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Wind resources of the Gulf of Suez and northern Red Sea, Egypt

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SYNOPSIS The results of a comprehensive, 5-year wind resource assessment programme in the Gulf of Suez are presented. The primary purpose has been to establish reliable and accurate wind atlas data sets for this area. With mean wind speeds and energy densities of 8-12 ms^{-1} and 500-1400 Wm^{-2}, respectively, at a height of 25 m over roughness class 0 (water), the wind resources of the Gulf of Suez are comparable to those of the most favourable regions in NW-Europe. The wind atlas methodology has proven very useful in the extreme climatic conditions of the desert. Applied with care, it can provide accurate predictions of the wind climate at candidate sites for wind turbines along the Gulf of Suez.

1 INTRODUCTION

It has long been recognized that the wind energy potential along the Gulf of Suez and the Red Sea (Fig. 1) is markedly higher than in other parts of Egypt—and most other parts of the North African deserts as well. However, early estimates of the mean wind speed [3], based on the existing network of synoptic meteorological stations in Egypt, range from only about 4 ms^{-1} in the northern part of the Gulf of Suez to about 6 ms^{-1} in the northern Red Sea—values which we today know are far too low.

In the 1970's and 80's a number of wind resource assessment studies were carried out in Egypt, including the erection of several wind-monitoring stations. These activities were summarized a decade ago by Renne et al. [8] and Elliott et al. [2], who also published a map showing the distribution of seven wind power classes over Egypt. Renne and Elliott [8, 2] reanalyzed the existing wind data obtained at stations run by the Egyptian Meteorological Authority and then verified and detailed these resource estimates through additional wind measurements at key locations, in particular along the Gulf of Suez and the Mediterranean coast. They further used climatological data on winds aloft and maps of pressure patterns and air flow, as well as topographical maps, in estimating the wind resources of the data-sparse areas. Their resource estimates were calculated from measured distributions of mean wind speed or, in cases where only average wind speeds were available, by assuming that the wind speeds are distributed according to the Rayleigh distribution. The wind resource estimates were referred to 10 metres above ground level (a.g.l.) over "areas free of local obstructions to the wind and to terrain features that are

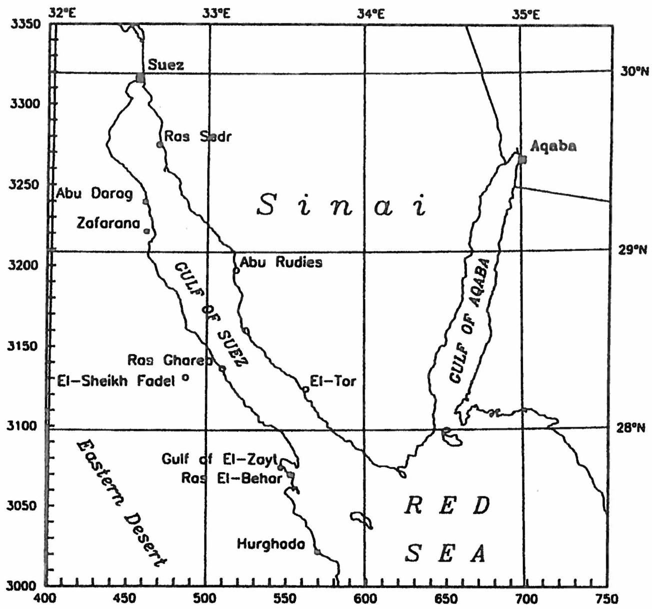

Figure 1: Overview map of the study area with the Gulf of Suez, the northern Red Sea, the Gulf of Aqaba, and the Sinai Peninsula. The four main wind atlas stations (∘), as well as several auxiliary stations (∘), are shown on both sides of the Gulf of Suez. Cartesian map coordinates are in kilometers, UTM zone 36.

well exposed to the wind, such as open plains, plateaus, and hilltops" [8]. Mean wind speeds in the Gulf of Suez were found to range from class 3 (5.1-5.6 ms^{-1}) in the northern part of the Gulf, to class 6 (6.4-7.0 ms^{-1}), covering the southernmost three quarters of the Gulf. At one station, the data even indicated class 7 (7.0-9.4 ms^{-1}), but this was attributed to the location on a well-exposed ridge [8], which was not representative of the terrain of the region in general.

