

Performance Analysis of Wind Turbines Using Environmental Parameters

(A Six-Decade Historical, Data-Driven and Model-Based Assessment of Wind Energy Potential and Turbine Performance Dynamics at Kohat Station, Pakistan, 1954–2010)

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Abstract Local wind speed and ambient conditions determine how much energy a wind turbine could deliver, but long historical records are rarely examined together with a transparent turbine model. This study assesses the estimated wind-energy potential of Kohat, Pakistan, from a workbook of monthly observations for 1954–2010 taken at 08:00 and 17:00 (684 records per time; 645 and 633 valid). The origin of the workbook could not be established, so the records are treated as an attributed dataset and not as a verified station archive. Wind speed, direction, temperature, relative humidity and calculated air density were combined with a hypothetical reference turbine (rotor diameter 90 m, hub height 80 m, $C_p = 0.45$, cut-in 3 m s^{-1} , 15% assumed loss) to derive wind power density (WPD) and modelled power. No measured turbine output exists, so all results are model estimates. Mean wind speed was 1.59 and 2.22 m s^{-1} and mean WPD was 3.97 and 13.43 W m^{-2} at 08:00 and 17:00. The cut-in speed was reached in 2.5% and 22.4% of valid months, giving modelled capacity factors of 0.05% and 0.92% when speeds are used as supplied (no height correction). Generation at 17:00 was concentrated in May–August. Annual means declined over the record, and the last 23 months showed a level shift that carries 31–37% of the estimated energy; both features need metadata checks. Hub-height extrapolation and cut-in speed dominated the sensitivity results, whereas C_p , loss allowance and density acted proportionally. On this dataset Kohat is a low-wind site, and the numerical yields are lower-bound, assumption-conditional estimates.

Keywords wind resource assessment, wind power density, reference turbine, air density, Weibull distribution, sensitivity analysis, Kohat, Pakistan

1. Introduction

Wind is among the most widely used renewable energy resources, and a credible estimate of the local wind resource is the first technical step in judging whether a site is worth developing. In Pakistan, where diversifying the generation mix is a long-standing aim, wind assessments have attracted steady attention (Khan and Tariq, 2018; Shoaib et al., 2017). Whether a location can support a turbine depends not on the average wind alone, but on how the wind is distributed in time, on the air in which the rotor operates and on the characteristics of the machine.

Wind turbines extract only part of the kinetic power passing through the rotor, and the power available scales with the cube of wind speed and linearly with air density (Manwell et al., 2009; Burton et al., 2011). A small bias in speed therefore becomes a large bias in estimated energy. Density in turn depends on temperature, pressure and humidity, so the ambient state of the

atmosphere enters the estimate twice: through the resource itself and through the conditions under which a turbine operates (Saint-Drenan et al., 2020; Pandit et al., 2023). Studies that assess a site from mean speed alone, or from one standard density, may therefore misstate both the resource and its uncertainty.

Resource assessments in Pakistan have mostly used short records from specific sites, typically with Weibull fitting and comparison of commercial turbines (Shoaib et al., 2017, 2019; Hedio, 2021; Sumair et al., 2021a; Saeed et al., 2021; Tahir et al., 2025). Long historical records offer a different view of variability, but they also raise questions of homogeneity, instrument change and provenance that short campaigns do not. A second difficulty is interpretive. When no turbine or SCADA data exist, calculated output is easily described as “actual” performance, although it reflects only the model assumed.

Two gaps follow from this. First, the studies cited above rely on measurement campaigns of a few years at selected sites, and long historical records are less often treated as a source of resource information, in part because their provenance and homogeneity are hard to document. Second, where no turbine output exists, the step from wind speed to energy is made through assumptions (hub height, power coefficient, losses, cut-in speed and air density) whose individual influence is not always reported. The present study addresses both gaps for Kohat by using the long record cautiously and by quantifying which assumptions control the modelled result.

This study uses a monthly workbook for Kohat covering 1954–2010 to examine (i) the temporal structure of wind speed and direction, (ii) the wind power density and modelled power of a hypothetical reference turbine, (iii) how temperature, humidity and density are associated with modelled output, and (iv) how sensitive the estimates are to the assumed hub-height extrapolation, cut-in speed, power coefficient, loss allowance and air pressure. The contribution is modest and specific: a documented, reproducible calculation chain for one long dataset, with observed, derived and assumed quantities kept apart and a quantified account of which assumptions control the answer. No claim is made that this is the first assessment of Kohat; that would require a systematic search which has not been done.

The objectives are: (1) to document and clean the dataset and identify quality issues; (2) to characterise the temporal variation of speed, direction, temperature and humidity; (3) to estimate hub-height speed, density and WPD with explicit assumptions; (4) to apply a reference-turbine model and estimate modelled power and energy; (5) to examine the association between environmental variables and modelled output; and (6) to test the sensitivity of the results to the main assumptions.

The study is intended to be useful in three ways. It provides a documented, assumption-explicit reference estimate of the wind resource implied by the Kohat records; it shows which of the assumptions behind such an estimate matter most, and therefore where measurement effort is best spent; and it offers a worked example of handling a long historical record of uncertain origin

without presenting model output as measured performance.

The remainder of the paper is organised as follows. Section 2 reviews related work on resource assessment in Pakistan and on power modelling. Section 3 describes the dataset, the cleaning steps and the calculation chain. Section 4 reports the results, Section 5 discusses them, Section 6 lists the limitations and Section 7 concludes.

2. Literature Review

Resource assessment in Pakistan. Khan and Tariq (2018) reviewed mast and SODAR measurements in Pakistan and stressed that measurement quality limits the reliability of yield estimates. Sumair et al. (2021a) fitted two-parameter Weibull distributions to five years of hourly data at 11 locations in southern Punjab and compared turbine models; related work by the same group examined shear coefficients and annual energy yield at coastal sites (Sumair et al., 2021b) and Weibull parameter estimation (Sumair et al., 2021c). Shoaib et al. (2017, 2019) and Hulio (2021) assessed Baburband, Nooriabad and Sujawal with Weibull methods. Saeed et al. (2021) combined Weibull fitting, a 20-turbine comparison and economic analysis for 18 locations. Tahir et al. (2025) assessed 12 low-wind sites, compared power-law and logarithmic extrapolation and evaluated a large set of commercial turbines. These studies share short or site-specific records, measured data from masts or stations, and turbine-specific calculations. None of them, as far as is reported here, addresses a half-century monthly record whose provenance is uncertain.

Power modelling. The IEC 61400-12-1 standard (International Electrotechnical Commission, 2017) defines measured power-performance testing. Gottschall and Peinke (2008) and the Power Curve Working Group (Lee et al., 2020) show that power-curve estimates depend strongly on the method used and that a single fixed coefficient is a simplification. Saint-Drenan et al. (2020) and Pandit et al. (2023) show that air density and other environmental conditions should enter power models explicitly.

What remains open. The literature establishes that hub-height extrapolation and turbine specification control yield, that density corrections matter, and that site results do not transfer between regions. It says less about how far a

deliberately simple model, applied to a long monthly record of uncertain origin, can support conclusions, and about which assumptions dominate. This study addresses that question for Kohat and reports its limits.

