Research Article

Wind Monitoring on the Island of Gozo

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Summary: *This research article reports salient wind characteristics resulting from field work carried out on one of the islands in the Maltese archipelago. Wind data gathered at Kerċem on the island of Gozo was processed using two analytical methods and the results were compared in order to present an indicative snapshot of this location's wind conditions. The average wind speeds at 10 metres and 18 metres above ground level were 4.92 m/s (average power density of 143 W/m^2) and 5.90 m/s (average power density of 244 W/m^2) respectively for a 30 calendar month time frame. Records indicated a predominant wind blowing from the West North West (between 285° and 315°) that was independent of the period of the year. Seasonal and diurnal variations were also assessed in order to provide a basis for wind turbine energy production estimates. These findings should throw more light on site-specific wind conditions on this small central Mediterranean island.*

Keywords: *wind energy, resource study, Maltese islands, Gozo.*

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Introduction

The central Mediterranean Maltese archipelago consists of three inhabited islands; namely Malta, Gozo and Comino. The islands have a combined land area of 315 km^2 and an estimated 1,291 persons per square kilometre (National Statistics Office 2008). Recent documents have recognized the potential offered by the wind as a renewable resource; although one also acknowledges that there could be barriers to the penetration of wind generation technologies due to the islands' particular characteristics (Ministry for Resources and Infrastructure 2006, Department of Information 2006, Farrugia et al. 2006). The penetration of wind energy conversion systems for electricity generation purposes is minimal; although interest in this renewable technology is increasing.

Wind resource studies conducted by the Institute for Energy Technology of the University of Malta have the primary aim of scientifically quantifying the local wind resource as a means of assessing the potential for wind energy conversions systems. Over the past few years, wind measurement programmes having time frames of twelve calendar months or more were carried out at different locations, in order to allow for a more representative snapshot of site-specific wind conditions on the islands.

A Wind Resource Study

Data Source

This article presents detailed findings of one such wind monitoring study carried out on the island of Gozo. In this case, wind conditions were monitored on an 18 metre high lattice mast located near Kerċem, on the south west side of the island. Figure 1 indicates the location of the monitoring site that has an elevation of approximately 145 metres above mean sea level. The site is located in complex terrain with coastal cliffs in close proximity to the south west of the discussed location. The mast was made available by Malta International Airport plc. (Malta International Airport plc.).

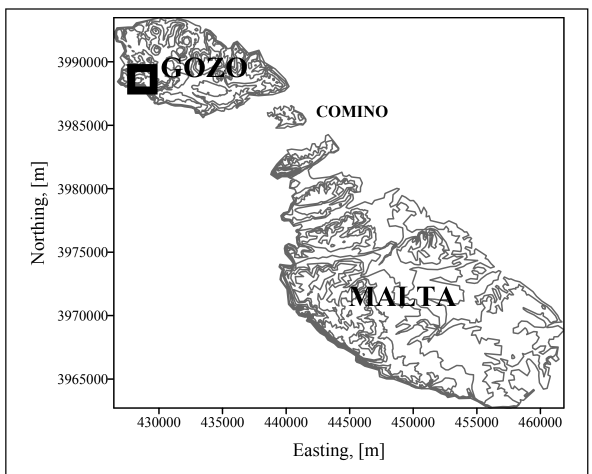

Figure 1: The Maltese archipelago is made up of the three main islands of Malta, Gozo and Comino. The site under discussion is on the south west side of the island of Gozo (indicated by a square).

Wind instrumentation consisted of a cup anemometer and wind vane at the highest extremity of the mast (18 metres above ground level) and a cup anemometer at 10 metres above the ground. The anemometer at this lower level

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was individually calibrated. The records from both anemometers were adjusted in accordance with the recommended transfer function (Lockhart and Bailey 1998). The 18 metre high instrument cluster was located clear of the top of the mast, whereas the 10 metre anemometer was installed on a boom attached upwind (with respect to the prevailing wind) of the mast to reduce the effects of the lattice structure at mid-level. Ambient air temperature was also recorded.

