Improved Wind Energy Production Prediction for Remote Aegean Sea Islands

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Abstract— **Weibull is the most established analytical probability distribution for the description of the wind potential in specific locations around the globe. Acknowledging this, the most common methods of Weibull estimation are currently evaluated for different, representative remote islands of the Aegean Sea. Accordingly, based on the fairly good evaluation of theoretical energy yield results, a new method for estimating Weibull is developed (i.e. the "E-Weibull") that aims at the improved description of a given wind regime in terms of wind energy yield. To this end, the energy-adjusted "E-Weibull" is next applied in the Aegean Sea area, with energy yield results being favourably compared with the ones produced by all other methods.**

Keywords- ***Wind potential; wind speed distributions; wind turbine; capacity factor***

I. INTRODUCTION

During the last 40 years considerable research effort has been made (e.g. [1-5]) in order to simulate the wind potential profile of an area using analytical relations. Up to now the most widely used mathematical approaches include the Weibull probability density and the more simplified Rayleigh distribution. In this context, both Weibull and Rayleigh have been extensively used in order to reproduce real world data concerning the expected wind speed probability distribution, in most cases successfully. However, their limited capacity to represent all types of wind regimes sufficiently (especially those where null speeds are of important frequency or where a bimodal distribution appears) introduces the need to also consider of additional distributions that may produce better results in the case of more unusual wind regimes.

Examples of such distributions, investigated by several authors [5-11], include the Gamma two and three parameter distribution, the two parameter lognormal distribution, the two parameter inverse Gaussian distribution, the two parameter normal truncated distribution, the two parameter square-root normal distribution, the three parameter beta distribution, the Pearson type V distribution, the maximum entropy principle distribution, the Kappa distribution and the Burr distribution, as well as distribution mixtures such as the singly truncated normal Weibull mixture and the Gamma Weibull mixture distribution. On the basis of these efforts, use of additional probability distributions, other than Weibull, may provide better description of wind speed measurements in cases of more unusual wind speed regimes, in the expense however of additional computational effort. On the other hand, it is almost certain that for the vast majority of wind potential patterns, there is no generally approved analytical relation that is more efficient than Weibull. To this end, if stressing the advantage of minimum computational effort, Weibull definitely comprises the basic analytical tool that describes the wind potential especially for high wind regions like the Aegean Archipelago.

At this point it is important to note that even little difference between the actual and the theoretically-produced wind speed regime often leads to severe overestimation or underestimation of the theoretical calculation of energy yield of a wind power station in relation to the real world output. To avoid facing such increased levels of uncertainty when using the results of mathematical distributions instead of detailed wind speed measurements, an effort is currently undertaken so as to evaluate the Weibull performance in terms of energy yield estimation. In this context, the graphic, the standard deviation, the maximum likelihood and the energy pattern factor methods are used for the estimation of the scale and shape factors of Weibull [12]. These methods are accordingly compared -in terms of energy yield estimation- with results obtained from the use of long-term, actual wind speed data. In the current study emphasis is given on the examination of representative wind regimes encountered in the area of the Aegean Sea, Greece. The specific area presents appreciable wind and renewable energy sources (RES) potential (see also Fig. 1) and thus encourages installation of new wind power projects [13,14], especially since the greatest part of the local electricity generation is still covered by oil-based thermal power stations at excessive electricity production cost [15].

Furthermore, based on the evaluation of theoretical results concerning wind energy yield, obtained from the application of the different methods/distributions to the areas of interest, a new method for estimating Weibull is currently developed that aims at the optimum description of a given wind regime in terms of wind energy yield. To this end, the energy-adjusted Weibull (i.e. the "E-Weibull") is next applied to the area of investigation, with energy yield results being favourably compared with the ones produced by the rest of Weibull methods and Rayleigh. Note at this point that the main advantages of the proposed "E-Weibull" distribution include its focus on the energy yield of a wind turbine, rather than on

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the description of the local wind potential for the entire wind speed range, as well as the requirement for minimum computational effort.