The existing wind data for the Gulf of Suez were re-analyzed in 1990 by the New and Renewable Energy Authority in Egypt and Risø National Laboratory; in the framework of the European Wind Atlas methodology. Based on the findings of this study it was decided to conduct a new wind resource assessment programme with the primary purpose of establishing reliable and accurate wind atlas data sets for the Gulf of Suez and northern Red Sea, in particular for the regions around Zafarana and Hurghada. Naturally, a secondary purpose was to evaluate the applicability of contemporary wind resource estimation and siting tools—in particular the European Wind Atlas methodology—to the extreme climatic conditions found in the desert.

2 NEW WIND-MONITORING STATIONS

In 1991, three new wind-monitoring stations were installed in the Gulf of Suez and northern Red Sea: at Abu Darag, Zafarana, and Hurghada, see Fig. 1. A fourth station was erected on the west shore of the Gulf of El-Zayt in 1994. The stations are all equipped with a cup anemometer and a wind vane 24.5 m a.g.l. as well as a shielded thermometer 2 m a.g.l. In addition, the station in Hurghada measures 3-second gust speeds, wind speed at 10 m, atmospheric pressure and temperature difference between the 24- and 2-m levels. Measurements are recorded every ten minutes and the results reported below were taken from 1991 to 1995. A full description of the meteorological stations is given in [6].

The accuracy of the wind speed measurements have been secured by wind tunnel calibration of the cup anemometers used; in some cases both before and after the period covered by the study. Table 1 and Fig. 2 provide summaries of the wind measurements obtained during a period of almost five years, from 1991-95.

Table 1: Overall summary 1991-95 of wind observations 24.5 m a.g.l. at the four new stations: Weibull A- and k-parameters, mean wind speed ($\overline{U}$), mean energy density ($\overline{E}$), and direction (D_U) and magnitude ($|U|$) of the mean wind vector. The frequency of occurrence of calms at all four stations is less than 0.1%.

Station	A [ms^{-1}]	k	$\overline{U}$ [ms^{-1}]	$\overline{E}$ [Wm^{-2}]	D_U [deg]	$\lvert U \rvert$ [ms^{-1}]
Abu Darag	10.3	3.75	9.0	625	358	7.8
Zafarana	10.3	3.38	9.1	647	000	7.3
G. El-Zayt	11.9	3.67	10.4	965	327	9.7
Hurghada	7.8	2.38	6.9	330	338	5.2

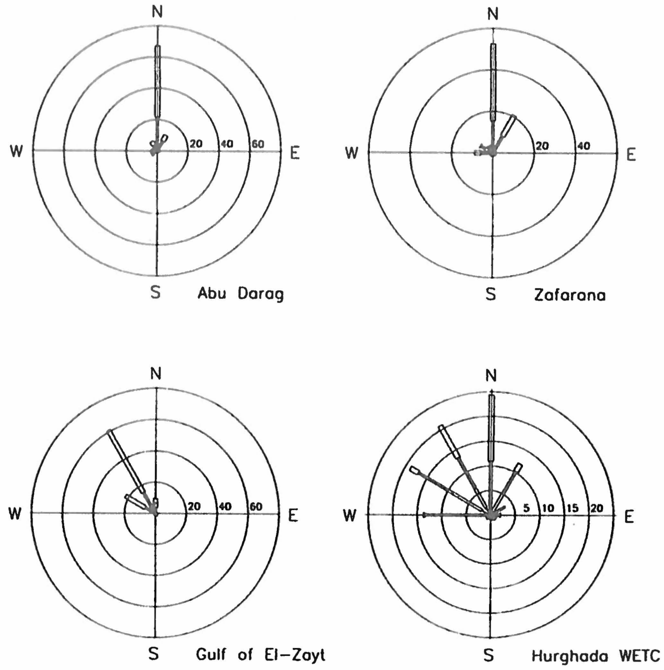

Figure 2: Wind roses for the four stations Abu Darag, Zafarana, Gulf of El-Zayt and Hurghada. Wind direction is shown in twelve 30° sectors (in %) and the distribution of mean wind speeds, U, in each sector is given in four classes: $0 \le U < 3$, $3 \le U < 6$, $6 \le U < 9$, $9 \le U$ ms^{-1}.