The Institute's wind monitoring programme at Kerċem spanned from August 1997 to March 2000. This particular analysis focused specifically on records taken from September 1997 to February 2000; that is a 30 calendar month time frame. Measurements at 10 metres above ground level (a.g.l.) covered the whole time frame, whereas those taken at 18 metres above ground level ranged from September 1997 to October 1998.

Methodology

A recent project focused on the design of diverse but interconnected spreadsheet templates to handle wind data collected in the Institute's different wind resource studies (Fernández Naveira 2007). These analytical tools were intended to enable quality control, to process the large data sets in a manageable manner, and finally to present salient parameters in tabular and graphical form. Two different methods were identified, compared and used to summarise the data in a way that would represent and report wind conditions at a particular location. These are the Direct Use of Data Method and the Method of Bins (Manwell et al. 2002). Both methods involve direct (non-statistical) methods of data analysis and facilitate wind resource characterization.

The analytical methodologies developed were tested on the data captured at Kerċem owing to its manageable data content and reasonable duration. This allowed for analyses of the more important parameters such as average wind speeds, wind speed frequency distributions, turbulence intensities and wind directions, amongst others. The detailed information for Kerċem generated using these analytical tools warrants full reporting in this research article.

Validation of the Data Set and Data Recovery

Validation routines were used to check the parameters collected and to identify and isolate any suspect values lying outside stipulated boundaries. Various validation checks were run to test for the following (AWS Scientific Inc. 1997):

- *Number of Records:* The number of data fields available were checked and compared to the expected number of measured parameters.
- *The Time Sequence:* The date and time were checked for integrity and continuity.
- *The Range Test:* Parameters recorded for wind speed, wind direction and temperature were stipulated to lie within reasonable parameter ranges.

The data recovery at 10 metres above ground level was 99.99%; implying that almost all the data during the 30 month time frame was collected without data loss. In fact, only two 10 minute records were missing; both occurring on 28 December 1998. All subsequent analyses of data captured at 10 metres above ground level used this data set.

During November 1998 the 18 metre level anemometer stopped working. Records from this sensor logged from the beginning of this month onwards were rejected. The total data recovery at 18 metres above ground level was 100% between September 1997 and October 1998. Data from October 1998 onwards was generated to complete the full 30 month time frame using information collated during the concurrent measurement period prior to sensor failure.

Mathematical Analyses

Vertical Extrapolation of Wind Speed

In order to have an extended insight of wind conditions at 18 metres above the ground after sensor failure, the wind speeds recorded at 10 metres were extrapolated to the higher level. A simple model that describes the vertical wind shear profile was used; namely the Power Law. This was utilised as follows:

$$U_{(18m)} = U_{(10m)} \left(\frac{h_{18m}}{h_{10m}} \right)^{\alpha} \tag{1}$$

Where:

$U_{(18m)}$ horizontal wind speed at a height of 18 metres above ground level (h_{18m});

$U_{(10m)}$ horizontal wind speed at 10 metres above ground level – also referred to as the reference height (h_{10m});

α Power Law exponent or Wind Shear Exponent.

An average monthly Power Law exponent value was used in this analysis.

The Direct Use of Data Method

The 10 minute average wind speed records were used to calculate specific wind resource indicators. For a certain number of records N and for a 10 minute average wind speed U_i, the following parameters were calculated (Manwell et al. 2002):

The average wind speed $\overline{U}$ in m/s, where:

$$\overline{U} = \frac{1}{N} \sum_{i=1}^{N} U_i \tag{2}$$

The turbulence intensity (of each 10 minute record) σ, where:

$$\sigma = \frac{standard\ deviation}{average\ wind\ speed} \tag{3}$$

The average power density $\frac{\overline{P}}{A}$ in W/m², where:

$$\frac{\overline{P}}{A} = \frac{1}{2} \cdot \rho \cdot \frac{1}{N} \sum_{i=1}^{N} U_i^3 \tag{4}$$

An air density ρ value of 1.225 Kg/m³ (25 ºC and 1 bar) was assumed representative of the Kerċem site as the average temperature over the 30 month measurement programme was 17.5 ºC with small pressure variations. A recent publication (Ahmed Shata, Hanitsch 2006) concluded that the variation in air density from standard air density along the Mediterranean Sea's coastline is very small.