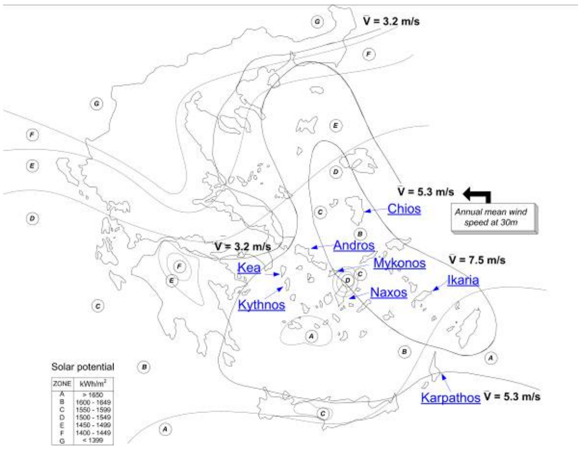


Fig. 1. Greek islands examined

II. METHODOLOGY

A. *Wind speed-related results*

Using the analysis included in several textbooks, see for example [12,16-19], the determination of Weibull parameters, are together with Rayleigh accordingly applied to eight different island areas of the Aegean Sea (Fig. 1), corresponding to different types of wind regimes. In this context, the islands of Kea, Chios, Kythnos, Naxos, Andros, Ikaria, Karpathos and Mykonos are currently selected, with the respective wind potential provided corresponding to typical wind years. More precisely, experimental wind speed measurements on an hourly basis for an entire year are used [20], with the respective data presented in Fig. 2. To this end, wind potential characteristics for the areas investigated are given in Table I, including the annual average wind speed, the standard deviation of annual wind speed measurements and the total number of calm spell events along with their max duration.

TABLE I. WIND POTENTIAL CHARACTERISTICS FOR THE AREAS OF INVESTIGATION

Island Area	**Mean annual wind speed (m/s)**	**Standard deviation (m/s)**	**Calm spells' (<4m/s) annual & max duration (hours)**
Kea	5.48	4.07	3795 – 174
Chios	5.79	4.60	3653 – 83
Kythnos	6.36	4.62	3120 – 57
Naxos	6.94	4.22	2427 – 71
Andros	9.16	4.85	1147 – 35
Ikaria	9.3	5.14	1614 – 45
Karpathos	9.09	5.29	1734 – 83
Mykonos	11.16	6.63	1285 – 38

Using the above dataset, application of the different Weibull methods and Rayleigh is undertaken in Fig. 3, where Weibull and Rayleigh probability density curves are plotted against the respective experimental data (given as histograms). In this regard, as it may be concluded, the eight selected areas present quite different wind regimes, including, smooth (e.g. Andros), near-unimodal (e.g. Kythnos) and bimodal (e.g. Kea) patterns, as well as regimes of high share of null wind speeds (e.g. Karpathos) or high share of extreme wind speeds (e.g. Mykonos), suggesting also areas of high, medium and low average wind speed (see also Fig. 2 and Table I).

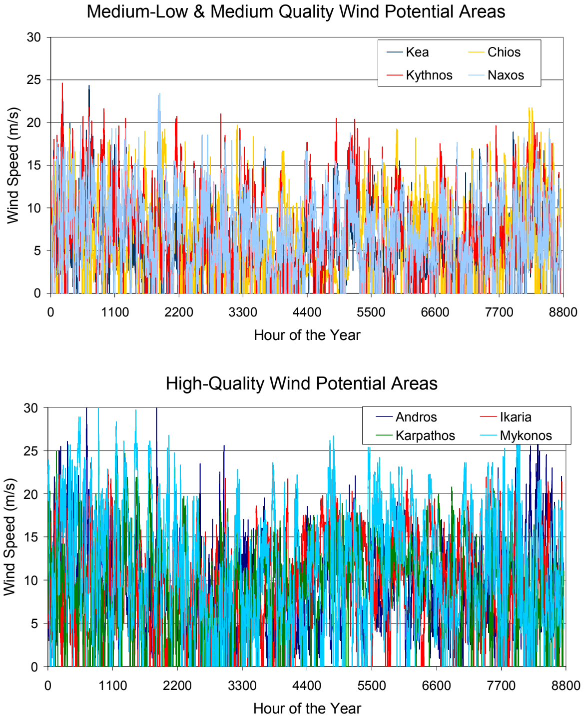
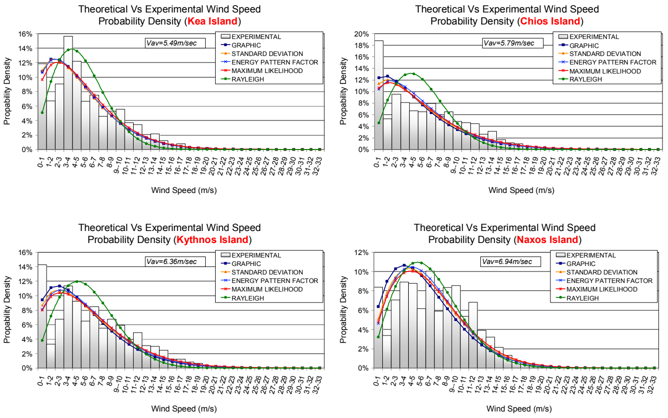


