ANALYSIS OF WIND POTENTIAL AND ENERGY PRODUCTION IN NAXOS ISLAND, GREECE

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Abstract :- A remote location in the northeastern part of Naxos Island, Greece, has been investigated with respect to wind power potential, using real data collected from a measurement mast. The obtained wind characteristics were statistically analyzed using the Weibull and Rayleigh distribution functions. The results from this investigation showed that the selected site falls under Class 7 of the international system of wind classification as the mean annual wind speed recorded in the area was 7.4 m/s and the corresponding annual mean power density was estimated to be 420 W/m^2. Furthermore, the prevailing wind directions characterizing the area were the northeastern and the north-northeastern. From the statistical analysis of these results, it was revealed that the Weibull model fitted the actual data better. This remark was further enhanced by the evaluation of the performance of these two distributions. Finally, the expected energy production from two potentially installed wind turbines of 1 MW and 2.5 MW has been determined, based on the available wind potential. The resulting annual energy production is 4 GWh$_e$ and 8 GWh$_e$ for the wind turbine of 1 MW and 2.5 MW respectively.

Key words:- Wind potential, Wind speed, Wind power density, Weibull and Rayeigh distribution, wind turbine, Greece

1. Introduction

The wind energy capacity has been utilised since antiquity for sailing and navigation purposes and the operation of windmills. As a result, great advances in the use of wind energy as a power source were made. During the post-war years, the introduction of nuclear power generation and the low prices of carbon fuels reduced dramatically the interest towards the use of wind energy. However, the ever-growing demand in energy – it is expected that by 2015 the worldwide demand in electricity will reach 19 trillion kWh [1], out of which more than 70,000 MW will correspond to the installed wind energy generating capacity in Europe [2] - and the public reluctance towards the installation and the operation of nuclear power plants, combined with the increasing environmental concerns in recent years about global warming and the harmful effects of carbon emissions, have created a new demand for ‘clean’ and ‘green’ energy sources, such as wind. Wind power has experienced once again a remarkably rapid growth in the past twenty years, as it is classified as a pollution free source of power.

Even though the use of wind energy been studied for many years due to the need for ‘greener’ ways of generating electricity, there has only been very broad information on the wind potential in the Aegean Sea and especially in remote locations. Mariopoulos and Karapiperis [3], carried out a preliminary study on the use of wind energy in Greece. Their work was expanded by Galanis [4] and Tselepidaki et al [5]. Later, in 1983, Lalas et al. [6] used data from the Hellenic National Meteorological Station for 22 locations around Greece to predict the corresponding wind potentials. The results of these works presented mainly an overview of the wind potential around Greece in general, and identified the high wind energy capacity existing over the Aegean Sea specifically. Nearly a decade later, Katsoulis [7] analysed the updated version (42 locations instead of 22) of Lalas et al. [6] data, part of which was obtained from Naxos station. Kaldellis [8],[9] has performed an extensive research in the utilisation of the wind potential of the Aegean Sea. In 2002, Kaldellis, [10], he used long-term (i.e. 4 years) wind speed data obtained from the Greek Public Power Corporation, for Kithnos, a relatively small island located in the southwest of the Aegean Sea in order to suggest the usage of a stand-alone wind power system for covering the energy requirements of the island. The analysis of the wind data showed that the island was characterised by strong winds, which reach an annual mean value of 7 m/s at 10 m height in several locations. The windiest season proved to be the winter and the calmest was towards the end of spring and the beginning of summer. Ozerdem and Turkeli [11], investigated the wind characteristics of Izmir, which is located near the Turkish coastline along the Aegean Sea. The results showed that the average speed at 10m was 7.03m/s whereas at 30m the corresponding value was 8.14m/s. Akpinar [12], statistically investigated the wind energy potential of the overall area of Elazig and the nearby regions of Maden, Agin and Keban (all situated along the coastline of the Marmara Sea) using wind speed data recorded over 72 months and by applying on it Weibull and Rayleigh distributions. The results of this investigation showed that Maden is ideal for grid-connected applications since the annual mean wind power density was found to be 246.27 W/m^2. On the contrary, the annual mean wind power densities in Elazig, Agin and Keban regions were not high enough for electrical production. The maximum annual mean wind speed recorded was 5.66 m/s in Maden. Further research in the northwestern Marmara region in Turkey was performed by Gökçek et al.[13]. Furthermore, they indicated that the Weibull shape parameter k ranged between 1.57 in autumn and 2.21 in summer, while the corresponding scale parameter c ranged between 4.56 m/s in autumn and 5.93 m/s in winter respectively. Also, according to [14] the region of Marmara has the highest wind energy potential. Finally, the south region of Marmara Sea was covered by a study carried out by Ucar and Balo [15], in Uludağ. The results obtained showed that the annual mean wind speed for the period under investigation was 7.08 m/s. It was found that the average values of the Weibull parameters k and c were 1.78 and 7.97 m/s respectively. As far as the calculated wind power was concerned, it was found that the lowest value was 335 W/m^2 observed during winter, while the highest was 925 W/m^2 and it was obtained during summer.

