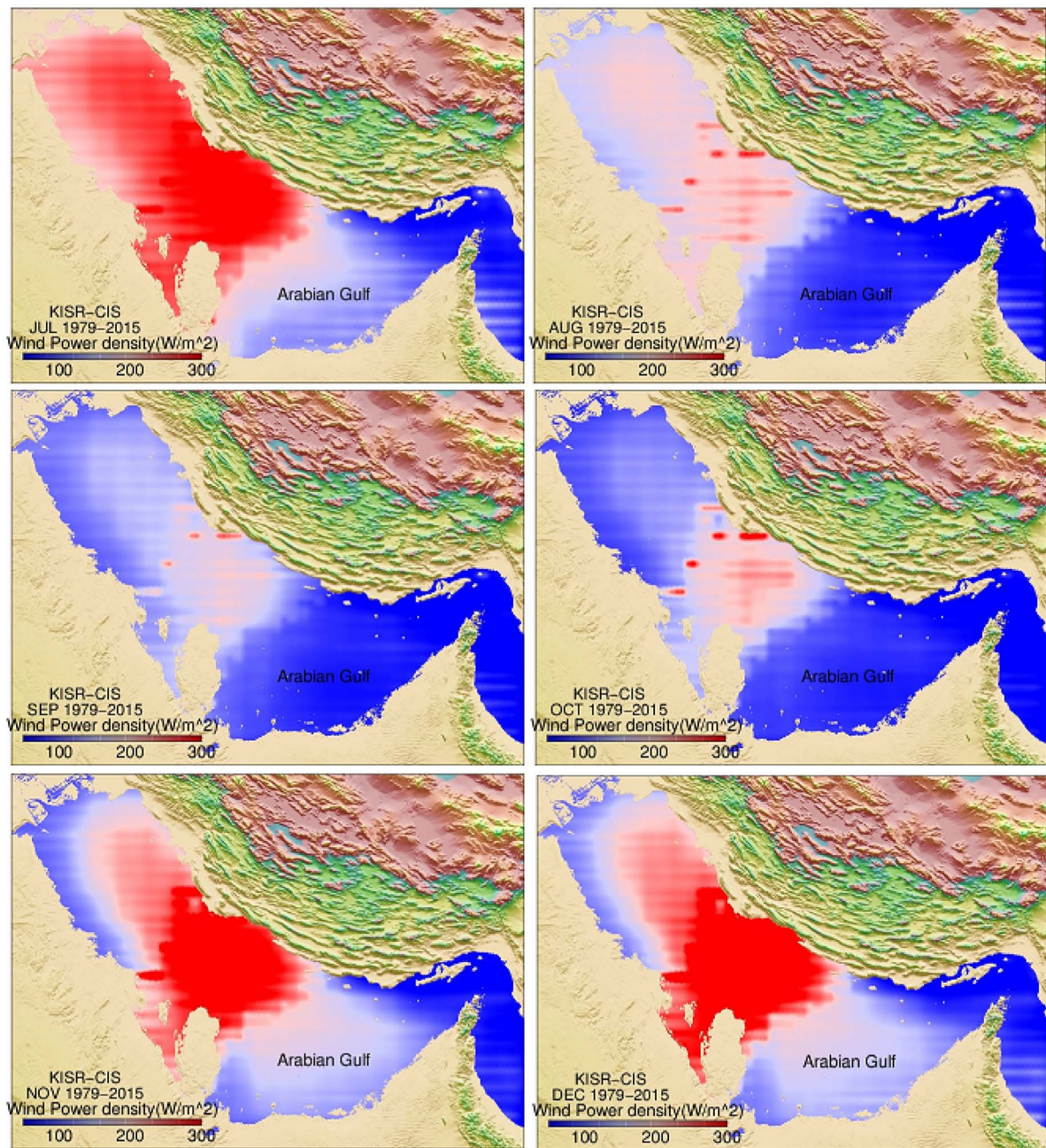
**Table 2.** Wind power class (Source: Wind power class 2014 [29]).

Wind Power Class	Wind Speed (m/s)	WPD ( $w/m^2$ )	Resource Potential
1	0 - 4.9	0 - 243	Not suitable
2	4.9 - 6.9	243 - 378	Marginal
3	6.9 - 7.5	378 - 500	Fair
4	7.5 - 8.1	500 - 616	Good
5	8.1 - 8.6	616 - 748	Excellent
6	8.6 - 9.4	748 - 978	Outstanding

**Table 3.** Monthly mean wind power densities ( $w/m^2$ ) for period of 1979-2015 for selected locations in the Arabian Gulf at hub height of 30 m above sea level.