3 DATA ANALYSIS

The wind speed and direction data obtained at the four stations described above, as well as recent and historic data from five auxiliary stations, have been analyzed using the Wind Atlas Analysis and Application Program (WAsP) to calculate wind atlas data sets for the nine stations [5]. The five auxiliary stations are Ras Ghareb, El-Sheikh Fadel and Ras El-Behar on the west shore of the Gulf of Suez; and Ras Sedr and El-Tor on the east shore, see Fig. 1. The data series from these stations cover periods of about one year.

For the flow modelling, the height variations of the terrain are described in digital terrain models, obtained by digitization of topographical maps. Since the terrain surrounding the stations is mostly quite flat out to several kilometers from the wind masts, the orographic corrections were in most cases found to be small or negligible. Only the station of Ras Ghareb, which is situated on a ridge SE of the town of Ras Ghareb, was found to be influenced significantly by orographic effects, with up to 13% speed-up in some sectors.

The roughness of the terrain has been assessed from topographical maps and aerial photographs, as well as during site visits. In addition, the aerodynamic roughness length, z_0, of typical desert surfaces have been estimated from wind profile analysis at the Hurghada station. This analysis shows that the sand surfaces are very smooth indeed—with a roughness length of the order of a few mm or less—and further indicates that the roughness is not constant, but increase with increasing wind

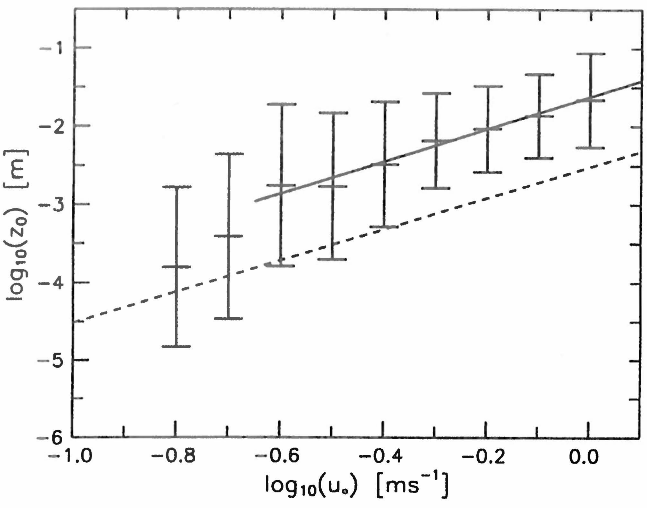

Figure 3: Roughness lengths, z_0, determined from wind and temperature profile analysis of the Hurghada data. Abscissa is the logaritm (base 10) of the friction velocity; ordinate the logaritm of the roughness length. Dashed line corresponds to (1), with $C_0 = 0.06$.

speed. This is illustrated in Fig. 3, where mean roughness length is plotted as a function of the friction velocity u_*. This characteristic of 'moving' surfaces like sand, snow and water is well known and it has been found [1] that the roughness length is proportional to the square of the friction velocity:

$$z_0 = C_0 \frac{u_*^2}{2g} \tag{1}$$

where C_0 is a constant and g is the acceleration due to gravity. For the natural desert surfaces in Hurghada we have also found that the roughness length is proportional to the square of the friction velocity, but the constant of proportionality in (1) is about an order of magnitude larger than reported in the literature. For the purpose of the wind atlas analysis and application presented here, the roughnesses are kept constant, because it is not possible in the models to specify roughness length as a function of; say, wind speed.

Only one station, El-Tor, is sheltered by near-by obstacles. These were identified and described during a site visit to the station.

In the final wind atlas analysis, the measured data are—to the extent that the models can adequately describe the flow—freed from the influence of local topography to become regionally representative [9]. For each station the wind climate is then specified as the Weibull A- and k-parameters for certain standard conditions; ie five heights, four roughness classes and twelve (or eight) sectors. These wind atlas data sets constitute the basis for assessments of the wind resource in the Gulf of Suez. The data and results of the wind resource assessment programme are published in detail in the report *Wind Atlas for the Gulf of Suez. Measurements and modelling 1991-95* [6].