As a step towards assessing the wind potential and energy production of the Aegean Sea the current study was set to evaluate real wind data. The wind speed and direction as well as the availability and the duration were assessed, and the results were statistically compared with Weibull and Rayleigh distribution functions. Both distribution functions were assessed in order to determine which described the actual data better.

2. Methodology and Materials

2.1 Site Description

Naxos Island (latitude 37^0 06′ N), Greece, is situated towards the middle of Cyclades, a complex of small to medium size islands, in the southern part of the Central Aegean Sea, and it is characterized by strong winds. The topography of the area is typically Aegean, characterized by hills and mountains covered with bushes, and very limited flat fields. It is situated at approximately 700m from the sea level and there are no physical obstacles to cause any problems to the installed system.

2.2 Wind data measurement mast

A 10m height mast, made out of steel in solid tubular form was used, strengthened by guyed wires in order to keep it in a vertical position. A cup anemometer and a wind vane were both installed at the top of the mast. The temperature and the relative humidity were also measured using a thermometer and a hydrometer respectively. Data obtained from all the installed instruments was acquired using a data logger. The data logger, which was connected with all the available sensors on the mast, recorded and stored the collected data in time – series format. Once the required data was stored, the transferring of it to the laboratory in Athens for processing was achieved via a GSM method used by the data logger. Finally, the required power for all the previously mentioned instruments was provided by 12 V battery, charged by a small pv panel. A photograph of the actual arrangement can be seen in Fig. 1.

Fig. 1 Photograph of the wind data measurement mast

2.3 Wind data collection and evaluation

Data collection was performed for a period of 12 months. The rate of the data recording was 144 per day in 10 minutes time intervals. The collected data included date and timestamp, minimum, maximum, average and deviation values of wind speeds at 10m height, wind directions divided in 16 sectors (within 360°), temperature, and relative humidity. Once the required data was stored in the data logger, it was sent directly via a GSM method to the Renewable Energy Laboratory in Athens where it was converted to a spreadsheet for easier processing. Before performing any analysis of the recording, it was necessary to evaluate the percentage of missing data that could have been lost due to weather or the malfunctioning of the instrumentation. It has been found that in overall the missing data did not exceed 7%, a percentage well within the acceptable standards [16].

After establishing this, the analysis and the evaluation of the recordings was performed and the monthly results are presented in the form of tables, pie-charts, histograms and polar diagrams. The corresponding Weibull and Rayleigh distributions were also determined. Additionally, the yearly wind speed variation was obtained in order to check the validity of the data and to extract any useful information regarding the wind potential of the location under consideration.

2.4 Wind turbines

In order to investigate the expected energy production in this site, two potentially installed wind turbines of 1 MW and 2.5 MW have been selected. The corresponding power curves are shown in Fig. 2. It is clear that the 1 MW wind turbine starts to produce power at 2 m/s wind speed and reaches its rated power at 13 m/s. On the other hand, the 2.5 MW turbine's cut-in speed is at 4 m/s and the rated power is produced at wind speeds higher than approximately 15 m/s.

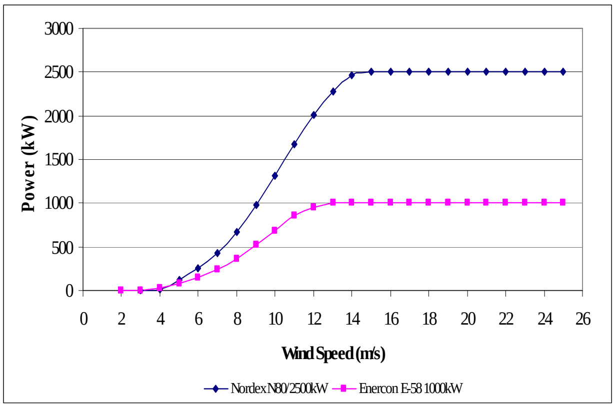

Fig. 2 Wind Turbines Power Curves

3. Results and discussion

3.1 Mean wind speed and wind direction analysis

The determination of the wind potential of the selected site was made by analysing in detail the wind characteristics, such as the wind speed, the prevailing direction, their duration and availability, as well as the resulting power density.

In Fig. 3, the monthly mean wind speeds are presented. As it can be seen, the windiest months were March and July with the mean wind speed reaching approximately 9 m/s, while the calmest month was June where the mean wind speed did not exceed 6 m/s. Using the data of this diagram, it has been calculated that the corresponding annual mean speed was approximately 7.4 m/s, indicating that the installation of a utility scale power plant would be viable, at least as far as the engineering part is concerned. By checking the pattern of the wind speed distribution, it becomes apparent that the high values recorded from January to March were followed by a significant decrease in April, May and June.