The Method of Bins

Using the Method of Bins involved binning the individual 10 minute average wind speed records within 1 m/s wind speed bins. 1 m/s bin widths with integer mid-points of 0, 1, 2, 3,… m/s were used. This bin width resulted in more representative histograms and also facilitates subsequent calculations on wind turbine performance. In this method, for a pre-defined number of bins N_B with bin mid-point m_j and number of occurrences in each bin f_j, the following parameters were calculated (Manwell et al. 2002):

average wind speed $\overline{U}$ in m/s, where:

$$\overline{U} = \frac{1}{N} \sum_{j=1}^{N_B} m_j \cdot f_j \tag{5}$$

average power density $\frac{\overline{P}}{A}$ in W/m², where:

$$\frac{\overline{P}}{A} = \frac{1}{2} \cdot \rho \cdot \sum_{j=1}^{N_B} m_j^3 \cdot f_j \tag{6}$$

Results

Comparison of the Two Methods on a Monthly Basis

Several parameters were calculated using the Direct Use of Data Method and the Method of Bins, but the most relevant two compared were the average wind speed and the average power density. Figure 2 illustrates the relative difference of the monthly average wind speeds derived using each of the two analytical methods. The maximum difference in the average wind speed values using the Direct Use of Data Method as reference never reached ± 1%. The average relative difference for all the months was 0.10% for the 18 metre data and 0.01% for 10 metre records. The average relative difference of the absolute value for all the monthly measurements was 0.21% for the 18 metre data and 0.15% for the data at 10 metres.

Figure 3 shows the relative difference of the monthly average power density values generated by the two methods. In this case, the average power density difference was 0.64% for the 18 metre level and 0.97% for the 10 metre data set. Most of the values were negative, implying that the Method of Bins yielded a marginally higher value for average power density than the Direct Use of Data Method. This was the case for both monitoring heights. There was one month, namely August 1999, during which the average power density relative difference calculated was comparatively more marked. This anomalous result could be explained by the fact that during the hotter months, the average power density is much lower than in the cooler months. This lower average power density value causes the relative difference between the methods to increase when the absolute difference between them was similar. Also, the average wind speed distribution during the summer months was shifted to lower wind speeds and the number of bins needed to encompass all the measurements was lower (for a constant bin width). In this specific case, the Method of Bins seemed to become less accurate.

An overall conclusion of this analysis is that the Method of Bins yielded results that were very similar to those derived from the Direct Use of Data Method.

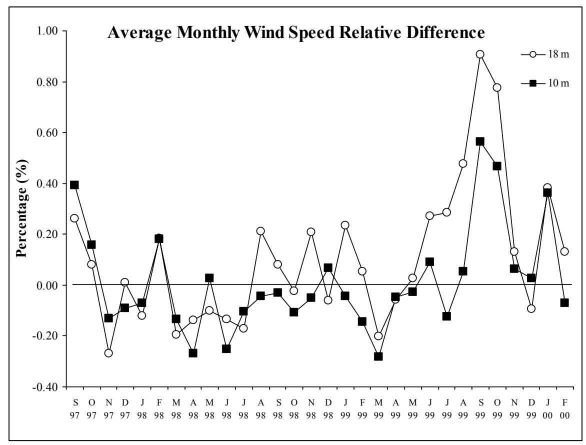

Figure 2: Relative difference between the monthly average wind speeds calculated using the Method of Bins and the Direct Use of Data Method. The latter method was used as reference at both measurement heights.