3. Materials and Methods

3.1 Dataset and study context

The analysis uses an Excel workbook attributed to the Kohat station (approximately 33.6° N, 71.4° E, about 490 m above sea level; these are approximate values for Kohat city because station coordinates are not in the file). The workbook covers January 1954 to December 2010 (57 years) and has one sheet each for 08:00 and 17:00 with 684 monthly records per sheet. Each record contains year, month, wind speed (knots), wind direction, wind speed at hub height (m s^{-1}), temperature, relative humidity, air density, WPD, theoretical power, net power, energy and losses. The data originator, instrument type, anemometer height, time standard and the nature of the monthly value (single reading or monthly mean) are not stated. The monthly value is treated as representative of the month, and the two times are analysed as separate series and never added. Table 1 lists the status of each variable, established by recalculating the workbook.

3.2 Data quality and preprocessing

Missing observations (coded -100, shown as N/A) were treated as missing. They affect 39 of 684 morning and 51 of 684 evening records; all morning gaps coincide with evening gaps, and the evening series also lacks all of 1966. No valid record exists for 1995 and 2008 (both series) or 1966 (evening); 1968, 1994 and 2009 are partial. One direction entry ("B04W") could not be interpreted and was excluded from directional statistics. Calm records number 2 (morning) and 7 (evening), and four evening speeds are exactly zero. Calculated columns were recomputed in Python and agreed with the workbook (WPD and power to better than 2×10^{-4} in their units; density to $5 \times 10^{-5} \text{ kg m}^{-3}$), and the workbook energy totals were reproduced. The original data were kept separate from the cleaned dataset. Duplicate detection and outlier screening beyond physical non-negativity were not documented in the source analysis.

3.3 Wind-speed characterisation

Speed in knots was converted to m s^{-1} ($\times 0.5144$). Mean, standard deviation, median, 90th percentile and range were computed per series from valid records. Monthly climatologies, four seasons (DJF, MAM, JJA, SON) and six sub-periods were used for temporal structure. Because speeds are right-skewed, power quantities were computed record by record and not from mean speed.

3.4 Weibull distribution analysis

Positive speeds of each series were fitted with a two-parameter Weibull distribution by maximum likelihood with location fixed at zero:

$$f(V) = (k/c)(V/c)^{k-1} \exp[-(V/c)^k] \quad (1)$$

where V is wind speed (m s^{-1}), k the shape factor (–) and c the scale factor (m s^{-1}). The fitted mean power density follows

$$\text{WPD} = \frac{1}{2} \rho c^3 \Gamma(1 + 3/k) \quad (2)$$

with ρ the air density (kg m^{-3}) and Γ the gamma function. Fit quality was summarised by the Kolmogorov–Smirnov statistic and by comparing fitted and observed means, WPD and exceedance of 3 m s^{-1} . Because parameters were estimated from the same data, the statistic is descriptive.

3.5 Wind-direction analysis

Quadrant bearings were converted to azimuths (e.g. N40W = 320°). Because angles wrap at 360° , the arithmetic mean can mislead, so the mean direction was computed from the sine and cosine components, which map each direction onto the unit circle and average it as a vector. For θ_i in radians:

$$\begin{aligned} x_m &= (1/n) \sum \cos \theta_i \\ y_m &= (1/n) \sum \sin \theta_i \\ \theta_m &= \text{atan2}(y_m, x_m) \\ R &= (x_m^2 + y_m^2)^{1/2} \end{aligned} \quad (3)$$

where R (0–1) measures directional concentration. Calm records were excluded from θ_m and counted in octant frequencies. Direction does not enter the power equations and is reported to describe the resource only.

3.6 Hub-height wind-speed estimation

The power law gives the speed at hub height:

$$V_h = V_r (h_h / h_r)^\alpha \quad (4)$$

where V_r is the speed at measurement height h_r (m), h_h the hub height (m) and α the shear exponent (–). The measurement height is not stated and the supplied hub-height column equals the observed speed in m s^{-1} , so the base case uses $\alpha = 0$, equivalent to assuming that the observations were made at 80 m. Standard anemometers are near 10 m, so the base case probably understates the speed at 80 m. The effect is quantified in Section 3.12 by assuming $h_r = 10$ m and $\alpha = 0.10, 1/7$ and 0.20 ; these are scenarios, not estimates for Kohat.

3.7 Air-density estimation

Temperature in kelvin is $T_K = T_C + 273.15$. Saturation vapour pressure e_s (hPa) was approximated with a Magnus-type expression, and vapour pressure $e = (RH/100) e_s$:

$$e_s = 6.112 \exp[17.67 T_C / (T_C + 243.5)] \quad (5)$$

$$\rho = (p - e)/(R_d T_K) + e/(R_v T_K) \quad (6)$$

where p and e are in Pa, $R_d = 287.05 \text{ J kg}^{-1} \text{ K}^{-1}$ and $R_v = 461.5 \text{ J kg}^{-1} \text{ K}^{-1}$. The constants in Eq. (5) are those of Bolton (1980).

The workbook contains no pressure data and reproduces Eq. (6) with $p = 101,325$ Pa, so density is a calculated quantity based on an assumed sea-level pressure; at about 490 m the pressure is roughly 5.7% lower. The same monthly T and RH are used for every year and for both observation times, so density has no interannual or diurnal variation.

3.8 Wind power density

$$\text{WPD} = \frac{1}{2} \rho V^3 \quad (7)$$

where WPD is in W m^{-2} , ρ in kg m^{-3} and V in m s^{-1} . For n valid records the mean is $\text{WPD}_{\text{mean}} = (1/n) \sum \frac{1}{2} \rho_i V_i^3$, which differs from the value computed from mean speed.

3.9 Turbine power modelling

The reference turbine is hypothetical: rotor diameter $D = 90$ m, hub height 80 m, assumed constant $C_p = 0.45$, and cut-in, rated and cut-out speeds of 3, 12 and 25 m s^{-1} (Table 2). These are modelling assumptions, not the characteristics of an installed machine. The swept area and the kinetic and extracted power are

$$A = \pi D^2/4 \approx 6,361.73 \text{ m}^2 \quad (8)$$

$$P_{\text{wind}} = \frac{1}{2} \rho A V^3, P_{\text{aero}} = P_{\text{wind}} C_p \quad (9)$$

where A is in m^2 and D in m. A fixed C_p is a simplification of a real, speed-dependent coefficient (Gottschall and Peinke, 2008; Lee et al., 2020), and P_{aero} is not electrical power.

3.10 Performance and loss modelling

A single fractional loss allowance $L = 0.15$ is applied once to P_{aero} . It is an assumption and not a measured loss from turbulence, wake, electrical conversion or availability:

$$P_{\text{net,mod}} = \min[(1 - L) P_{\text{aero}}, P_{\text{rated}}] \quad (10)$$

for $V_{ci} \leq V < V_{co}$; $P_{\text{net,mod}} = 0$ otherwise

$P_{\text{net,mod}}$ is modelled power, not measured output. The rated plateau is inactive in the base case because no record reached V_{rated} ; the workbook values used for the base case contain no plateau term. The nominal rated power and capacity factor are defined from the same model:

$$P_{\text{rated}} = \frac{1}{2} \rho_{\text{std}} A V_{\text{rated}}^3 C_p (1 - L) \approx 2,575 \text{ kW} \quad (11)$$

$$\text{CF} = \text{mean}(P_{\text{net,mod}}) / P_{\text{rated}} \quad (12)$$

with $\rho_{\text{std}} = 1.225 \text{ kg m}^{-3}$. P_{rated} is a conventional denominator derived from the model and is not a manufacturer rating, so CF is a ratio of two modelled quantities and is not comparable with measured capacity factors. Energy is $E = \sum P_i \Delta t_i$ (kWh), using each valid monthly value times the hours in the calendar month (February = 28 days). This assumes the monthly value represents the whole month, which is a strong assumption.