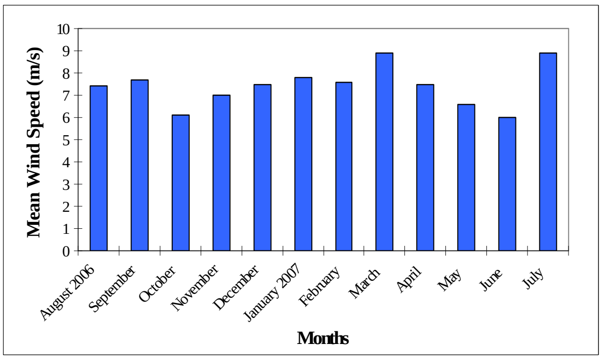

Fig. 3 Monthly mean wind speeds at 10 m height

It is believed that these high values were the result of the Vardar, a north wind blowing across the whole of the Balkan Peninsula, especially during the winter. Another factor contributing in this phenomenon was the decrease in temperature during winter and spring. Even though this decrease was expected, it caused thermal convection which in turn resulted in some of the momentum of the upper air (i.e. air that moves at higher velocity) to be transmitted to the surface layers and therefore the noticed increase in the previously mentioned monthly mean wind speeds was caused. On the other hand, the sudden increase observed in July could be attributed to the Etesians, a local circulation system of strong winds affecting the Aegean Sea during the summer months. These observations agreed with the findings of Lalas et al [6], and of Katsoulis [7]. However, a discrepancy, in the range of 10%, between their results and those obtained in the current study was observed, which is believed that it was due to the different altitude of the measurement mast and the number of daily observations.

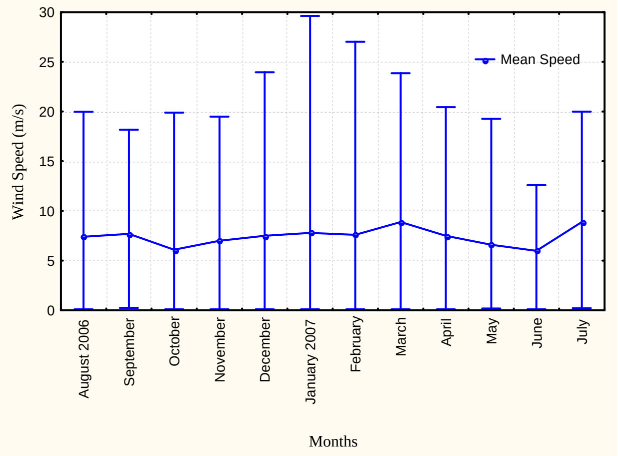

Fig. 4 Monthly variation of wind speed with respect to the mean value

When observing the monthly variation of the wind speed with respect to the corresponding mean value, as shown in Fig. 4, it is apparent that the biggest difference between the maximum and the minimum values occurred in January.

It is believed that this difference was due to intense solar radiation, which in turn resulted in turbulence and mountain winds phenomena, both of which could be responsible for the occasionally high values in the wind speed.

Another interesting outcome of the analysis of the mean wind speed was its diurnal variation. As shown in Fig. 5, the diurnal variation can be taken as approximately constant for all the months considered, apart from June where a significant depression occurred between 10 am and 7 pm, and March during which there was a strong front from 7 am to 2 pm.

As an overall overview though, it is safe to say that the selected location presented a fairly stable and quite high pattern on the diurnal annual wind speed variation.

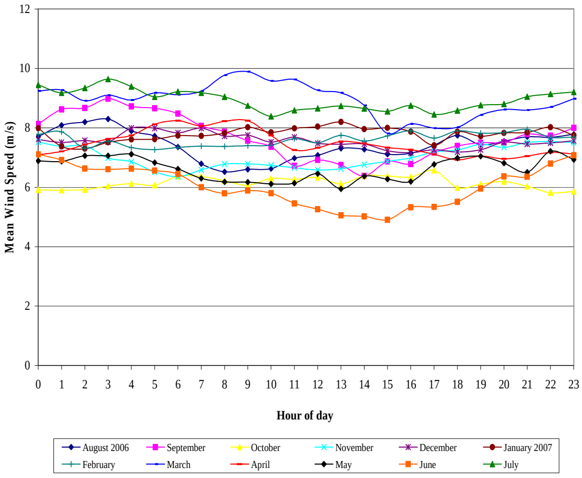

Fig. 5 Diurnaly mean wind speeds variation for every moth

Based on the results obtained from the mean wind speed analysis, combined with the commercially international system of wind classification shown in Table 1, it was noted that the measurement site falls under Class 7, indicating that it was suitable for large scale electricity generation.

Wind Power Class	Wind Power Density at 10m height (W/m^2)	Wind Speed at 10m height (m/s)
1	≤100	≤4.4
2	≤150	≤5.1
3	≤200	≤5.6
4	≤250	≤6.0
5	≤300	≤6.4
6	≤400	≤7.0
7	≤1000	≤9.4

Table 1 International system of classification for wind by Elliott and Schwartz (1993)

3.2 Wind direction

Usually, in wind data analysis, the prediction of the wind direction is also very important, especially when planning the installation and the micrositting of a wind turbine or a wind farm. The annual wind rose based on time, is shown in Fig.6 .