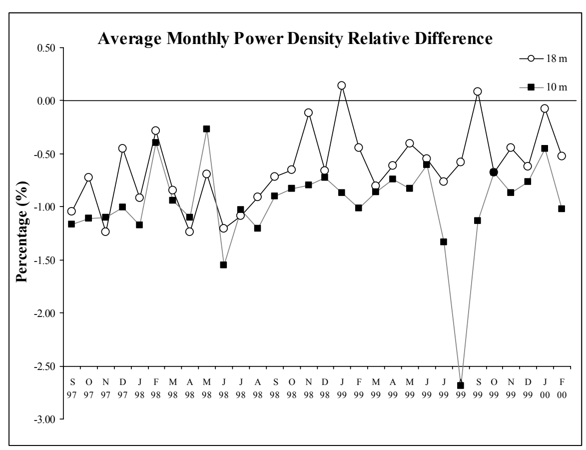

Figure 3: Relative difference between the monthly average power densities calculated by the Method of Bins and the Direct Use of Data Method at both measurement heights. The second method was once again taken as reference.

Detailed Results of the Kerċem Data Sets

The majority of results reported in this study from this point onwards used the Direct Use of Data Method as basis. The average wind speed and average power density recorded for the period September 1997 to October 1998 were 4.68 m/s and 124 W/m^2 at 10 metres above ground level. The corresponding parameters at 18 metres above ground level were 5.62 m/s and 206 W/m^2. In earlier work conducted at the Institute for Energy Technology leading up to an analysis of wind data from locations on the main island of Malta, a different analytical method was used on the Kerċem data set (Leddin 2003). Results were similar to those being presented in this research article.

Figure 4 illustrates the wind frequency distributions for both heights and the wind speed distribution by direction measured at 18 metres above ground level during the overall 30 month period. The wind rose generated using 12 direction sectors showed predominant winds coming from the sectors between the West and North cardinal directions. This conforms to results yielded by other studies reporting wind direction characteristics for the archipelago (Department of Civil Aviation 1988, Darmanin 1995, Farrugia 1998). In the sector-wise average wind speed analysis, it was observed that the average wind speed was slightly higher when blowing from these direction sectors. The wind direction frequency distribution is particularly useful in identifying the most suitable sites for wind turbine installation, avoiding objects upwind (with respect to the prevailing winds) of a prospective wind turbine installation and in the design of multiple wind turbine arrays.

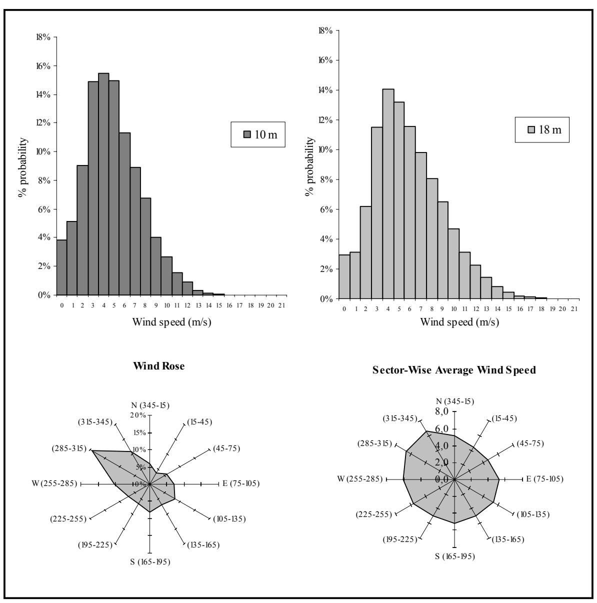

Figure 4: Wind speed and wind direction distributions at 10 metres and 18 metres above ground level. The wind rose and sector-wise wind speed distribution are only for 18 metres.

The wind speed histograms indicate that:

- the frequency distributions had the same trend with pronounced peaks close to the mean wind speed values at both monitoring heights.
- the 18 metre level histogram was shifted to higher wind speeds and the frequency peak was somewhat lower.