3.11 Statistical analysis

Trends in annual mean speed (years with at least six valid months) were estimated by ordinary least squares, Kendall's τ (Mann, 1945) and the Theil–Sen slope (Sen, 1968). Rank methods were used because speeds are skewed and contain outliers. The evening–morning difference was tested with a paired Wilcoxon signed-rank test (Wilcoxon, 1945). Associations between speed, temperature, humidity, density and modelled power were measured with Spearman's ρ_s . Consecutive months are serially dependent, and temperature, humidity and density are repeated monthly values, so p -values are descriptive and are not evidence of independent effects. Computations used Python (pandas, NumPy, SciPy, Matplotlib; Virtanen et al., 2020; Hunter, 2007).

3.12 Sensitivity analysis

The mean modelled power was recomputed with one assumption changed at a time: shear ($\alpha = 0.10, 1/7, 0.20$ from 10 m to 80 m, with power above 12 m s⁻¹ capped at rated), C_p (0.35, 0.50), L (0.10, 0.25), air density scaled to $p \approx 95.5$ kPa, and cut-in speed (2.0, 2.5 m s⁻¹).

3.13 Model evaluation

No measured turbine or SCADA output is available, so predictive accuracy (R^2 , MAE, RMSE) cannot be reported and none is claimed. Evaluation is limited to internal reproducibility (recalculation of every derived workbook column) and to a qualitative comparison with published studies. A hold-out or measured-data validation remains future work.

4. Results

All power and energy values are model estimates for the reference turbine, with speeds used as supplied ($\alpha = 0$). “Morning” and “evening” denote the 08:00 and 17:00 series. Tables 1–9 and Figures 1–14 are at the end of the manuscript.

4.1 Data completeness and descriptive statistics

Valid records number 645 (94.3%) at 08:00 and 633 (92.5%) at 17:00. Temperature, relative humidity and density take only twelve distinct values, one per calendar month (mean T 25.2 °C, mean RH 49.1%, mean p 1.177 kg m⁻³, range 1.119–1.234 kg m⁻³). Evening winds were stronger: the evening mean was 1.39 times the morning mean, the evening value exceeded the morning value in 66% of the 633 months valid in both series, and a paired Wilcoxon test gave $p < 0.001$ (Table 3). Morning speeds never exceeded 3.96 m s⁻¹, whereas the evening series reached 10.60 m s⁻¹ in June 2009 (WPD 672 W m⁻²). The mean of V^3 exceeded the cube of the mean speed by factors of 1.66 (morning) and 2.14 (evening).

4.2 Temporal variation

Long-term. The 12-month rolling mean of both series falls from the 1960s to a minimum in the 1990s and then rises; 2009–2010 stands out (Figs. 1 and 3). Sub-period evening means fall from 2.61 m s⁻¹ (1954–1959) to 1.49 m s⁻¹ (1990–1999, WPD 4.6 W m⁻²) and rise to 2.47 m s⁻¹ (2000–2010, WPD 26.5 W m⁻²). In the morning series the 1980s and 1990s yield no modelled generation. Annual trends are given in Table 4. The morning decline (annual means from about 2.1 m s⁻¹ in the 1960s to below 1 m s⁻¹ in the 1990s) is too large to attribute to climate without station metadata; instrument replacement, a change in anemometer exposure or a change in observing practice cannot be excluded.

Level shift. The last 23 valid months (2009–2010) average 2.45 m s⁻¹ (morning) and 4.12 m s⁻¹ (evening), against 1.56 and 2.15 m s⁻¹ for 1954–2008 and 0.97 and 1.96 m s⁻¹ for 1996–2008. These months (3.4% of the records) supply 36.9% (morning) and 30.7% (evening) of the total estimated energy. They are flagged and not corrected.

Seasonal. The two times have opposite seasonal behaviour (Table 5, Fig. 4). At 17:00 the speed is highest in summer (June mean 3.60 m s⁻¹, WPD 45.7 W m⁻²; May–August above 2.6 m s⁻¹) and below 1 m s⁻¹ in November and December. The share of months at or above cut-in rises from about 2% in January to 64% in June and is zero from October to December. At 08:00 the monthly means vary between 1.09 m s⁻¹ (August) and 1.93 m s⁻¹ (February) and never approach cut-in.

4.3 Wind-speed distribution and direction

The Weibull fits (Table 6, Fig. 6) reproduce the mean speed and WPD closely, but they overestimate the probability of exceeding cut-in (3.8% vs 2.5% at 08:00 and 24.8% vs 22.4% at 17:00), so the upper tail is not well represented. At 08:00, 77.8% of records come from the NW octant (circular mean 323°, $R = 0.79$). At 17:00, 68.5% come from the NE, E and SE octants (circular mean 87°, $R = 0.46$; Fig. 7). The near-reversal suggests a diurnal flow pattern whose cause was not tested.

4.4 Environmental parameters and air density

Temperature ranges from 12 °C (January) to 38 °C (July), relative humidity from 32% (June) to 62% (January, August) and calculated density from 1.234 kg m⁻³ (January) to 1.119 kg m⁻³ (July), a seasonal reduction of 9.3% (Fig. 8). These values repeat every year, so interannual changes in WPD and power arise from wind speed alone. Using monthly density instead of a constant 1.225 kg m⁻³ lowers the mean WPD by 3.2% (morning) and 6.1% (evening).

4.5 Wind power density, modelled power and energy

The modelled net power is zero in 97.5% (08:00) and 77.6% (17:00) of months (Table 7, Fig. 10). The morning series generates in at least one month in only 10 of 55 years with valid data, and the evening series in 46 of 54. Energy is dominated by few months: June 2009 supplies 10.7% of the evening total, the five highest months 20.7% and the ten highest 30.8%; May–August account for 78.7% of the evening energy (Figs. 11 and 12). The highest annual value is 2,881 MWh yr⁻¹ in 2009, almost four times the next (732 MWh yr⁻¹ in 2010). The two series are alternative estimates for the same months and are not combined. The long-term means drawn in Fig. 11 (11.9 and 213.3 MWh yr⁻¹) differ slightly from the Table 7 values because they average years with at least six valid months.

4.6 Association between environmental variables and modelled output

The correlation of speed with WPD and P_{wind} is mathematical, since speed is an input (Table 8, Fig. 13). The correlation of speed with $P_{\text{net,mod}}$ is 0.73 (evening) and 0.27 (morning, where almost all values are zero). Correlations with temperature, humidity and density have opposite signs at the two times and describe the coincidence of seasonal cycles; they do not indicate causation, and density is calculated from temperature and humidity, so independent effects cannot be separated.