Fig. 2. Year-round hourly wind speed measurements for the areas examined

With this in mind, it appears that certain wind patterns are better described, while others suggest rather poor performance for certain curves. For example, what may be concluded is that smooth, bell-shaped wind patterns, such as the one of Andros Island, imply best curve fitting regardless of the distribution and method of estimation. On the other hand, for areas such as Karpathos and Mykonos, where owed to the increased probability of meeting high or even extreme wind speeds, both Weibull and Rayleigh present rather poor performance.



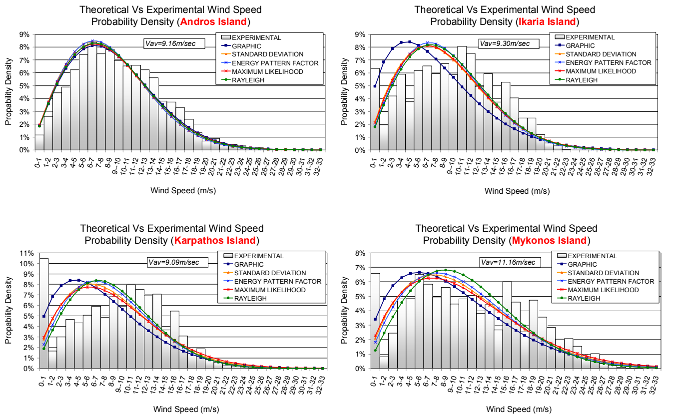


Fig. 3. Performance of Weibull (different estimation methods) and Rayleigh distributions in the description of the examined areas wind regimes

B. *Wind energy yield-related results*

By acknowledging the fact that ineffective description of the local wind regime entails misjudgement in the evaluation of the expected wind energy yield, estimation of the corresponding capacity factor "CF" of a wind power station - *via the calculation of the power coefficient "ω"*- is accordingly undertaken, on the basis of equation (1), allowing in this way estimation of the annual energy yield "E", if a mean technical availability value "Δ" is also introduced (see also equations (2) and (3)) [5, 21]. In this regard, note that the power coefficient concerns only the range of speeds between the cut-in "V_c" and cut-out "V_f" wind speed of the wind turbine each time examined, while P(V) is the wind turbine power output vs. wind speed. Keep in mind that the power output of the commercial wind turbines outside this wind speed range is zero, thus the accuracy of the analytical equations used to describe the available wind potential does not really affect the value of expected energy yield. Note also that "f(V)" is the probability density distribution of the wind potential under evaluation, while "P_o" is the rated power of the selected wind turbine.

$$\omega = \int_{V_c}^{V_f} \frac{P(V)}{P_o} \cdot f(V)dV \tag{1}$$

$$E = CF \cdot P_o \cdot 8760 \tag{2}$$

$$CF = \omega \cdot \Delta \tag{3}$$

III. THE ENERGY CALCULATION ACCURACY PROBLEM

Actually, to illustrate the total energy yield difference induced by the use of theoretical distributions instead of actual data, in Fig. 4 one presents the comparison between the theoretical value "ω_{th}" and the respective experimental value "ω_{exp}". Based on the results of the figure, what may be noted is that in all areas examined, use of theoretical distributions suggests considerable difference (underestimation) between the theoretical and actually expected energy yield (being currently represented by the annual power coefficient value).