Figures 5 to 8 show the wind speed frequency distributions for 10 and 18 metres above ground level, and the wind roses and sector-wise average wind speeds for data measured at 18 metres only, classified by four 3-month groupings. Regarding the wind speed frequency distributions, the same behaviour described in the case of the overall data set were observed. During the period March – April – May (Figures 6a and 6b) and September – October – November (Figures 8a and 8b), the wind speed frequency distributions were similar for both monitoring heights.

The wind speed histograms at 18 metres were once again shifted to higher wind speeds and the frequency peaks were lower in the four groups. On comparing the different month groupings, several characteristics were observed. During the hottest months (Figures 7a and 7b), the wind speed frequency distributions were shifted to the left; i.e. there were wind speed occurrences between 2 m/s and 6 m/s and fewer wind speed occurrences above 10 m/s. On the other hand, the wind speed distributions during the colder months (Figures 5a and 5b) showed slightly wider distributions.

The wind roses (Figures 5c, 6c, 7c and 8c) showed predominant winds coming from the West North West throughout the whole year. In the sector-wise average wind speed analysis (Figures 5d, 6d, 7d and 8d), it was observed that the average wind speeds were slightly higher when blowing from the prevailing wind direction for most of the different groups of months. The results obtained dividing the 30 month timeframe into 3 month periods confirmed the seasonal wind speed variation; with higher average wind speeds exhibited during the month groupings associated with the cooler seasons (See Figures 5d to 8d).

Analyses of the Monthly Wind Parameters for the 30 Month Time Frame

The variations of the more important wind parameters over the 30 month period are shown in Figures 9 to 12. The average wind speed and average power density at 10 metres above ground level for the overall 30 month data set were 4.92 m/s and 143 W/m^2 respectively. The average wind speed was 5.90 m/s with an average power density of 244 W/m^2 at the higher level.

The monthly average wind speeds were higher at the 18 metre level than at the reference height (10 metres) as shown in Figure 9. A higher average power density was observed at 18 metres than at the 10 metre height as expected (See Figure 10). The difference between the 10 metre and 18 metre monthly average wind speed values was uniform; however, this did not apply to the monthly average power density values. Understandably, the differences at both heights became bigger when wind speeds were higher, as average power density is proportional to the wind speed cubed.

Figure 5: December – January – February

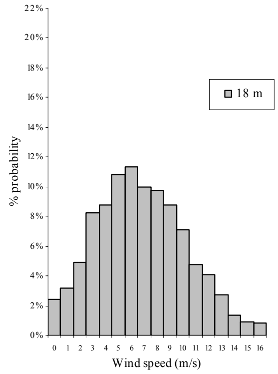

Figure 5a:

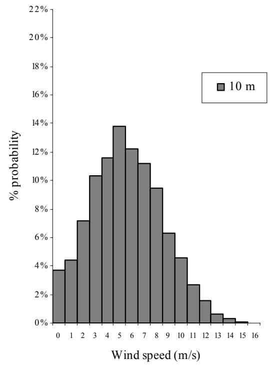

Figure 5b:

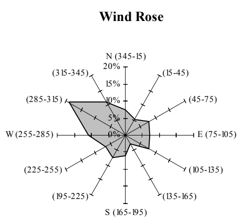

Figure 5c:

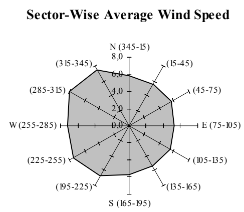

Figure 5d:

Figure 6: March – April – May

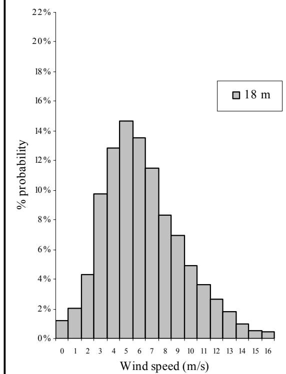

Figure 6a:

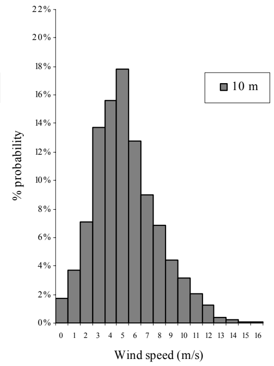

Figure 6b:

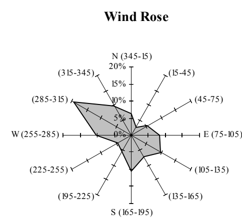

Figure 6c:

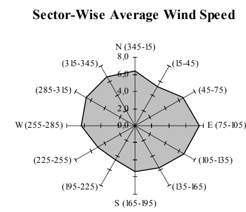

Figure 6d:

Figure 7: June – July – August

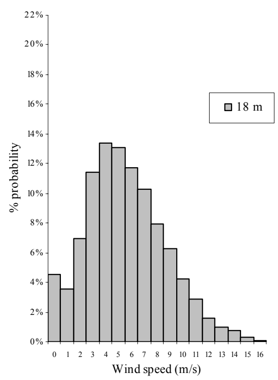

Figure 7a:

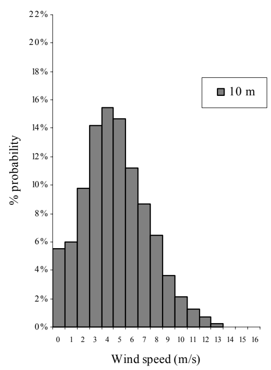

Figure 7b:

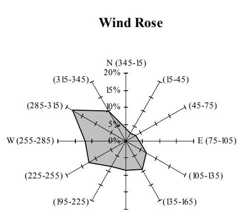

Figure 7c:

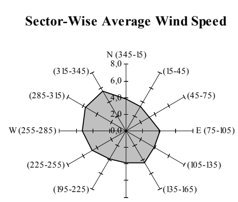

Figure 7d:

Figure 8: September – October – November

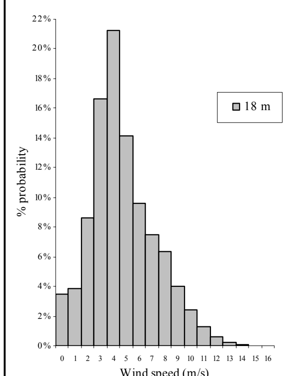

Figure 8a:

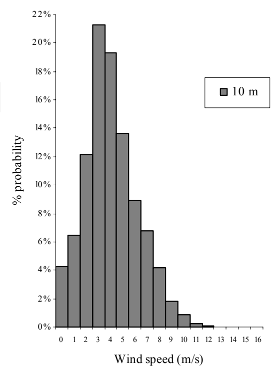

Figure 8b:

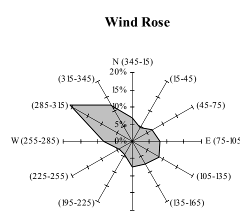

Figure 8c:

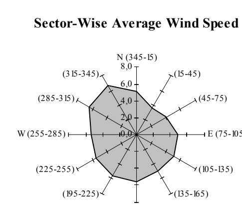

Figure 8d:

Figures 5 to 8: Wind speed frequency distributions, wind roses and sector-wise average wind speed distributions for both heights for the four 3-month groupings. Once again, the wind roses and sector-wise average wind speed distributions are for 18 metres above ground level only.

Monthly turbulence intensities were higher at the 10 metre level (Figure 11). Wind conditions closer to the ground are typically more turbulent - although this is heavily dependent upon a number of site-specific factors.

Regarding maximum gusts, the highest wind speed recorded during the first 14 months at 18 metres a.g.l. was 26.78 m/s. This event occurred at 11:47 p.m. during the night of 20 January 1998 and the gust blew from West by North (280º). The speed recorded at the lower level at the same time was 22.71 m/s. The highest instantaneous wind speed recorded at 10 metres above ground level during the overall 30 month data set occurred at 10:35 a.m. on 12 February 1999. This gust blew with a speed of 26.89 m/s from the South South West (205º).

