

Wind Energy Resource Assessment and Turbine Energy Yield Using the Weibull Distribution

Senthil R. Velumani¹, Bhavana S. Karthikeyan²

ABSTRACT

The energy a wind turbine will produce at a site depends on how windy the site is and on how the turbine converts wind into power, and estimating it before installation is essential to deciding whether a site is worth developing. This study assesses the wind energy resource at a site and estimates the energy a turbine would yield there, combining a statistical description of the wind with the turbine's power curve. The distribution of wind speeds at the site was represented by the Weibull distribution, a two-parameter form widely used for this purpose, and the turbine's output was described by its power curve, which gives the power produced at each wind speed, zero below a cut-in speed, rising to a rated power, held constant to a cut-out speed, and zero beyond; the expected energy yield and the capacity factor were obtained by combining the two. The Weibull distribution represented the spread of wind speeds compactly through its two parameters, and combining it with the power curve gave the expected power and hence the annual energy yield and the capacity factor, the fraction of the turbine's rated output actually achieved. The yield depended strongly on the windiness of the site, a higher mean wind speed greatly increasing the energy because the power available in the wind rises steeply with speed, and on the match between the turbine's characteristics and the site's wind. The study shows that combining a Weibull description of the wind with the turbine power curve gives a sound estimate of energy yield for resource assessment, and it discusses the sensitivity of the yield to the wind resource and the turbine.

KEYWORDS: *Wind energy, Resource assessment, Weibull distribution, Power curve, Capacity factor, Energy yield, Wind speed, Renewable energy, Turbine*

INTRODUCTION

Wind energy is among the most important sources of renewable electricity, and the decision to develop a site for wind power rests on how much energy a turbine would produce there. This energy cannot be known with certainty in advance, since it depends on the wind, which varies, but it can be estimated, and an accurate estimate is essential: a site with too little wind will not repay the investment, while a windy site may be very productive. Estimating the energy yield before installation is therefore a central task of wind energy development, known as resource assessment.

The energy a turbine yields depends on two things: how windy the site is, that is, the distribution of wind speeds it experiences, and how the turbine converts wind into power, described by its power curve. The wind speed at a site is not constant but varies from calm to strong, spending different amounts of time at different speeds, and this distribution must be characterised. The turbine's power curve gives the power it produces at each wind speed, and has a characteristic shape: no power below a cut-in speed at which the turbine starts, rising power as the wind strengthens, a constant rated power once the turbine reaches its limit, and a shutdown above a cut-out speed at which high winds would damage it.

This paper assesses the wind energy resource at a site and estimates the energy a turbine would yield, combining a statistical description of the wind with the turbine's power curve. The distribution of wind speeds is represented by the Weibull distribution, widely used for this purpose, and the turbine's output by its power curve, the expected energy yield and the capacity factor being obtained by combining the two. The aim is to show how this combination gives a sound estimate of energy yield for resource assessment and to discuss the sensitivity of the yield to the wind resource and the turbine.

LITERATURE REVIEW

Wind energy resource assessment is well established, and the literature describes both the statistical characterisation of the wind and the estimation of energy yield from it. The distribution of wind speeds at a site is commonly represented by the Weibull distribution, a two-parameter form that fits observed wind speeds well across many sites, its two parameters describing the typical speed and the spread. The turbine power curve, giving power against

wind speed, is the standard description of a turbine's conversion of wind into power.

ESTIMATING ENERGY YIELD

The literature sets out the estimation of energy yield:

- The Weibull distribution represents the proportion of time the wind spends at each speed through its two parameters.
- The power curve gives the power produced at each wind speed, with its cut-in, rated, and cut-out features.
- Combining the two, by weighting the power at each speed by the time spent at that speed, gives the expected power and hence the energy yield.
- The capacity factor, the ratio of the actual energy yield to that if the turbine ran at rated power continuously, summarises how fully the turbine is used.

A recurring conclusion is that this combination gives a sound estimate of energy yield, and that the yield is highly sensitive to the wind resource because the power available in the wind rises with the cube of the wind speed.

Studies of wind resource assessment report that the Weibull distribution represents site wind speeds well and that combining it with the power curve gives reliable estimates of energy yield and capacity factor. The literature emphasises the strong dependence of the yield on the wind speed, since the power in the wind varies as the cube of the speed, so that a modest increase in the mean wind speed produces a large increase in energy, and notes the importance of matching the turbine's characteristics to the site's wind for a good capacity factor.

RESEARCH GAP

Although wind resource assessment is well established, a concise account that combines a Weibull description of the wind with a turbine power curve to estimate energy yield and capacity factor, and that shows the sensitivity of the yield to the wind resource and the turbine, remains useful as a clear illustration of the method. There is therefore value in a study that presents the power curve and the wind distribution together and relates the energy yield to both.