4.7 Sensitivity to model assumptions

Hub-height extrapolation and cut-in speed dominate (Table 9, Fig. 14). Under the most favourable tested scenario ($\alpha = 0.20$) the evening capacity factor is 4.0%. Across the tested shear range the modelled evening annual energy is 462–901 MWh yr⁻¹, against 208 MWh yr⁻¹ in the base case. Two further analyses are still needed: results with and without 2009–2010, and a seasonally balanced annual-mean trend.

5. Discussion

What the data show. The Kohat workbook describes a weak resource. Mean speeds of 1.6–2.2 m s⁻¹ and mean WPD of 4–13 W m⁻² are far below the speeds at which a turbine with a 3 m s⁻¹ cut-in generates for much of the time, so the modelled output is zero in most months. Generation is a summer-evening phenomenon (May–August at 17:00), consistent with the opposite seasonal behaviour of the two series. Because power scales with V^3 , the few months above 5 m s⁻¹ carry a large share of the energy, and the Weibull tail mismatch means that fitted distributions would overstate the generating fraction.

Role of environmental variables. Density varies by 9.3% over the year, but its influence is small compared with the cubic dependence on speed: using monthly density instead of a constant value changes mean WPD by 3–6%, whereas the shear assumption changes modelled power by more than 100%. The speed–temperature–density correlations at 17:00 (0.53 and –0.49) show that the windiest months are the hottest and least dense. This is a seasonal coincidence in repeated monthly values and should not be read as a mechanism. Since the same T and RH apply to both times of day, the density penalty at 08:00 and 17:00 is not independent information, and the morning–evening difference arises from wind speed alone.

Long-term decline and 2009–2010 shift. Both are statistically visible but cannot be assigned a physical cause from this dataset. A decline of 0.2–0.3 m s⁻¹ per decade in the morning series is large compared with the decadal variability usually attributed to climate, and an abrupt rise in the last two years is typical of an instrument or practice change. These are hypotheses; the data cannot discriminate between them. Until metadata are checked, totals and annual energy should be

quoted with and without 2009–2010.

Comparison with published studies. The values are low even compared with other low-wind Pakistani sites. Tahir et al. (2025) report a mean speed of 3.09 m s^{-1} at 80 m and WPD of 33 W m^{-2} at 50 m for Peshawar, both in the lowest class, and Sumair et al. (2021a) report $3.6\text{--}4.4 \text{ m s}^{-1}$ at 50 m for southern Punjab.

The speeds here are not height-adjusted and cover a different period, so the comparison is qualitative. The conclusion also agrees with Tahir et al. (2025) on the benefit of a low cut-in speed, which matches the large sensitivity to cut-in found here.

Practical implications. A turbine of the assumed type would operate rarely at the supplied speeds. Even with $\alpha = 0.20$ the evening capacity factor is only 4.0%, far below the values usually sought for commercial wind projects.

The conclusion that Kohat is a low-wind site on this dataset is therefore robust to the assumptions tested, whereas the numerical energy values are not. The most useful next step is hub-height measurement, not further refinement of this model.

6. Limitations

- **Dataset.** Provenance, instrument, anemometer height, time standard and the meaning of the monthly value are unknown. A long record does not guarantee homogeneity, and two features (the 1980s–1990s decline and the 2009–2010 shift) suggest inhomogeneity. Two observations per day do not represent the diurnal cycle, turbulence or short-term variability.
- **Environmental inputs.** Temperature and humidity are a monthly climatology repeated every year and used for both times of day. Pressure is fixed at the standard sea-level value, roughly 5.7% above the expected site value.
- **Model.** The turbine is hypothetical with constant C_p , a step at cut-in and a single assumed 15% loss. $P_{\text{net,mod}}$ is not measured power; P_{rated} is a model-defined denominator and CF is not a measured capacity factor. Energy assumes that one monthly value represents the whole month.
- **Hub-height speed.** Speeds were used as supplied ($\alpha = 0$). Shear scenarios assume 10 m measurements, which is itself an assumption.

- **Statistics.** Trend and correlation p-values are descriptive because of serial dependence and repeated monthly values; the Kolmogorov–Smirnov statistic uses fitted parameters.

- **Validation.** No SCADA, measured power or independent resource data were used.

Future work should verify the station metadata, replace the base case by a documented shear exponent and station pressure, use a manufacturer power curve, test homogeneity, use higher-resolution data and compare with Peshawar and other stations.

7. Conclusion

This study used a monthly Kohat dataset (1954–2010) of uncertain provenance and a hypothetical reference turbine to estimate wind-energy potential and to test which assumptions control the result. Mean speeds were 1.59 m s^{-1} (08:00) and 2.22 m s^{-1} (17:00), mean WPD was 3.97 and 13.43 W m^{-2} , and the 3 m s^{-1} cut-in was reached in 2.5% and 22.4% of valid months. With speeds as supplied, modelled mean net power was 1.32 and 23.75 kW (CF 0.05% and 0.92% of a model-defined 2,575 kW), concentrated in May–August at 17:00. Annual means decline over the record and a level shift in 2009–2010 carries 31–37% of the estimated energy; both need metadata checks. Hub-height extrapolation and cut-in speed dominate the uncertainty, while C_p , loss allowance and density scale the output proportionally. Even the most favourable tested scenario gives a capacity factor of about 4%. On this dataset Kohat is a low-wind site; the numbers are model estimates, not measured turbine performance, and they should be validated with hub-height measurements.

Data availability statement

The analysed workbook is an attributed, non-public historical dataset for Kohat (1954–2010). The workbook, variable definitions and calculation procedures are available from the author on reasonable request, subject to any restrictions of the data provider.

Code availability statement

The Python scripts (pandas, NumPy, SciPy, Matplotlib) used for recalculation and figures are available from the author on reasonable request.

Conflict of interest

The author declares no known financial or personal conflicts of interest.

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Tables

Table 1. Status of the workbook variables.

Variable	Status	How obtained
Wind speed (knots); direction	Observed (as supplied)	Direction as quadrant bearings (e.g. N40W) or compass codes (C = calm)
Temperature; relative humidity	Supplied	Identical for a given calendar month in every year (monthly climatology)
Hub-height speed	Derived	Speed in knots $\times 0.5144 \text{ m s}^{-1}$; no height correction
Air density	Derived	Eq. (6) with T, RH and fixed $p = 101,325 \text{ Pa}$
WPD, P_{aero}	Derived	Eqs. (7) and (9), $A = 6,361.73 \text{ m}^2$, $C_p = 0.45$
$P_{\text{net,mod}}$ (workbook: "actual power")	Derived, modelled	0 below 3 m s^{-1} ; $0.85 \times P_{\text{aero}}$ otherwise
Energy; modelled loss and non-operation	Derived	$E = P_{\text{net,mod}} \times \text{hours in month (February = 28 days)}$; $\text{loss} = P_{\text{aero}} - P_{\text{net,mod}}$

Table 2. Reference-turbine parameters (assumptions, not measured characteristics).

Parameter	Value
Rotor diameter D	90 m
Hub height h_h	80 m
Power coefficient C_p (assumed constant)	0.45
Loss allowance L (assumed)	0.15
Swept area A	$6,361.73 \text{ m}^2$
Cut-in / rated / cut-out speed	$3 / 12 / 25 \text{ m s}^{-1}$
Nominal rated power P_{rated} (Eq. 11)	2,575 kW

Table 3. Descriptive statistics of valid records (minimum values omitted; $P_{\text{net,mod}}$ is zero below cut-in).