4 WIND RESOURCES OF THE GULF OF SUEZ AND NORTHERN RED SEA

As might be expected from our knowledge of the general circulation of the atmosphere [3, 4], the winds in the Gulf of Suez are predominantly northerly, see Fig. 2. At Abu Darag and Zafarana, the wind blows from north more than half of the time; at Gulf of El-Zayt the wind occurs more than 60% of the time in a 30-degree sector centered around 330°. Consequently, the length of the mean wind vector is more than 80% of the mean wind speed at these stations, see Tab. 1. The Weibull k-parameters are high compared to most stations situated in eg the Westerlies, and the numbers of calms low. The wind climate of the Gulf of Suez is thus fairly steady, with respect to both wind speed and direction.

The strongly preferred wind directions are not only due to a general pressure gradient from north to south, but are also caused by channeling of the wind flow between the mountain ranges that border the Gulf of Suez on both sides—reaching heights of 1000 m or more above sea level. The topography is also partly responsible for the generally high mean wind speeds measured along the west shore of the Gulf of Suez. As the flow enters the Red Sea the terrain opens up, the wind looses momentum, and the mean wind speed immediately decreases by about 20 per cent.

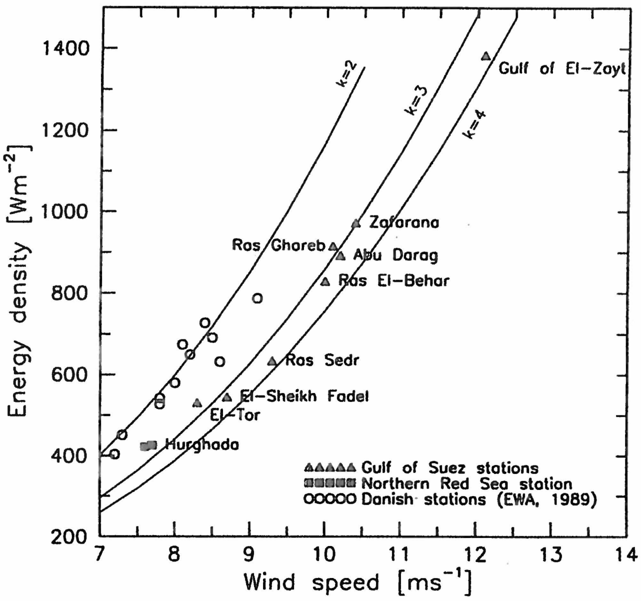

Figure 4: Mean wind speeds and energy densities at a height of 25 m over roughness class 0 (water) for nine stations along the Gulf of Suez and northern Red Sea. For Hurghada, estimates from both the 24.5- and 10-m measurement levels are shown. The Danish stations of the European Wind Atlas [9] are shown for comparison.

The wind atlas analysis allow us to estimate and compare wind climates under certain standard conditions. As an example, Fig. 4 shows values of mean wind speed and mean energy density for the nine stations, corresponding to a height of 25 m over roughness class 0 (water). For comparison, similar data are also shown for the Danish stations given in the European Wind Atlas [9]. With mean wind speeds and energy densities of 8-12 ms^{-1} and 500-1400 Wm^{-2}, respectively, the wind resources in the Gulf of Suez are comparable to those of the most favourable regions in NW-Europe.

Figure 4 also shows that the wind resources vary considerably over the 270-km distance from Ras Sedr in the north to Hurghada in the south; for comparison, the Danish stations cover an area with a diameter of approximately 400 km. Mean wind speeds range from 7.7 ms^{-1} at Hurghada to 12.1 ms^{-1} at Gulf of El-Zayt, a factor of 1.6, and mean energy densities from 426 Wm^{-2} at Hurghada to 1385 Wm^{-2} at Gulf of El-Zayt, more than three times the Hurghada value.

4.1 Geographical variation of the wind resource

The geographical distribution of the wind resource is shown in Fig. 5 as the estimated, long-term mean wind speeds at a height of 25 m a.g.l. over roughness class 0. This map thus shows what *would* have been measured at the locations of the stations if the surroundings were simply (open) water.