OBJECTIVES

The objectives of this study are:

- To represent the distribution of wind speeds at a site by the Weibull distribution.
- To describe a turbine's output by its power curve, with its cut-in, rated, and cut-out features.
- To estimate the expected energy yield and the capacity factor by combining the wind distribution with the power curve.
- To examine the sensitivity of the yield to the wind resource and the turbine characteristics.

METHODOLOGY

Wind Distribution and Power Curve

The distribution of wind speeds at the site was represented by the Weibull distribution, whose two parameters, a shape and a scale, describe the spread and the typical magnitude of the wind. The turbine's output was described by its power curve, giving the power at each wind speed: zero below the cut-in speed, rising with the wind to the rated power, constant at the rated power up to the cut-out speed, and zero above it, where the turbine shuts down to avoid damage. The parameters are summarised in Table 1.

Table 1: Site and turbine parameters

Parameter	Description
Wind distribution	Weibull, with shape and scale parameters
Cut-in speed	Wind speed at which the turbine starts
Rated speed	Wind speed at which rated power is reached
Cut-out speed	Wind speed at which the turbine shuts down
Rated power	Maximum power output of the turbine

Energy Yield Estimation

The expected energy yield was estimated by combining the wind distribution with the power curve: the power produced at each wind speed, given by the power curve, was weighted by the proportion of time the wind spent at that speed, given by the Weibull distribution, and summed to give the expected power, from which the annual energy yield followed. The capacity factor

was obtained as the ratio of this yield to the energy the turbine would produce running at rated power continuously. The sensitivity of the yield to the wind resource and the turbine was then examined.

RESULTS AND FINDINGS

The combination of the wind distribution and the power curve gave the expected energy yield, the two being shown together in Figure 1. The power curve rose from zero at the cut-in speed, increased steeply with the wind to the rated power, remained constant at the rated power to the cut-out speed, and fell to zero beyond; the Weibull distribution showed the wind spending most of its time at moderate speeds, with less time at very low or very high speeds. The energy yield came from the overlap of the two: the turbine produced most of its energy at the wind speeds that were both productive on the power curve and common in the distribution.

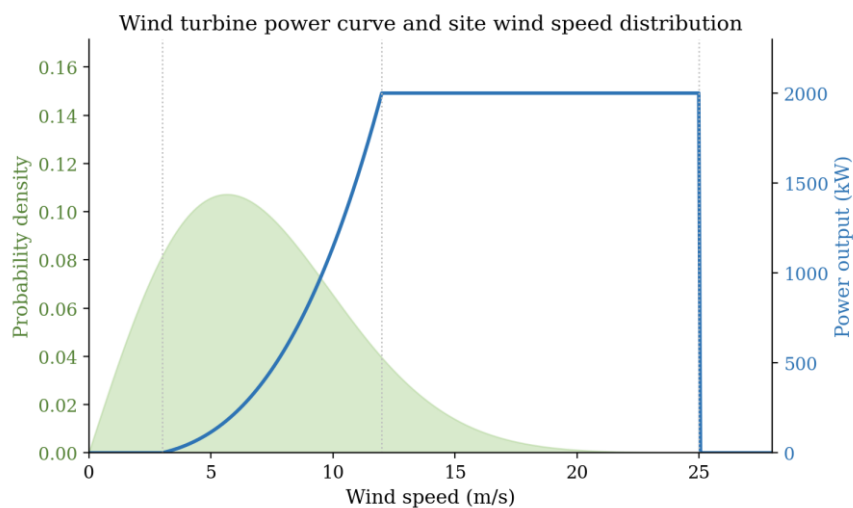


Figure 1: Turbine power curve and the site wind speed distribution

The estimated yield depended strongly on the windiness of the site. Because the power available in the wind rises with the cube of the wind speed, a site with a higher mean wind speed yielded far more energy than a less windy one, a modest increase in mean speed producing a large increase in energy. The capacity factor, the fraction of the rated output actually achieved, reflected how fully the turbine was used and depended on the match between its cut-in, rated, and cut-out speeds and the site's wind. The yield and capacity factor are summarised in Table 2.

Table 2: Energy yield and capacity factor

Quantity	Description
Expected power	From power curve weighted by wind distribution
Annual energy yield	Expected power over the year
Capacity factor	Yield relative to continuous rated output
Sensitivity	Rises steeply with mean wind speed

DISCUSSION

The results show that combining a Weibull description of the wind with the turbine power curve gives a sound estimate of energy yield for resource assessment. The method is sound because it accounts properly for both factors that determine the yield: how often the wind blows at each speed, captured by the distribution, and how much power the turbine produces at each speed, captured by the power curve. Weighting the one by the other and summing gives the expected power, and hence the energy that the turbine would produce at the site, which is exactly what resource assessment requires.

The strong dependence of the yield on the wind speed is the most important finding for siting. Because the power available in the wind rises with the cube of the speed, the energy yield is highly sensitive to the windiness of the site: a site with a mean wind speed even modestly higher than another may yield substantially more energy, and conversely a site with too little wind yields little however good the turbine. This is why the choice of a windy site is paramount in wind energy development, and why accurate assessment of the wind resource, through the distribution, is so important; a small error in the estimated wind speed translates into a large error in the estimated energy.