Variable	Time	Mean	SD	Median	90th pct.	Max
Wind speed (m s^{-1})	08:00	1.59	0.73	1.59	2.57	3.96
	17:00	2.22	1.25	2.11	3.69	10.60
WPD (W m^{-2})	08:00	3.97	4.76	2.28	10.42	34.77
	17:00	13.43	33.56	5.68	29.19	672.04
P_{aero} (kW)	08:00	11.37	13.63	6.54	29.84	99.53
	17:00	38.45	96.08	16.26	83.57	1,923.90
$P_{\text{net,mod}}$ (kW)	08:00	1.32	8.47	0.00	0.00	84.60
	17:00	23.75	83.55	0.00	71.03	1,635.31

Table 4. Trend tests on annual mean wind speed (years with at least six valid months; p-values descriptive). R^2 of the OLS fits is 0.43 (08:00) and 0.04 (17:00).

Series	Years	OLS slope (m s^{-1} per decade)	p (OLS)	Kendall τ	p (τ)	Theil-Sen (m s^{-1} per decade)
08:00, 1954–2010	53	−0.224	< 0.001	−0.55	< 0.001	−0.270
17:00, 1954–2010	52	−0.076	0.173	−0.34	< 0.001	−0.162
08:00, excl. 2009–2010	–	−0.294	< 0.001	−0.64	< 0.001	–
17:00, excl. 2009–2010	–	−0.176	< 0.001	−0.45	< 0.001	–

Table 5. Seasonal means of speed V (m s^{-1}), WPD (W m^{-2}), modelled net power (kW) and share of months at or above cut-in.

Season	V 08:00	V 17:00	WPD 08:00	WPD 17:00	$P_{\text{net,mod}}$ 08:00	$P_{\text{net,mod}}$ 17:00	$\geq$ cut-in 08:00 (%)	$\geq$ cut-in 17:00 (%)
Winter (DJF)	1.68	1.46	4.9	4.2	1.7	3.5	3.1	3.8
Spring (MAM)	1.81	2.79	4.7	17.1	0.9	29.1	1.9	36.5
Summer (JJA)	1.28	3.10	2.2	28.1	0.9	58.7	1.2	44.7
Autumn (SON)	1.60	1.51	4.1	4.2	1.8	3.3	3.8	4.5

Table 6. Two-parameter Weibull fits (maximum likelihood) to positive wind speeds.

Quantity	08:00	17:00
Values fitted	645	629
Shape k	2.32	1.88
Scale c (m s^{-1})	1.80	2.51
Weibull / observed mean speed (m s^{-1})	1.59 / 1.59	2.23 / 2.22
Weibull / observed mean WPD (W m^{-2})	3.97 / 3.97	13.35 / 13.43
Kolmogorov–Smirnov statistic	0.042	0.039
$P(V \geq 3 \text{ m s}^{-1})$, Weibull / observed (%)	3.8 / 2.5	24.8 / 22.4

Table 7. Modelled power, energy and conventional capacity factor (model estimates; speeds as supplied, $\alpha = 0$).

Quantity	Unit	08:00	17:00
Mean WPD	W m^{-2}	3.97	13.43
Mean P_{wind}	kW	25.3	85.5
Mean P_{aero}	kW	11.37	38.45
Mean $P_{\text{net,mod}}$	kW	1.32	23.75
Months at or above cut-in	count (%)	16 (2.5)	142 (22.4)
Mean $P_{\text{net,mod}}$ in generating months	kW	53.4	105.9
Estimated annual energy (mean monthly energy $\times 12$)	MWh yr^{-1}	11.4	208.0
Total estimated energy, 1954–2010	MWh	614.3	10,970.6
Capacity factor ($P_{\text{rated}} = 2,575 \text{ kW}$)	%	0.05	0.92

Table 8. Spearman rank correlations between wind speed and other variables ($n = 645$ and 633 ; all $p < 0.001$, descriptive only because months are serially dependent).

Pair	ρ_s 08:00	ρ_s 17:00
Speed – temperature	−0.20	0.53
Speed – relative humidity	−0.14	−0.36
Speed – air density	0.22	−0.49
Speed – WPD	1.00	1.00
Speed – $P_{\text{net,mod}}$	0.27	0.73

Table 9. One-at-a-time sensitivity of modelled mean power (shear scenarios assume measurements at 10 m; densities scaled by the pressure ratio; power above 12 m s^{-1} capped at rated).

Scenario	Mean $P_{\text{net,mod}}$ 08:00 (kW)	Change	Mean $P_{\text{net,mod}}$ 17:00 (kW)	Change	Energy 17:00 (MWh yr^{-1})
Base case (as supplied)	1.32	–	23.7	–	208
Shear $\alpha = 0.10$ (from 10 m)	8.67	+555%	52.7	+122%	462
Shear $\alpha = 1/7$ (from 10 m)	14.27	+978%	70.2	+196%	615
Shear $\alpha = 0.20$ (from 10 m)	24.74	+1,769%	102.9	+333%	901
$C_p = 0.35$	1.03	–22%	18.5	–22%	162
$C_p = 0.50$	1.47	+11%	26.4	+11%	231
$L = 0.10$	1.40	+6%	25.1	+6%	220
$L = 0.25$	1.17	–12%	21.0	–12%	184
Density at $\approx 95.5 \text{ kPa}$	1.25	–6%	22.4	–6%	196
Cut-in 2.0 m s^{-1}	7.11	+437%	31.1	+31%	272
Cut-in 2.5 m s^{-1}	4.31	+225%	28.4	+20%	249