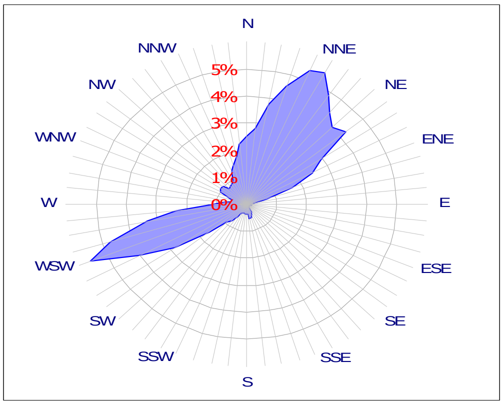

Fig. 6 Annual wind rose based on time

Most of the time, the prevailing winds in Naxos Island were the north-northeastern, the northeastern, and the west-southwestern. This was a well-expected outcome since this particular region is influenced by the winds blowing from the Balkan Peninsula. Therefore, it is worthwhile to remark that the area under investigation showed a significant stability as far as the percentage of time a wind was blowing from a particular direction was concerned. Nearly similar trends can also be seen in Fig. 7, where the annual wind rose based on energy, is presented.

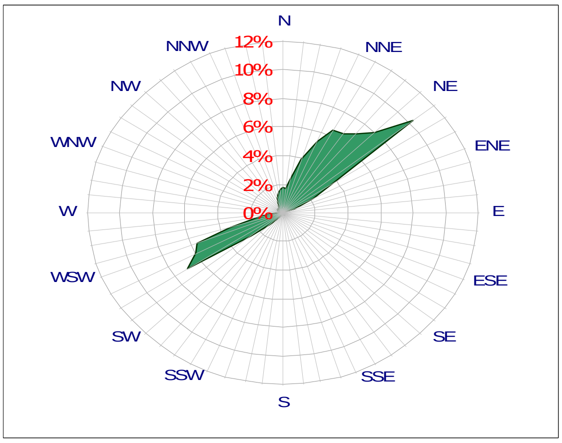

Fig. 7 Annual wind rose based on energy

Again the prevailing directions indicated were the northeastern, the north-northeastern, and the west-southwestern. It should be mentioned that the percentage of energy depicted in the wind roses of Fig. 7 corresponds to the distribution of the available wind energy and not that delivered by a potentially installed wind turbine. Although, the difference is relatively small, it is mainly associated with the cases where the wind speed from a particular direction is larger than the turbine's cut-out speed.

Finally, in both Fig. 6 and 7, the calms have not been considered as it is believed that during the calms the direction recorded by the wind vanes was not necessarily representative.

Conclusively, the outcomes of the analysis of the wind direction are presented in Fig. 8 and 9, in which the prevailing wind directions and the corresponding percentages of time and available wind energy for each month studied are included.