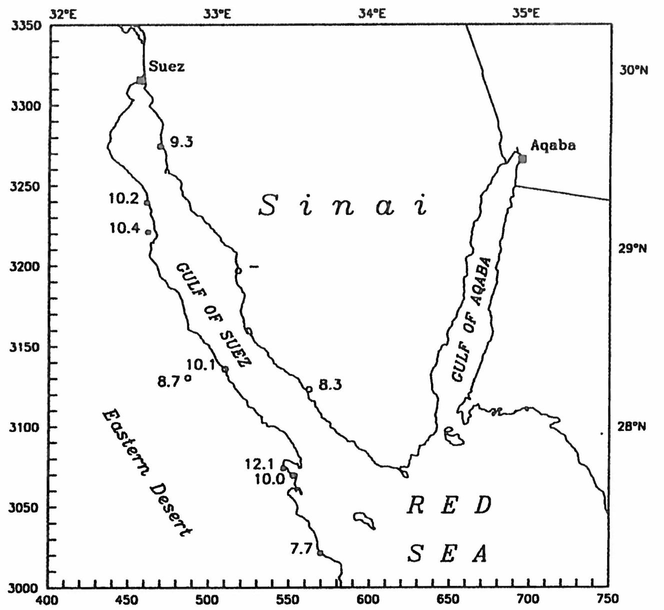

Figure 5: Mean wind speeds in ms^{-1} at a height of 25 m over roughness class 0 at the four main wind atlas stations (•) and five auxiliary stations (o). Cartesian map coordinates are in kilometers, UTM zone 36.

The west shore of the Gulf of Suez—from Abu Darag in the north to Ras El-Behar in the south—is characterized by mean wind speeds and energy densities of 10-10.5 ms^{-1} and 830-970 Wm^{-2}, respectively, estimated at a height of 25 m over roughness class 0. The stations therefore indicate that the near-coastal wind energy resource is consistently high along the west shore of the Gulf of Suez. The inland gradient of the wind climate cannot be described in detail from the data available; however, one inland station 20 km from the coastline (El Sheikh Fadel) indicate a gradient of the order of 0.5 ms^{-1} per 10 km. In the Zafarana region, this decrease in the wind resource with increasing distance from the coastline is apparently not found; at least over the first 5 km from the coast.

The east shore of the Gulf of Suez—from Ras Sedr in the north to El-Tor in the south—seems to have a somewhat lower wind resource than the west shore; however, the information for this part of the Gulf is based on about one-years-worth of data from two stations only. These indicate mean wind speeds and energy densities of 8.3-9.3 ms^{-1} and 530-630 Wm^{-2}, respectively. With only two stations, none of which are instrumented to the standard of the main wind atlas stations, the resource estimates given for the eastern shore are therefore less detailed and reliable than for the west shore.

For the northernmost part of the Gulf of Suez—north of Abu Darag and Ras Sedr—the wind resources are most likely lower than described above and decreasing towards north. Even though no wind atlas analysis has been carried out for this part of the Gulf, a fairly low wind resource is indicated by published mean wind speed values for the city of Suez [7], as well as by previous wind resource investigations [2]. The nature of the atmospheric circulation and topographical features of this region seem not to favour high wind speeds; this is further supported by the common observation, that the sea surface is usually calm in this area and white caps are only seen when going further south.

The southernmost part of the Gulf of Suez—where the Gulf of Suez widens out into the Red Sea—seem to be a region of large horizontal gradients in the wind resource. The highest wind resource recorded for any site in the Gulf of Suez is found here, at the station on the west shore of the Gulf of El-Zayt. The characteristic mean wind speeds and energy densities are about 12 ms^{-1} and 1400 Wm^{-2}, respectively. Historic data from a nearby site, however, show an almost 20% lower mean wind speed. This difference could be partly caused by the two different and rather short observation periods, as well as the fact that the stations are of quite different type; but also suggest that this part of the Gulf of Suez experience large gradients in the resource.

A large gradient in the wind energy resource is also apparent between the southernmost part of the Gulf of Suez and the northern part of the Red Sea. At the Wind Energy Technology Center in Hurghada, the characteristic mean wind speeds and energy densities are about 7.7 ms^{-1} and 425 Wm^{-2}, respectively. This significant decrease in the wind resource from the values found in the Gulf of Suez takes place over less than 50 km.