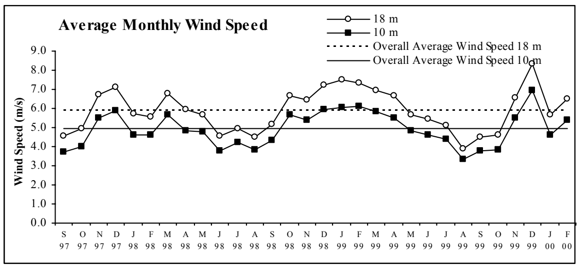

Figure 9: Monthly and overall (shown as horizontal lines) average wind speed during the 30 month measurement period.

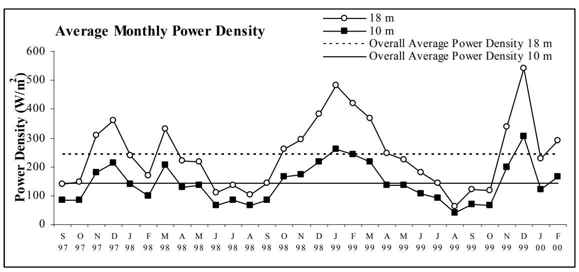

Figure 10: Monthly and overall (shown as horizontal lines) average power density values during the 30 month measurement period.

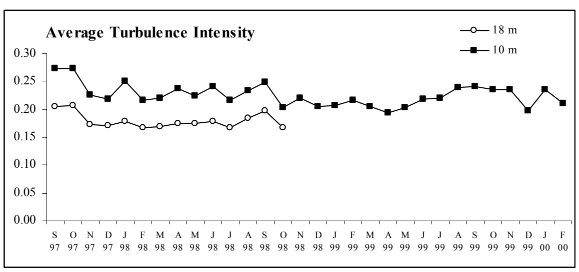

Figure 11: Monthly average turbulence intensity values.

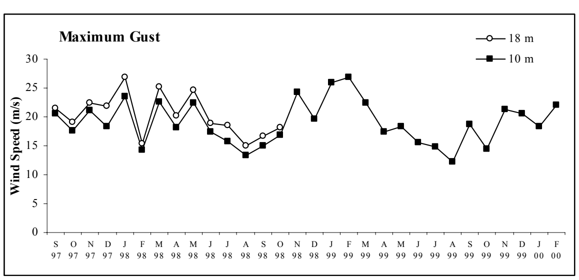

Figure 12: Monthly maximum gust wind speeds.

The diurnal variation of wind speed was also calculated using the overall Kerċem data set (Figure 13). Wind speeds were higher during the day than during the night. This pattern supported results obtained in other studies carried out for the Maltese islands (Scerri and Farrugia 1996, Farrugia 1998). In this case, the difference between the highest and lowest values for both heights was not more than 25%. This percentage was lower than the 80% obtained for the seasonal variation as described later on; so the average wind speed seasonal variation (and consequently the average power density) is more significant in terms of evaluating the wind resource potential for electrical energy generation purposes.

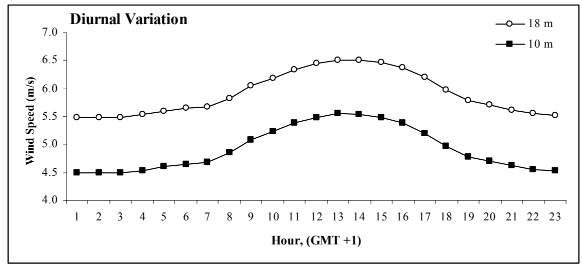

Figure 13: Average wind speed by hour of the day.