	Kuwait E48°18'0.0" N29°12'0.0"	Saudi Arabia E50°30'0" N26°36'0.0"	Bahrain E50°48'0.0" N26°18'0.0"	Qatar E51°18'0.0" N26°12'0.0"	Unit Arab Emirate E54°48'0." N25°00'0.0"
January	141	349	385	329	138
February	175	381	428	389	168
March	175	326	356	348	176
April	156	233	247	240	151
May	157	255	282	296	160
Jun	259	405	428	378	115
July	233	272	276	264	110
August	167	184	188	169	77
September	125	154	163	143	71
October	101	166	179	161	64
November	124	279	310	276	107
December	139	329	357	297	113

**Figure 6.** Monthly distribution of wind power density ( $w/m^2$ ) at 30 m over Arabian Gulf Waters for periods of (1979-2015) for January to June.



**Figure 7.** Monthly distribution of wind power density ( $w/m^2$ ) at 30 m over Arabian Gulf Waters for periods of (1979-2015) for July to December.

1979-2015. According to this table, the central region of the Arabian Gulf (Saudi Arabia, Bahrain and Qatar) has a good wind power regime for economical installation of large-scale wind power production, lying in Class 2 as shown in **Table 2**. However, the wind power potential is low during September and October.

#### **4. Assessment of Wind Power Density Potential at G.C.C Countries**

The Interest in renewable energy in the GCC countries has been on the rise in

recent years. With the region's consumption expected to continue growing at a fast pace over the next two decades, renewable energy have become an important consideration in government strategies to diversify the domestic energy mix. The renewable energy could also help mitigate the natural gas shortages GCC economies could experience over the coming decades. In Kuwait, Saudi Arabia and the UAE, local production has already been outstripped by domestic market consumption. To examine the wind power potential of the GCC countries over their territorial waters in Arabian Gulf, **Table 4** is provided.

- Countries, which are located at the central zone of Arabian Gulf waters (such as Saudi Arabia, Bahrain and Qatar) have annual wind power of 277, 300, 275  $w/m^2$ , respectively. This order of wind power is attractive for large-scale power production, lying in Class 2 of the US wind power density classification (Elliott [28]).
- Countries located at the South zone of Arabian Gulf waters (United Arab Emirate) have annual wind power of 120  $w/m^2$ , which is low for economic large-scale power production.
- Countries located at the north zone of Arabian Gulf waters (Kuwait) have annual wind power of 166  $w/m^2$ , which is acceptable for economical medium-scale power production.

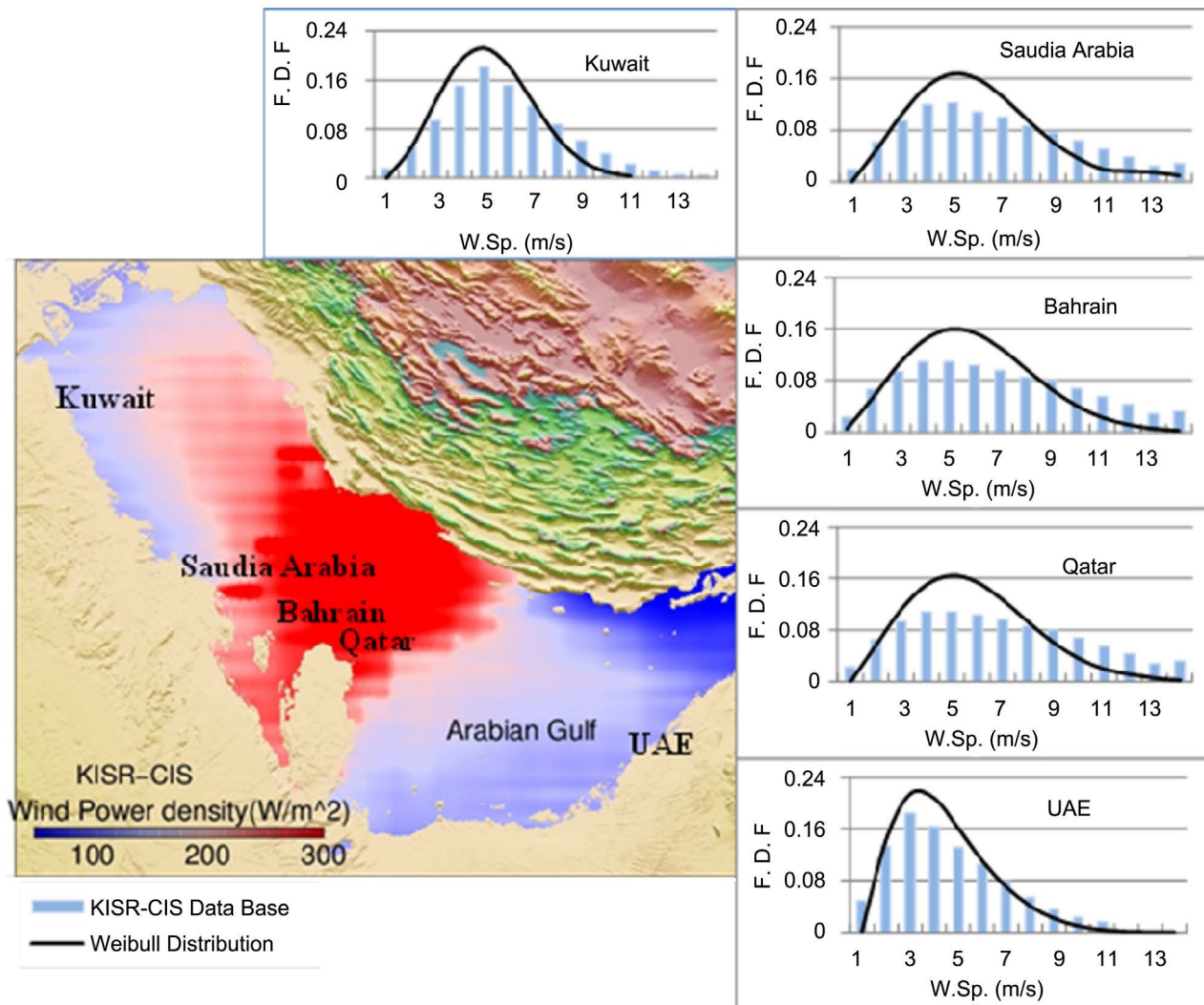
It is important to compare the probability distribution of the wind power assessed based on the data and derived from Weibull distribution to assess how good Weibull distribution is for the present study. **Figure 8** shows such plot. It is found that the prediction by Weibull distribution compares satisfactorily with the estimate of the actual data for the locations indicated in **Table 4**.