5 APPLICATION OF THE WIND ATLAS

The wind atlas methodology makes it possible to predict the wind climate at any site (and height) around the stations, as long as the overall wind climate can be assumed to be basically the same as that of the station(s) used for the prediction [9]. In the case of the Gulf of Suez, this means that large parts of the near-coastal land areas along the Gulf are now covered by wind atlas data, whereas the predictions become increasingly uncertain with increasing distance to the coastline. In the mountains, and further inland, we wouldn't expect the wind atlas and models to give accurate predictions, since the wind climate there most likely is completely different from that along the Gulf of Suez.

The wind atlas predictions provide estimates of the sector-wise distribution of the wind direction as well as the distribution of the wind speeds within each sector. Given the power curve of a specific wind turbine we are therefore able to estimate the actual energy production of this turbine at different sites. This is illustrated in Fig. 6, which shows the estimated power production of a 600-kW wind turbine exposed to the different wind climates in the Gulf of Suez/Red Sea. For comparison, the production of the same type of turbine has been calculated for the wind climates of 22 British stations given in the European Wind Atlas [9]. The wind resources of the near-coastal Eastern Desert are thus comparable to—or even higher than—the highest estimates derived from the British stations.

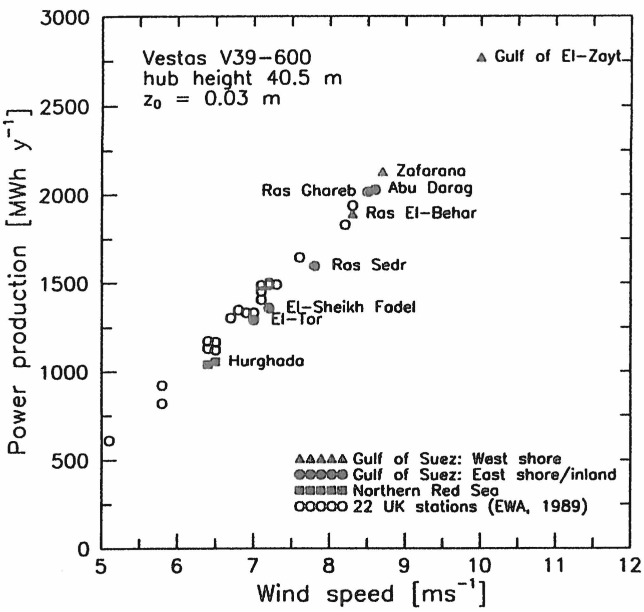

Figure 6: Mean wind speeds and the power production of a 600-kW wind turbine. For comparison, the same information for 22 British stations is also shown.

The roughness of the desert along the Gulf of Suez is often low and uniform compared to sites found in the temperate latitudes. This is illustrated in Fig. 7, where the yearly energy production of a 450-kW wind turbine is shown as a function of distance to the coastline in the Gulf of Suez. The production is calculated along a 20-km long profile, from 10 km inland to 10 km offshore, using wind atlas data from Zafarana and the actual topography in the modelling. The profile is then roughly perpendicular to the coastline and to the prevailing wind direction. For comparison, calculations for a similar 20-km profile near Vindeby, Denmark, are also shown. The world's first offshore wind farm was constructed here in 1990-91 and the Vindeby profile is also roughly perpendicular to the local coastline and local prevailing wind direction.

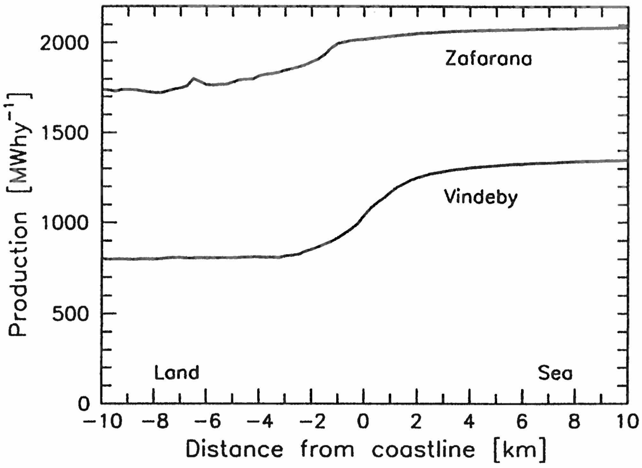

Figure 7: Estimated mean power production of a 450-kW wind turbine in the Gulf of Suez and in Denmark. The power productions are calculated at 250-m intervals along a 20-km profile perpendicular to the coastline. The profiles are situated close to Zafarana and Vindeby, respectively.