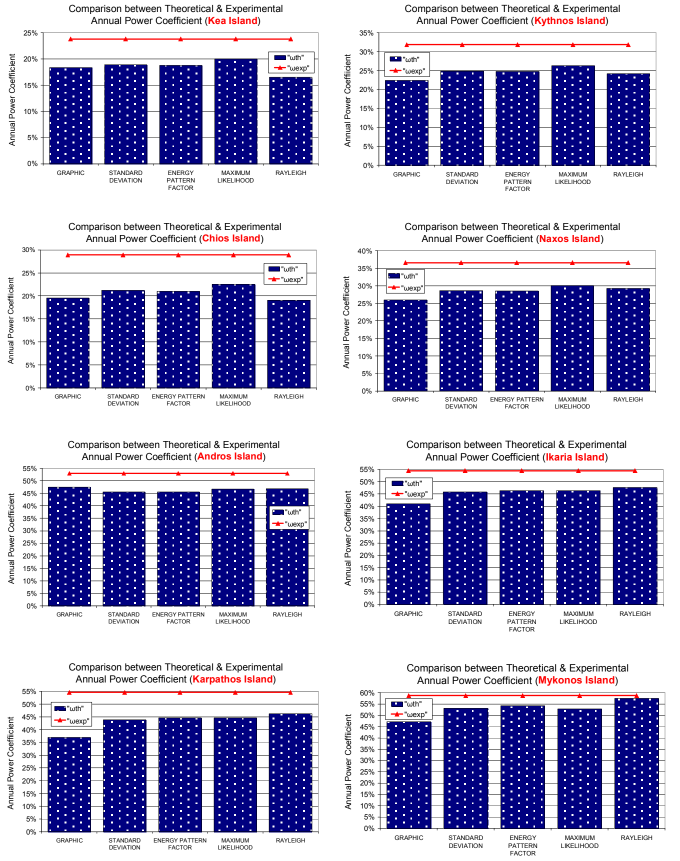


Fig. 4. Performance of Weibull (different estimation methods) and Rayleigh in terms of wind energy yield estimation

At the same time, it should also be noted that despite the satisfactory curve fitting for e.g. the case of Naxos (see Fig. 3), the deviation in terms of annual energy yield is considerable, clearly demonstrating that previous high quality results concerning description of wind speed regimes do not necessarily determine the output quality in terms of the total annual expected energy yield. This can be explained by the fact that different wind speeds carry different weight factors in terms of expected energy yield, determined by the wind power curve of the wind turbine each time examined. The opposite behaviour is noted in the case of e.g. Karpathos, where despite the fact that theoretical curves largely fail to describe the wind speed distribution, they do not entail analogous difference between "ω_{exp}" and "ω_{th}".

Accordingly, what also becomes evident from the comparison between theoretical and experimental power coefficient results is that both graphic Weibull and Rayleigh often induce considerable deviation (i.e. underestimation), which although associated with poor curve fitting performance in the case of Rayleigh, is not as obvious for the graphic Weibull (e.g. Ikaria and Karpathos). On the other hand, the rest of Weibull methods present similar results and little variation among them (with maximum likelihood again producing marginally better results), with the levels of deviation from the experimental energy yield much depending on the area each time examined.

Finally, emphasizing on Weibull, synopsis of "δω" results (see also equation (4)) is given in Fig. 5, where the range of "δω" variation (for all four Weibull methods applied) along with the corresponding average value are provided in relation to the quality of the local wind potential as the latter is determined by the experimental value of "ω_{exp}". As it may be distinguished, there are two main island groups; the first including the islands of Andros and Mykonos and the second including the rest of islands. To this end, "δω", kept below 15% on average for the first island group and ranging between 20% and 30% for the second group, indicates that the specific value is independent from the wind potential quality and seems to depend more on the wind regime pattern. Note that the mean power coefficient deviation "δω" practically defines (see equation (3)) the corresponding capacity factor "δCF" deviation.