Figures

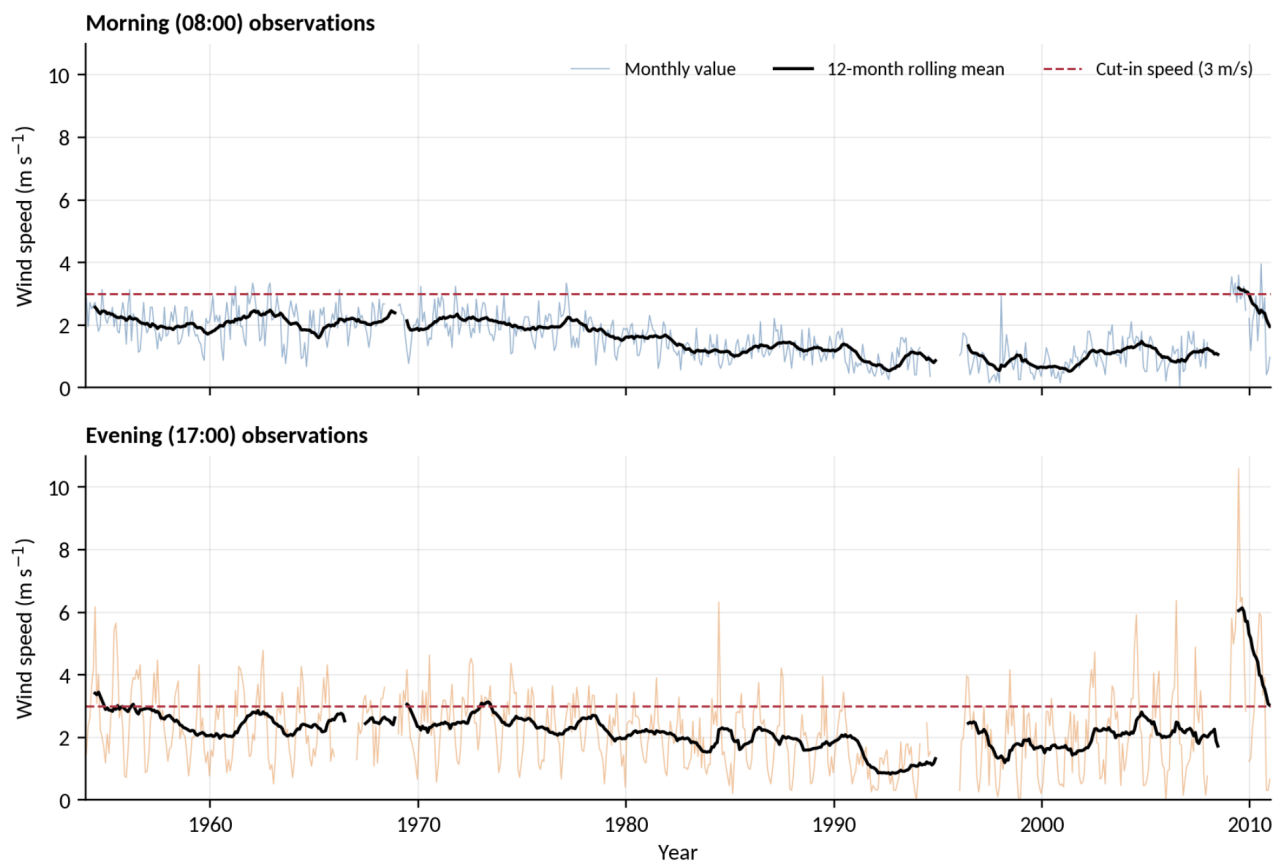


Figure 1. Monthly wind speed at 08:00 and 17:00, 1954–2010, with the 12-month rolling mean and the 3 m s^{-1} cut-in speed. Gaps are missing records.

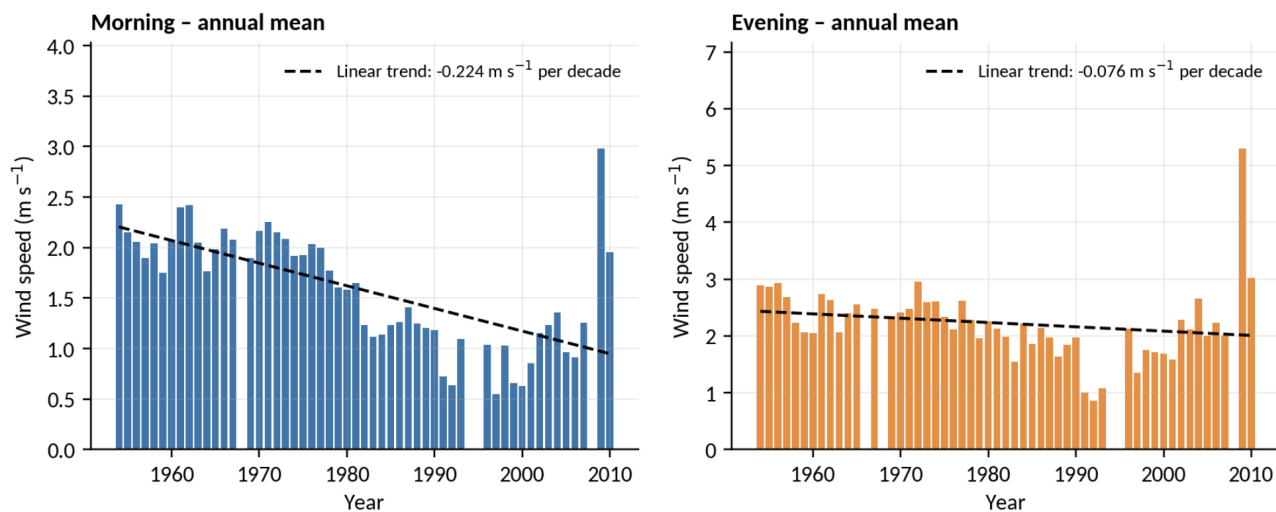


Figure 2. Annual mean wind speed (years with at least six valid months) with the least-squares trend line.

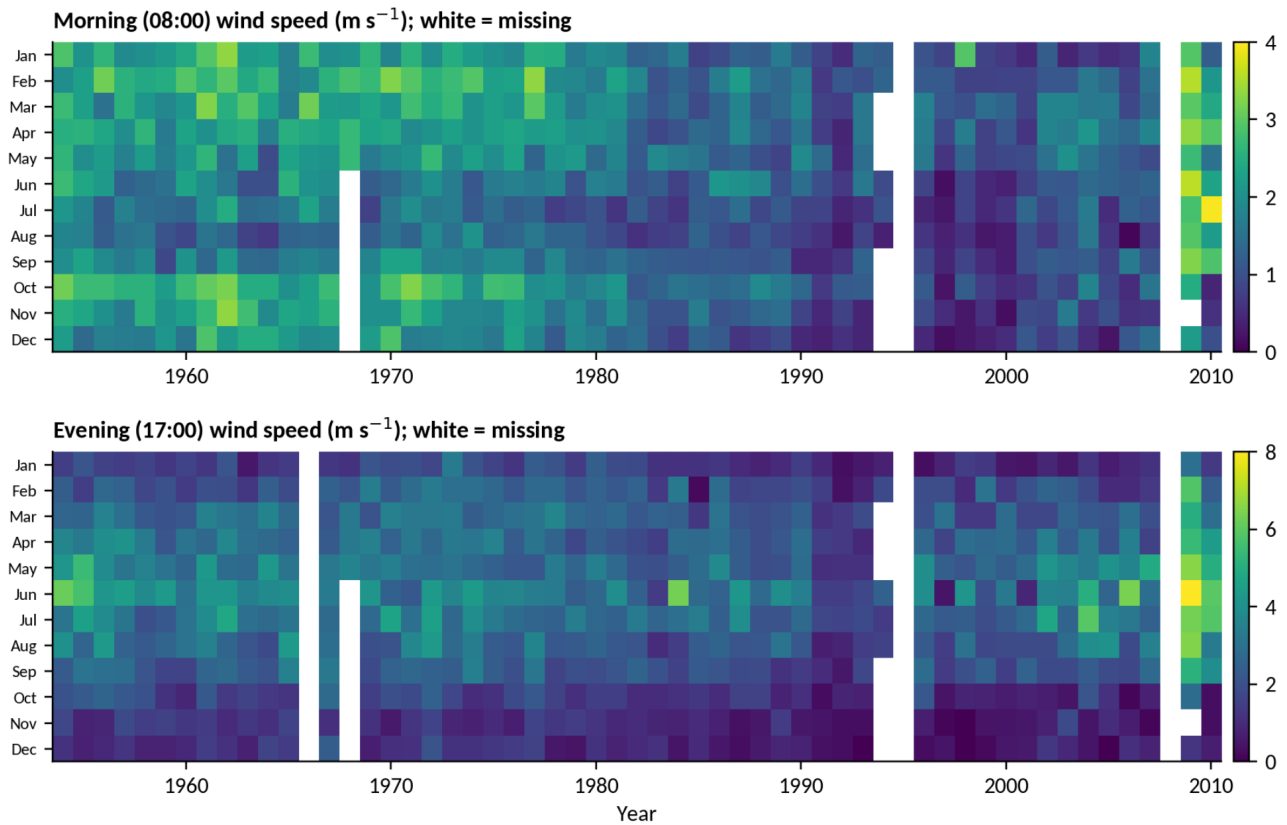


Figure 3. Wind speed by year and calendar month at 08:00 and 17:00 (white cells are missing records).