Over sea, the production in the Gulf of Suez is estimated to be around 50 per cent higher than for a similar offshore site in Denmark. Over land, the production in the Gulf decreases to about 80 per cent of the offshore value, whereas the energy production in the Danish example falls to about 60 per cent of the corresponding Danish offshore value. The inland potential in the Gulf of Suez near Zafarana is therefore twice as high as the inland potential close to Vindeby. The different ratios of inland-to-offshore potential are mainly due to the different surface roughnesses of the Egyptian desert and open Danish farmland, respectively; the desert being much smoother to the wind flow.

5.1 Vertical extrapolation of wind resource estimates

All year round, the stability of the atmosphere close to the desert surface shows a pronounced diurnal variation; from strongly stable conditions during night-time, to unstable conditions during the day [6]. The surface-layer is therefore only close to neutral during short transitional periods around sunrise and sunset. This, of course, has direct implications for the instantaneous wind profiles, but might also affect the vertical extrapolation of the wind speed distributions.

The mast in Hurghada features cup anemometers at two levels, at 10 and 24.5 m a.g.l., and Tab. 2 gives mean wind speeds and energy densities for five heights, esti-

Table 2: Estimated vertical profiles of mean wind speed ($\overline{U}$) and energy density ($\overline{E}$) at the Wind Energy Technology Center in Hurghada. Estimates are based on wind speeds measured at the 10- and the 24-m levels, respectively. Figures in bold face are the self-predictions and therefore close to the measured values.

	Hurghada 10 m		Hurghada 24 m	
z	$\overline{U}$	$\overline{E}$	$\overline{U}$	$\overline{E}$
[m]	[ms^{-1}]	[Wm^{-2}]	[ms^{-1}]	[Wm^{-2}]
10	**6.0**	**233**	6.1	230
25	7.0	339	**7.1**	**336**
50	7.8	454	7.9	453
100	8.9	675	9.1	684
200	10.7	1182	10.9	1221

mated from the measured wind speed distributions at these two levels. These profiles indicate that accurate predictions at hub height are possible if the atmosphere is on average close to neutral. It should be emphasized, that the roughness of the surface was estimated independently from analysis of neutral wind profiles and during site visits.

6 OTHER CLIMATE STATISTICS

In addition to a more reliable and accurate picture of the wind climate and wind resources along the Gulf of Suez, the wind resource assessment programme has also provided valuable information on other climate statistics, some of which may be important for the design and implementation of future wind energy projects in this area. The Wind Atlas for the Gulf of Suez [6] contains information on barometric pressure, air temperature, vertical air temperature gradient, land and sea surface temperatures, atmospheric stability, wind speed profiles, aerodynamic roughness lengths, observed and estimated extreme wind speeds, and gustiness of the wind.

7 CONCLUDING REMARKS

The wind resource assessment programme described above and published in [6] documents in detail the existence of a widespread and high wind resource along the Gulf of Suez—even higher than was hitherto assumed [3, 8, 2]. It further establishes the meteorological basis for utilization of wind energy in this region, and includes the information necessary for the siting of wind turbines and for the estimation of their annual energy production.

From a wind-prospecting point of view it is worth noting that the existence of such a high wind resource in the Gulf of Suez is only partly resolved by the existing meteorological network; and with much less accuracy and detail than would be required for most wind power assessments. This highlights the need for more detailed analyses—as well as additional wind measurements—in other parts of Egypt; and indeed in many other parts of the world.

The wind atlas methodology, originally developed for wind resource assessment and siting in Europe, has proven very useful in the extreme climatic conditions of the desert. Applied with care, it can provide accurate predictions of the wind climate at candidate sites for wind turbines along the Gulf of Suez; and the experience obtained can be used in other places with a similar climatology.

ACKNOWLEDGEMENTS

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