$$\delta\omega = \frac{\left|\omega_{exp} - \omega_{th}\right|}{\omega_{exp}} \qquad (4)$$

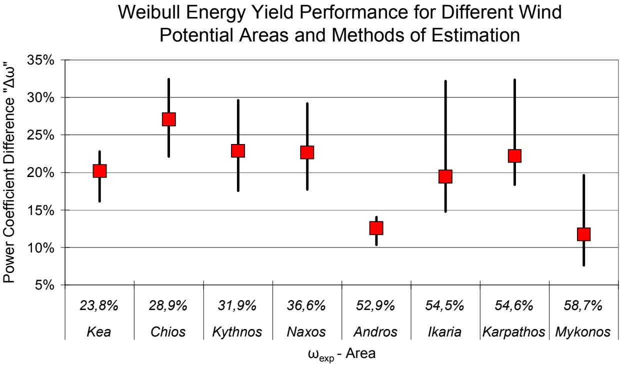


Fig. 5. Energy yield performance variation of the different Weibull estimation methods in relation to the quality of the wind potential examined

IV. PROPOSED SOLUTION

Taking into account the results of the previous section, it becomes clear that estimation of a given wind turbine energy yield cannot be determined by the performance of theoretical wind speed distributions aiming at the improved description of the entire wind regime instead of the wind energy yield. To this end, by arguing on the usefulness of a theoretical tool that will approximate the actual wind energy yield of a given wind machine operating under certain wind potential characteristics, an effort is made in the current section to develop an energy-adjusted Weibull distribution named "E-Weibull". For this purpose, we support that in order to improve the performance of Weibull in terms of expected energy yield approximation, emphasis should be given on the exploitable part of a given wind potential, i.e. wind speeds allowing operation of a certain wind turbine. In this context, the following steps are followed during the theoretical calculation of the expected wind energy yield of a wind turbine to be operated in a specific area:

- Exclude wind speeds of 0m/s that, in case of high frequency, largely affect Weibull performance.
- Exclude wind speeds less or equal to "V_c" (for example equal to 4m/sec), that are normally determined by high probability density values and that do not contribute in the wind turbine operation. For these wind speed values wind power output is zero.
- Exclude wind speeds greater or equal to "V_f" (for example equal to 25m/sec) defining zero energy production areas.
- Apply the "E-Weibull" using weight factors "w(V)" over the entire range of wind speeds -based on the wind power curve each time examined- that will modify the initial probability density distribution to a new energy oriented one "$f_e(V)$" and improve the accuracy of power coefficient values in accordance with equations (5) and (6).

$$f_e(V) = f(V; w(V)) \qquad (5)$$

$$\omega_e = \int_{V_c}^{V_f} \frac{P(V)}{P_o} \cdot f_e(V)\,dV \qquad (6)$$

Note that the weight factor distribution should follow the power curve of the selected wind turbine (normally values should range between zero and one), while for a more general application one may use the numerical values resulting from a typical power curve of a contemporary commercial wind turbine, without significant loss of accuracy. In any case the weight factor distribution of equation (5) may be estimated using equation (7), i.e.:

$$w(V) = \frac{P(V)}{P_o} \qquad (7)$$

To apply the above steps, graphic Weibull is currently used, owed to the fact that as earlier seen (Fig. 3) it is the Weibull calculation method that overall resulted in the greater deviation from the respective experimental energy yield (or annual power coefficient). In this context, to present changes induced by the application of the above successive steps (or different Weibull approaches), the example of Ikaria is used in Fig. 6.