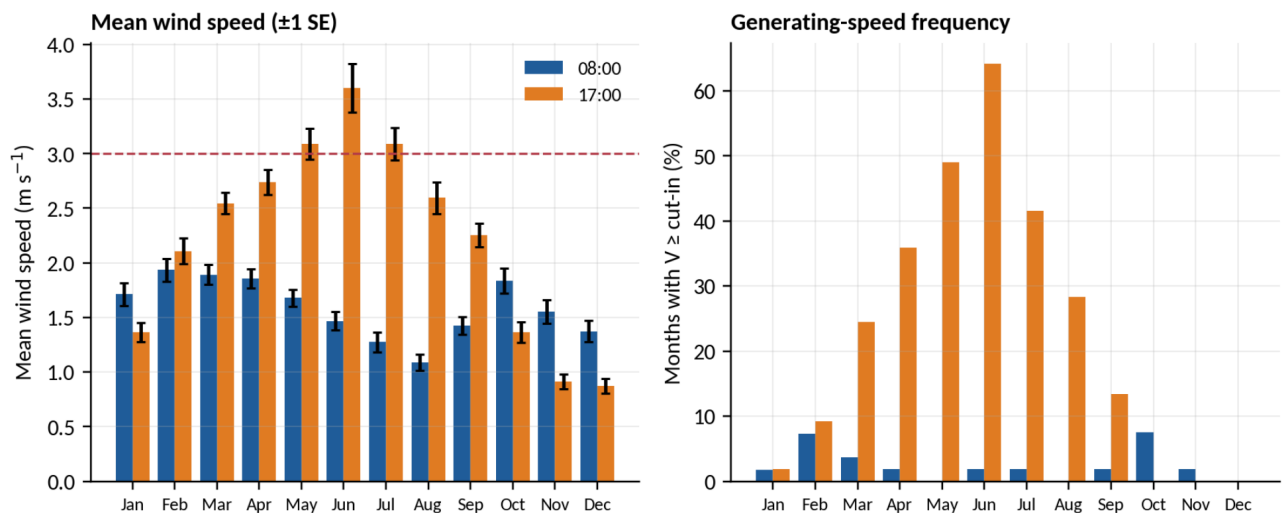


Figure 4. Monthly mean wind speed (error bars: ± 1 standard error) and percentage of months with wind speed at or above the 3 m s^{-1} cut-in.

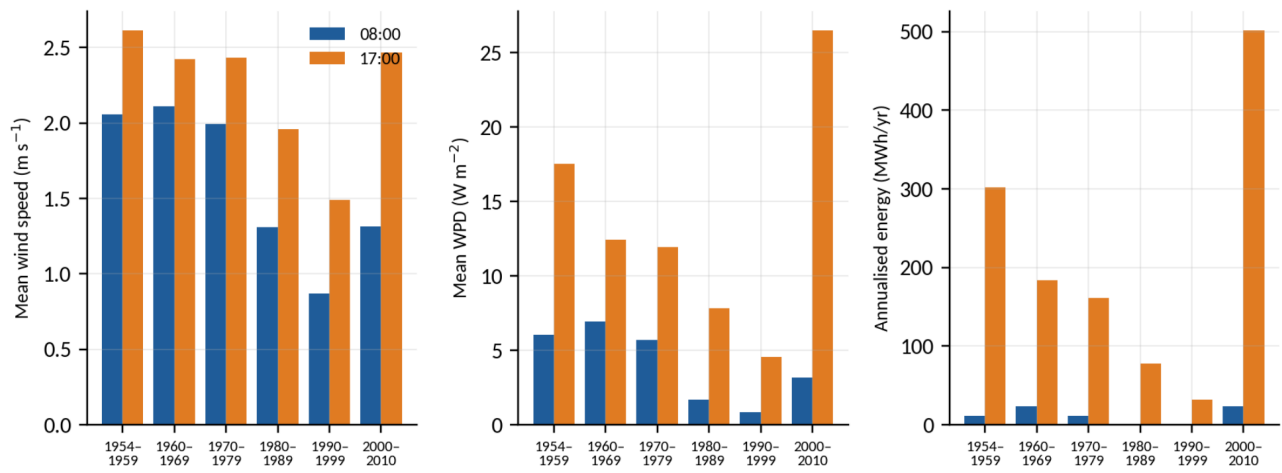


Figure 5. Sub-period comparison of mean wind speed, mean WPD and annualised estimated energy.

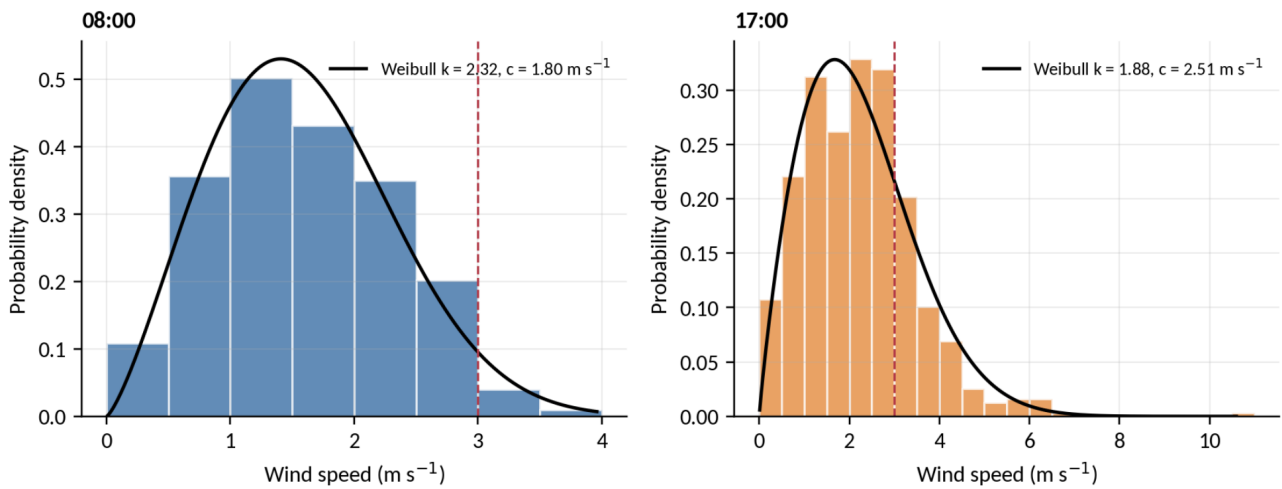


Figure 6. Histograms of wind speed (0.5 m s^{-1} bins) with fitted Weibull density and the cut-in speed (dashed).