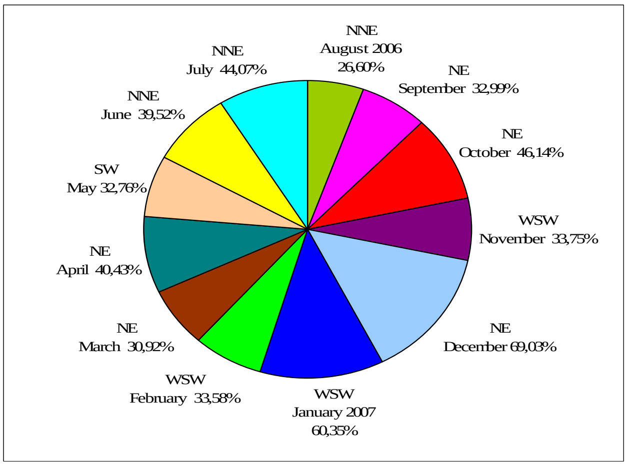

Fig. 8 Best monthly prevailing wind directions based on time

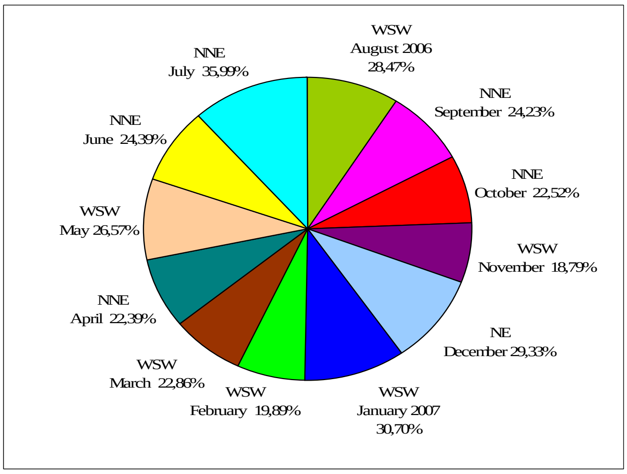

Fig. 9 Best monthly prevailing wind directions based on available wind energy

When comparing these figures, it becomes obvious that the best wind sector based on time did not necessarily coincide with the best sector based on the available wind energy. This remark was not unexpected when considering that although wind might be blowing from one direction for a relatively long period, the corresponding speeds recorded might not be high enough to produce the maximum available energy. Therefore, only in November, December, January, February, June and July the best wind sector based on time was the same as the corresponding best sector based on energy. The highest percentage of time wind was blowing from a particular direction, namely the north-northeastern, was 35.99%, and it was recorded in July. On the contrary, the highest percentage of available wind energy was obtained from the northeastern direction, it was 69.03%, and it was recorded in December.

Finally, the effect of turbulence intensity with respect to the monthly prevailing wind directions was also considered, as shown in Fig. 10.

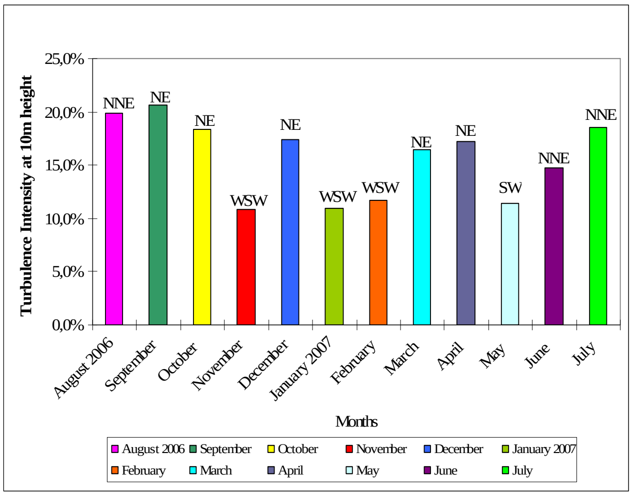

Fig. 10 Annual variation of turbulence intensity

It is apparent that turbulence intensity was relatively high in the northeastern and the north-northeastern sectors at 10m height. Although it is believed that these results were due to the effects of the area topography and the surface roughness influence at this height, further investigation at bigger heights with turbulence-free characteristics would be a more realistic representation of the site.

3.3 Wind power density analysis

The results of the wind speed variation and the prevailing wind directions which characterised the location under investigation were further analysed with respect to the corresponding mean wind power density. Fig. 11 shows a histogram of the monthly variation of the mean wind power density.

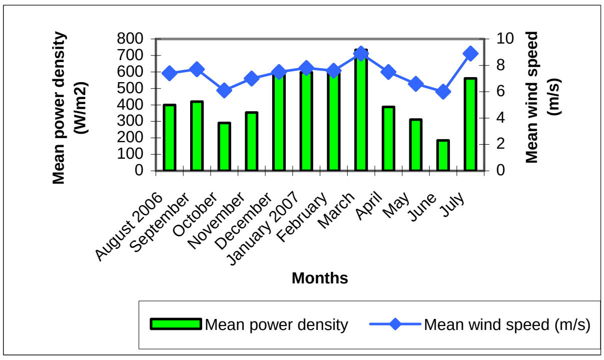

Fig. 11 Monthly variation of the mean power densities and mean wind speed

As it can be seen, in October and in November the estimated mean wind power densities were almost half of that obtained in March (i.e. maximum value). Moreover, a gradual increase was observed during the winter months (i.e. December, January and February), with a peak value of approximately 730 W/m^2 in March. This increase was followed by a sudden decrease from the end of spring to the beginning of summer (i.e. April, May and June), and an increase again in July. The observed increase in July was attributed to the Etesian winds, which, as already explained, characterised this particular period. As already mentioned, the highest value was around 730 W/m^2 in March, while the lowest value was approximately 180 W/m^2 in June. The resulting mean annual wind power density was estimated to be 420 W/m^2. This value, and the corresponding annual mean wind speed, verifies that the northeastern part of Naxos Island falls into Class 7 of the commercially international system of wind classification according to Elliott and Schwartz [17].

A comparison of the monthly mean wind speeds and mean wind power density is shown also in Fig. 5. It is clear that the two curves have similar changing trend. However, the rate of change is different as a small variation in the wind speed can cause larger wind power density predictions due to the fact that the wind power density is proportional to the cube of the wind speed. This effect is more pronounced at higher wind speed conditions. To conclude with, from the analysis of the collected data, it became apparent that for the purpose of mapping the variation of the wind potential of the northeastern part of Naxos Island, it was better to choose the wind power density since it incorporated not only the distribution of wind speeds, but also the dependence of the power density on air density and on the cube of the wind speed.