The capacity factor draws attention to the match between the turbine and the site. A turbine produces its rated power only in strong winds, and at a site where such winds are infrequent it will spend much of its time producing less, giving a lower capacity factor; matching the turbine's characteristics, particularly the wind speed at which it reaches rated power, to the site's wind improves the capacity factor and the use of the turbine. The Weibull distribution is valuable because it summarises the site's wind in two parameters, allowing the yield to be

estimated without a full record of every wind speed, though its accuracy depends on how well it fits the actual wind. The practical conclusion is that the combination of Weibull distribution and power curve is a sound and convenient basis for wind resource assessment, the main caveats being that the estimate depends on the accuracy of the wind data and the fit of the distribution and that real yield is also affected by losses and turbine availability not captured here.

CONCLUSION

The wind energy resource at a site and the energy a turbine would yield were assessed by combining a Weibull description of the wind with the turbine power curve. The Weibull distribution represented the spread of wind speeds compactly through its two parameters, and combining it with the power curve, by weighting the power at each speed by the time spent at that speed, gave the expected power and hence the annual energy yield and the capacity factor. The yield depended strongly on the windiness of the site, because the power in the wind rises with the cube of the speed, and on the match between the turbine and the site's wind. The study shows that combining a Weibull description of the wind with the turbine power curve gives a sound estimate of energy yield for resource assessment, that the yield is highly sensitive to the wind resource so that accurate wind data and a good distribution fit are essential, and that matching the turbine to the site improves the capacity factor, with real yield also affected by losses and availability not captured here.

LIMITATIONS

The following limitations apply to this study:

- The estimate depends on the accuracy of the wind data and on how well the Weibull distribution fits the actual wind.
- Real energy yield is reduced by losses and by turbine downtime and availability, which were not modelled.
- The wind was characterised by a single distribution and did not capture seasonal and directional variation in full.
- A single turbine power curve was considered, and yield depends on the turbine chosen.

FUTURE SCOPE

Future work could extend the present study as follows:

- Use of measured wind data over long periods to fit the distribution and capture seasonal and directional variation.
- Inclusion of losses and turbine availability to estimate the realised rather than ideal yield.
- Comparison of different turbines to find the best match to a site's wind.
- Assessment of the uncertainty in the estimated yield arising from uncertainty in the wind data.
- Extension to multiple turbines and wake effects in a wind farm.

REFERENCES

1. Manwell, J. F., McGowan, J. G., & Rogers, A. L. (2009). *Wind energy explained: Theory, design and application* (2nd ed.). John Wiley & Sons.
2. Burton, T., Jenkins, N., Sharpe, D., & Bossanyi, E. (2011). *Wind energy handbook* (2nd ed.). John Wiley & Sons.
3. Carta, J. A., Ramírez, P., & Velázquez, S. (2009). A review of wind speed probability distributions used in wind energy analysis. *Renewable and Sustainable Energy Reviews*, 13(5), 933–955.
4. Justus, C. G., Hargraves, W. R., Mikhail, A., & Graber, D. (1978). Methods for estimating wind speed frequency distributions. *Journal of Applied Meteorology*, 17(3), 350–353.
5. Celik, A. N. (2004). A statistical analysis of wind power density based on the Weibull and Rayleigh models. *Renewable Energy*, 29(4), 593–604.
6. Akdağ, S. A., & Dinler, A. (2009). A new method to estimate Weibull parameters for wind energy applications. *Energy Conversion and Management*, 50(7), 1761–1766.
7. Albani, A., & Ibrahim, M. Z. (2017). Wind energy potential and power law indexes assessment for selected near-coastal sites in Malaysia. *Energies*, 10(3), 307.
8. Jangamshetti, S. H., & Rau, V. G. (1999). Site matching of wind turbine generators: A case study. *IEEE Transactions on Energy Conversion*, 14(4), 1537–1543.
9. Lun, I. Y. F., & Lam, J. C. (2000). A study of Weibull parameters using long-term wind observations. *Renewable Energy*, 20(2), 145–153.

10. Ackermann, T. (Ed.). (2012). *Wind power in power systems* (2nd ed.). John Wiley & Sons.

***Author for Correspondence**

Senthil R. Velumani

E-mail: senthil.velumanie313223@gmail.com

¹Associate Professor, Department of Electrical Engineering, JKKN College of Pharmacy

²Assistant Professor, Department of Electrical Engineering, JKKN College of Pharmacy, JKKN College of Pharmacy

Received Date: February 24, 2026

Accepted Date: March 07, 2026

Published Date: March 29, 2026

Citation: Senthil R. Velumani, Bhavana S. Karthikeyan. Wind Energy Resource Assessment and Turbine Energy Yield Using the Weibull Distribution. International Journal of Smart Power and Renewable Energy. 2026; 2(1): 10-18p.