Synopsis of 12 Calendar Months

Wind parameters for the 30 months were processed further in order to present a 12 month synopsis of parameters for this location. The average wind speed is shown in Figure 14. The calculated annual average wind speed for 12 months was 4.87 m/s with an average power density of 139 W/m^2 at the 10 metre level. The same parameters at the higher level were 5.84 m/s and 236 W/m^2 respectively. The seasonal trends showed that wind speeds were lower in the hot months than during the cooler months. August had the lowest calculated average wind speed (3.61 m/s and 4.20 m/s at 10 m and 18 m respectively) and December was the windiest month of the average year (6.26 m/s and 7.57 m/s at 10 and 18 metres above ground level respectively) at both monitoring heights. This behaviour once again corresponded to trends described for other local sites. This seasonal difference is an important characteristic of wind behaviour in the Maltese islands.

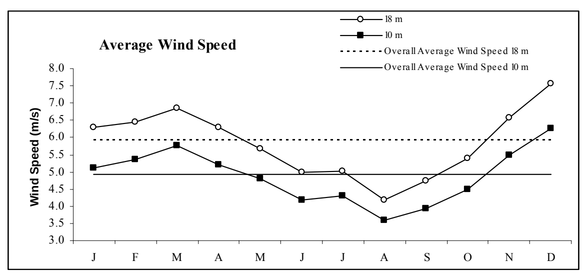

Figure 14: Average wind speed by month.

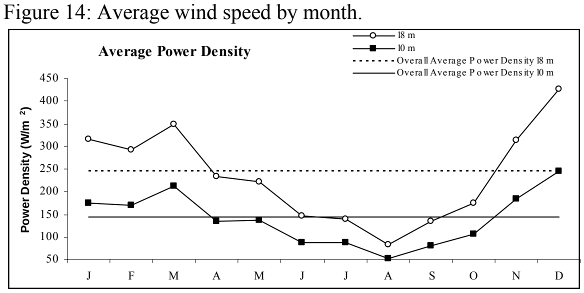

Figure 15: Average power density by month.

The average power densities are shown in Figure 15. The lowest and the highest average power density values were also in August (53 W/m^2 at 10 metres and 83 W/m^2 at 18 metres) and December (245 W/m^2 at 10 metres a.g.l. and 428 W/m^2 at 18 metres). From these results, it appears that the seasonal variation should be considered a key parameter in wind energy conversion systems' performance estimates. Meanwhile, the turbulence intensity seasonal variation (Figure 16) did not reveal any particularly discernible patterns. It was observed that August, September and October had higher values of average turbulence intensity. The months of February to May and December exhibited below average values.

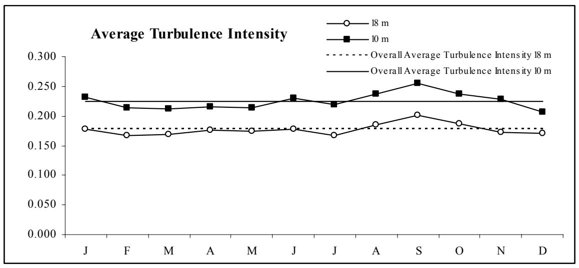

Figure 16: Average turbulence intensity by month.

Conclusions

The following conclusions were drawn from this investigation:

- The Direct Use of Data Method and the Method of Bins both give good approximations of salient wind characteristics at this location. The differences between the methods could be considered insignificant.
- The average wind speeds at Kerċem in Gozo obtained for the 30 month period of measurements were 4.92 m/s at 10 metres above ground level and 5.90 m/s at 18 metres above ground level. There was a predominant wind coming from the West North West (between 285° and 315°), that did not depend on the period of the year.
- Average wind speed values indicate that Kerċem enjoys a reasonably good wind resource. Long term average values for another site in the Maltese archipelago; namely Swatar near Rabat in Malta, were 5.7 m/s at 25 metres above ground level and 4.1 m/s at 10 metres a.g.l. (Martín Sánchez, 2008). Arguably, the Swatar site did have different site specific characteristics.
- Seasonal and diurnal variations in wind speed should be considered in order to estimate the energy yield of wind energy conversion systems. This research study indicated that the seasonal variation in wind speed has a larger effect than the diurnal variation.

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- The Socrates ERASMUS Student Exchange Programme 2006/7 and their respective Universities that made this work possible.

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