3.4 Probability Density Functions

Simple knowledge of the mean wind speed of the selected area could not be taken as sufficient for obtaining a clear view of the available wind potential. Therefore, in order to surpass the non-predictability of the wind characteristics, a statistical analysis was considered necessary. For this reason, Weibull and Rayleigh distribution models were applied. Weibull distribution is widely used in the wind speed data analysis [18], [19],[20],[21]. Fig. 12 shows the probability density function of the annual wind speed distribution, in which Weibull and

Rayleigh models have been fitted. The probability density function indicates the fraction of time for which a wind speed possibly prevails at the area under investigation. Hence, it can be observed in Fig. 6 that the most frequent wind speed expected in the area under investigation is around 7 m/s, a value which corresponds to the peak of the probability density function curve. This result agrees with that already obtained from the initial analysis of the mean wind speed. It is also clear in Fig. 12 that the chances of wind speed exceeding 20 m/s in this region were very limited. The previously mentioned remarks were further supported by the Weibull curve. On the contrary, Rayleigh curve was slightly shifted to the left, indicating a lower possibility of a lower maximum wind speed occurring.

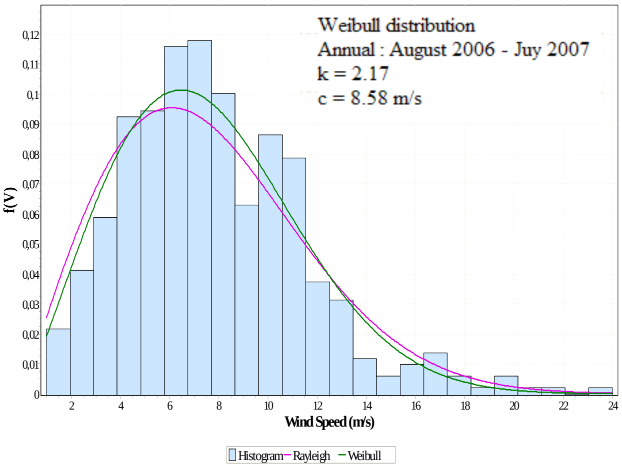

Fig. 12 Probability density distribution of annual wind speeds

The relatively large annual values of the Weibull parameters k and c found, 2.17 and 8.58 m/s respectively, verified the existence of a high wind potential of good quality in the area. Even though the difference between the two models was relatively small, Weibull appeared to represent the actual data better.

Another important aspect considered during the statistical analysis was the prediction of the time for which a potentially installed, in this area, wind turbine could be functional. In order to achieve that, the determination of the cumulative distribution function was required. Since this function indicates the fraction of time the wind speed is below a particular speed, by taking the difference of its values the corresponding time for which the turbine would be functional can be estimated.

The obtained cumulative function is shown in Fig. 13. Weibull and Rayleigh models have also been included.

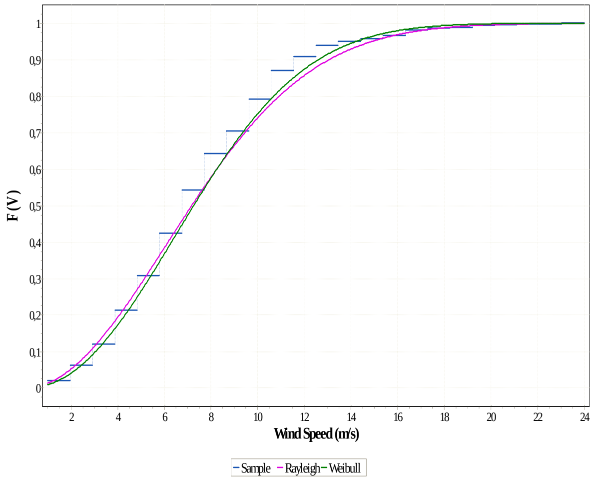

Fig. 13 Cumulative distribution function of the annual mean wind speed

Even though the difference between the two models was relatively small, Weibull appeared to represent the actual data better.

In order to evaluate the performance of the two models considered, an error analysis was carried out. The mean root-square error (RMSE) parameter, the Chi-square (χ^2) test, and the modelling efficiency (EF) test were used in the current investigation, and the results are presented in Table 2.