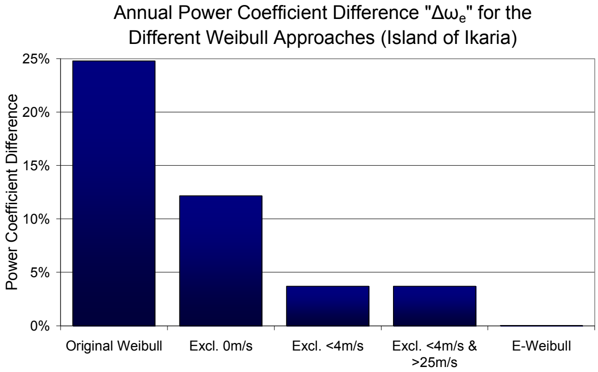


Fig. 6. The impact of applying different Weibull approaches on the annual power coefficient difference using as an example the island of Ikaria

More specifically in Fig. 6 the impact of successive steps on "$\delta\omega_e$" (see also equation (8)) is provided. According to the figure results, failure of the original graphic Weibull to approach the wind energy yield is gradually alleviated by the application of successive steps. In this context, use of "E-Weibull" is critical in the minimization of "$\delta\omega_e$", considering that the current approach includes -on top of all previous steps- the use of weight factors over the entire wind speed range, with wind speeds corresponding to the nominal part of the wind power curve being assigned with a greater "value".

$$\delta\omega_e = \frac{\left|\omega_{\exp} - \omega_{th-e}\right|}{\omega_{\exp}} \qquad (8)$$

Accordingly, final results obtained by the application of "E-Weibull" for all areas examined are given in Fig. 7. Again, performance of "E-Weibull" is evaluated on the basis of "$\delta\omega_e$", with results obtained clearly demonstrating its advantage over the original graphic Weibull. In fact, as one may see, "$\delta\omega_e$" is almost zeroed in all cases examined for "E-Weibull", while it exceeds 20% -with the exception of Andros island- when the original Weibull is applied. Again, it should be emphasized that the proposed "E-Weibull" method is easily applicable for every existing wind turbine, without the need for considerable computational effort.

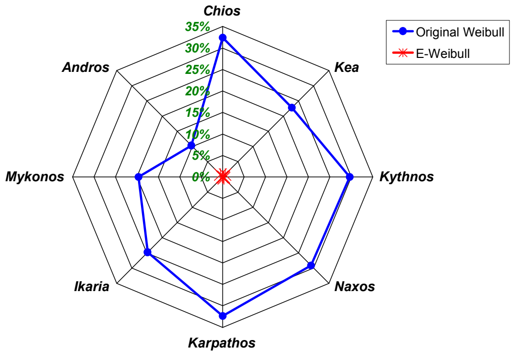


Fig. 7. Comparison of the original Weibull and "E-Weibull" in terms of annual power coefficient (capacity factor) difference for several remote island areas examined

V. CONCLUSIONS

Realizing that established wind speed distributions cannot always provide sufficiently reliable estimations of the wind energy yield -irrespectively of their performance in describing different types of wind regimes- an effort was undertaken in the current study in order to develop a new, energy-adjusted Weibull, i.e. the "E-Weibull". Prior to that, to determine the levels at which both Weibull and Rayleigh distributions fail to provide a secure prediction of the expected energy yield for a given wind turbine operating in an area of certain wind characteristics, representative wind regimes from eight different island areas of the Aegean Sea were used. At the same time, the most widely applied methods for the estimation of Weibull were investigated and evaluated along with Rayleigh in terms of expected energy yield approximation. According to the results obtained, the difference between theoretical and actually expected energy yield varied significantly, being in most cases quite severe, i.e. above 20%.

Based on this outcome, a new energy-adjusted "E-Weibull" distribution was developed and evaluated. The basic idea of this effort was to focus on the accurate prediction of the energy yield of a wind turbine, instead of finding the best Weibull calculation method, or the more accurate and complicated analytical relation, so as to describe the entire wind potential of a candidate area. In this context, although successive steps were used in the development of the "E-Weibull", it was its final analytical distribution that produced the best results. The specific distribution uses appropriate, energy-related weight factors assigned to wind speed bins according to the power curve of the wind turbine to be installed. To this end, the proposed methodology is thought to provide a rather useful analytical tool that can drastically and effectively produce accurate wind energy yield estimation on the basis of minimum computational effort. To conclude, the proposed "E-Weibull" distribution provides significantly better calculation results than the previous analytical relations used in comparison with experimental data, thus improving considerably the reliability of energy predictions in case of new wind power installations.

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