## 5. Conclusions

The potential of wind energy resource over Arabian Gulf waters, covering 2300 grid points is carried out using data available with Coastal Information System

**Table 4.** Mean wind power densities ( $w/m^2$ ) for period of 1979-2015 over Arabian Gulf waters at hub height of 30 m above sea level for GCC countries.

G.C.C. Countries	Map Location	Mean Annual WPD $w/m^2$	Total Annual Energy (8760 hr) $w/m^2$
Kuwait	E48°18'0.0" N29°12'0.0"	166	1454
Saudi Arabia	E50°30'0.0" N26°36'0.0"	277	2426
Bahrain	E50°28'0.0" N26°18'0.0"	300	2628
Qatar	E51°18'0.0" N26°12'0.0"	275	2409
Unit Arab Emirate	E54°48'0.0" N25°00'0.0"	120	1051



**Figure 8.** Comparison of the probability distribution function (PDF) of wind speeds derived from CIS database data at Elevation 30 m above sea level with Weibull distribution for periods 1979-2015 for G.C.C. countries.

(CIS) data base from 1979 to 2015. The probability density and power density were derived from these data. Weibull probability density function has been fitted to the wind speed data and the wind power density was evaluated. The study is carried out at 10 m, 30 m and 50 m elevations. The most important conclusions of this study are summarized as follows:

- The central location of the Arabian Gulf has higher annual average wind speed, ranging from 6 - 8 m/s at 10 m elevation, 7 - 8 m/s at 30 m elevation and 8 - 9 m/s at 50 m elevation.
- The scale parameter  $c$  at central location of Arabian Gulf is found to range from 6 - 8 m/s for 10 m elevation, 7 - 8 m/s for 30 m elevation and 8 - 9 m/s for 50 m above sea level.
- The Weibull shape parameter  $k$  varies from 2.5 - 3 at the north and central of the Arabian Gulf.
- The annual mean wind power density over Arabian Gulf Waters is the high-

est in the central region of the Gulf. The power density at 10 m, 30 m and 50 m hub height varies between 200 to 300 w/m<sup>2</sup>, 200 to 300 w/m<sup>2</sup> and more than 300 w/m<sup>2</sup> respectively.

- It is attractive to install large scale wind power generation at the central region of the Arabian Gulf and at elevations of 30 m or 50 m, since this region lies in Class 2 category of the Wind Energy Resource Atlas of the United States (Elliott [28]).
- The wind power density is attractive especially in summer season around the central region location in Arabian Gulf (Saudi Arabia, Bahrain and Qatar).

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