	Weibull			Rayleigh		
	RMSE	χ^2	EF	RMSE	χ^2	EF
August 2006	$6.512*10^{-3}$	$4.665*10^{-5}$	0.971	$6.786*10^{-3}$	$4.824*10^{-5}$	0.968
September	$10.096*10^{-3}$	$11.4*10^{-5}$	0.925	$10.634*10^{-3}$	$13.82*10^{-5}$	0.904
October	$8.786*10^{-3}$	$8.390*10^{-5}$	0.957	$8.023*10^{-3}$	$6.706*10^{-5}$	0.964
November	$10.057*10^{-3}$	$11.2*10^{-5}$	0.946	$11.685*10^{-3}$	$14.4*10^{-5}$	0.927
December	$12.8*10^{-3}$	$17.9*10^{-5}$	0.853	$15.575*10^{-3}$	$25.3*10^{-5}$	0.783
January 2007	$12.056*10^{-3}$	$15.8*10^{-5}$	0.916	$13.381*10^{-3}$	$18.7*10^{-5}$	0.896
February	$8.393*10^{-3}$	$7.66*10^{-5}$	0.941	$12.871*10^{-3}$	$17.3*10^{-5}$	0.862
March	$7.118*10^{-3}$	$5.527*10^{-5}$	0.955	$8.27*10^{-3}$	$7.153*10^{-5}$	0.939
April	$11.126*10^{-3}$	$13.6*10^{-5}$	0.936	$15.336*10^{-3}$	$24.6*10^{-5}$	0.881
May	$4.02*10^{-3}$	$1.779*10^{-5}$	0.989	$5.37*10^{-3}$	$3.036*10^{-5}$	0.980
June	$10.503*10^{-3}$	$13.1*10^{-5}$	0.951	$18.452*10^{-3}$	$36.9*10^{-5}$	0.851
July	$15.299*10^{-3}$	$25.7*10^{-5}$	0.897	$27.6*10^{-3}$	$79.8*10^{-5}$	0.666
Annual	$\mathbf{9.730*10^{-3}}$	$\mathbf{11.388*10^{-5}}$	**0.936**	$\mathbf{12.867*10^{-3}}$	$\mathbf{21.044*10^{-5}}$	**0.880**

Table 2 Error analysis of the statistical models used

According to these tests, a distribution function better approximates the actual data when the values of RMSE and χ^2 are close to zero, an the values of EF approach unity. By checking the results presented in Table 1 it is clear that Weibull model described better the observed data.

Thee results were also in accordance with the probability difference of the two models shown in Fig. 14

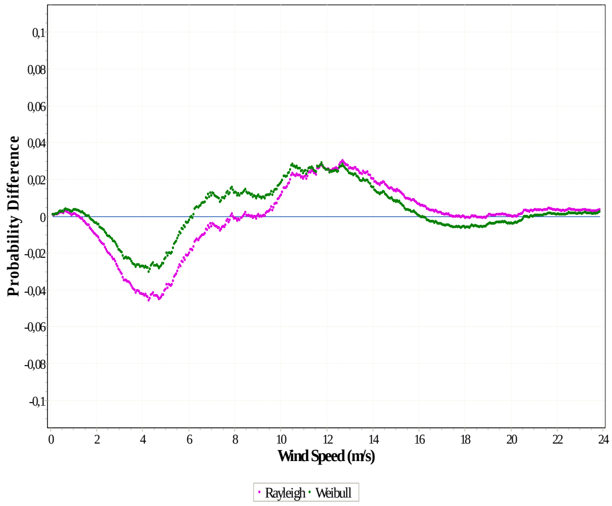

Fig. 14 Probability difference of Weibull and Rayleigh models

After establishing the performance of the two distribution functions, the Weibull parameters k and c were further studied.

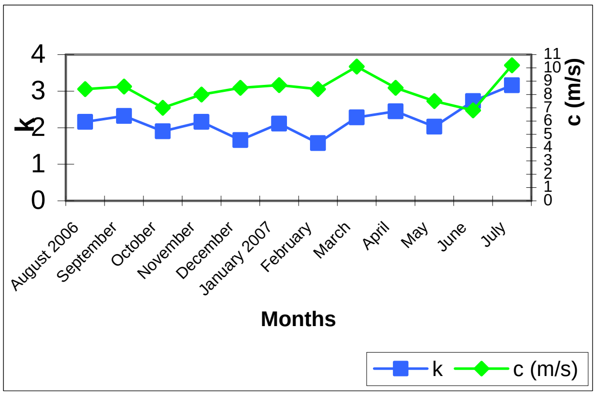

Fig. 15 Annual variation of Weibull shape and scale parameters

Fig. 15 presents the annual variation of k and c parameters. It can be noted that the values of k varied significantly during the year with the minimum value being slightly over 1.5 in February and the maximum value being close to 3.5 in July. On the other hand, the scale parameter c, had a smaller variation than k parameter, and it ranged from approximately 7 m/s in October to 10 m/s in March and July. These results were higher than the findings of Katsoulis [7] who estimated k to be 1.4 and c = 6.9 m/s and the geographical distribution of k and c parameters shown in Fig. 16 and 17.

Figure 16 Geographical distribution of Weibull shape parameter k (Kaldellis 1999)

This can be easily understood when considering that the wind potential of the region cannot be taken as high but unaltered. Moreover, the peaked wind distribution observed, can be correlated with the high values of k parameter.

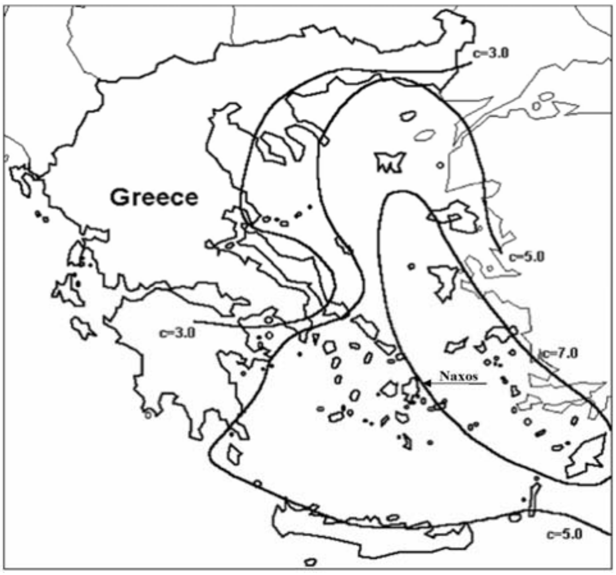

Fig. 17 Geographical distribution of Weibull scale parameter c (Kaldellis 1999)

3.5 Energy production

Fig. 18 shows the expected electrical energy production from the selected wind turbines with the actual wind speed. Although wind speed increased in January with respect to December value, the expected electrical energy production from the turbines decreased. This effect can be explained when considering the deviation of the maximum speeds recorded during this particular month from the corresponding mean value (Fig. 4). It is believed that although strong winds might be blowing in the area during that period, their duration was possibly not too long in order to be fully utilised by the wind turbines. Besides, it is known that strong winds of long duration characterise a good quality wind potential. This remark can be further supported when seeing how well the turbines responded to the available wind in March and in July.

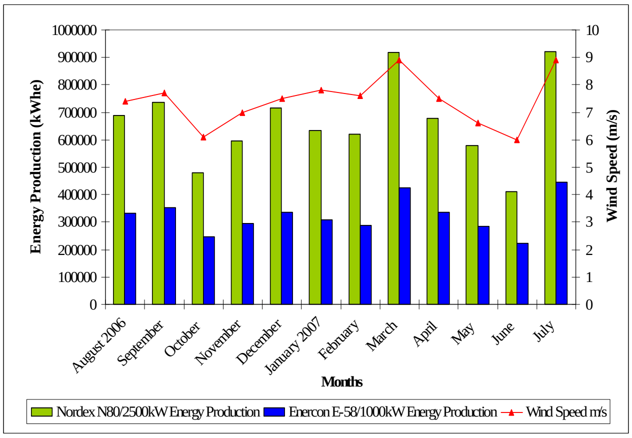

Fig. 18 Comparison of expected electrical energy production from the selected wind turbines with the actual wind speed

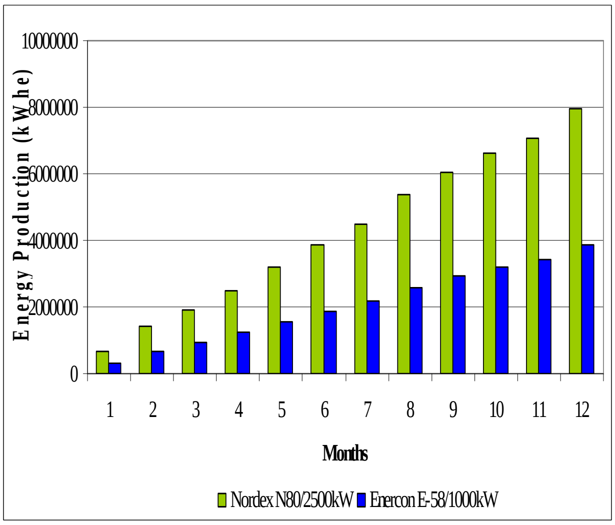

Fig. 19 Cumulative annual energy production of selected wind turbines

Finally, the cumulative annual energy production of the selected wind turbines can be seen in Fig. 19. It is apparent that the annual energy that can be produced by a 2.5 MW wind turbine is 8 MWh$_e$, whereas a 1 MW turbine can only produce 4 MWh$_e$.

4. Conclusions

The main conclusions drawn from this investigation into the wind characteristics of the northeastern part of Naxos Island were:

- The Central Aegean Sea shows a very pronounced wind potential.
- The windiest months were March and July with the mean wind speed reaching approximately 9 m/s, while the calmest month was June where the mean wind speed did not exceed 6 m/s.
- The annual mean wind speed was approximately 7.4 m/s.
- The measurement site falls under Class 7, indicating that it was suitable for large scale electricity generation
- Most of the time the prevailing winds in the area under investigation were the northeastern, the north-northeastern, and the west-southwestern.
- The highest value of the mean power density was around 730 W/m^2 in March, while the lowest value was approximately 180 W/m^2 in June.
- The mean annual wind power density was estimated to be 420 W/m^2.
- The large annual wind power density observed in the area was the result of the winter months contributions.
- The annual energy production by a 2.5 MW wind turbine is 8 GWh$_e$, whereas a 1 MW turbine can only produce 4 GWh$_e$.
- Weibull parameters k and c were found to be 2.17 and 8.58 m/s respectively.
- Weibull distribution represented the actual data better.

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