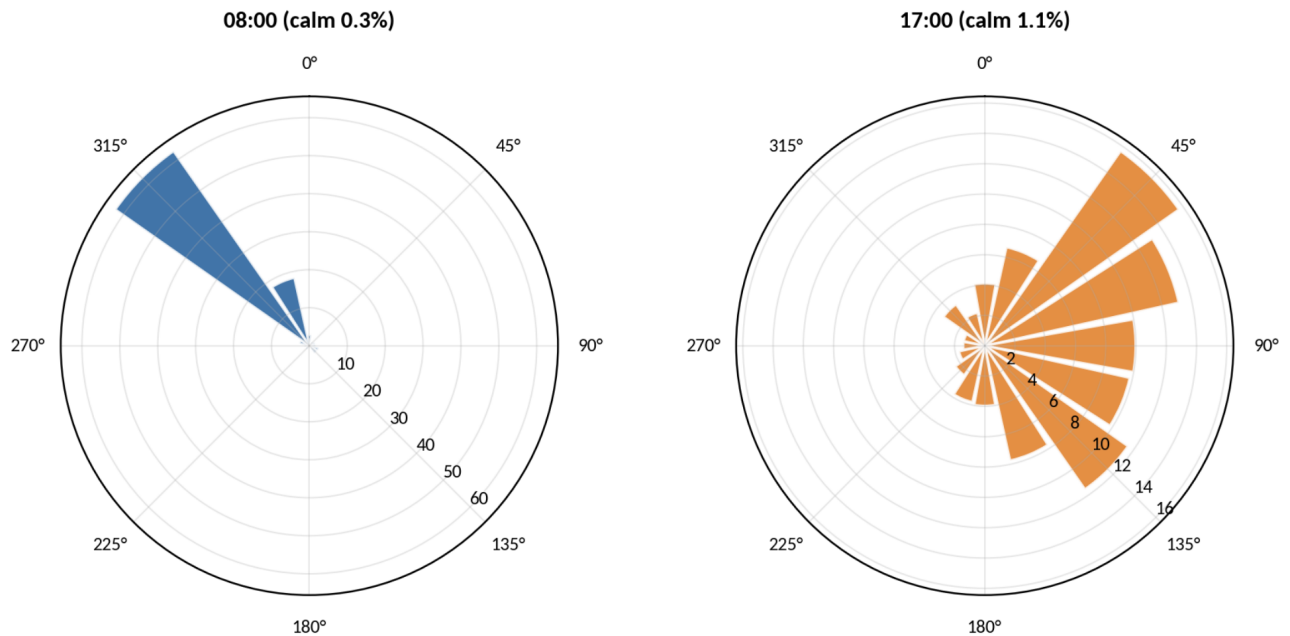


Figure 7. Wind roses (16 sectors of 22.5° , percentage of valid records) for the morning and evening observations.

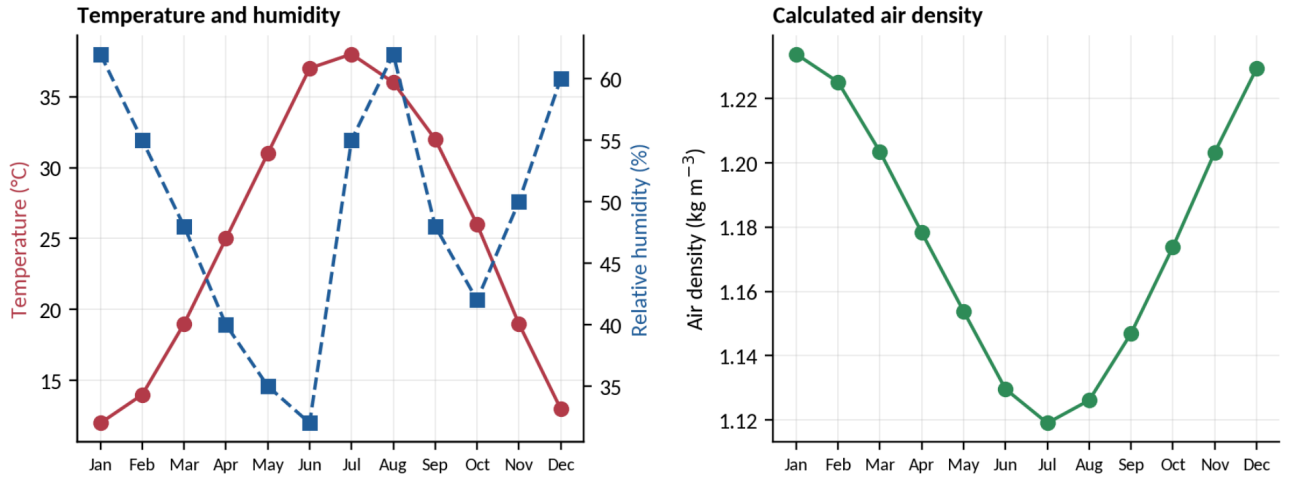


Figure 8. Monthly values of temperature, relative humidity and calculated air density (identical in every year of the dataset).

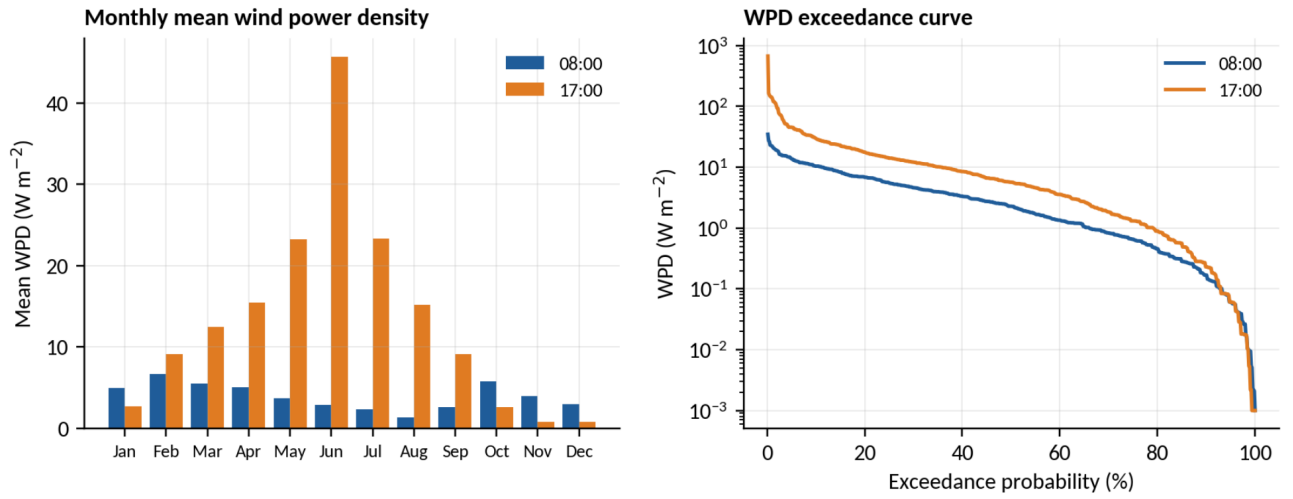


Figure 9. Monthly mean wind power density and WPD exceedance curve (logarithmic axis).

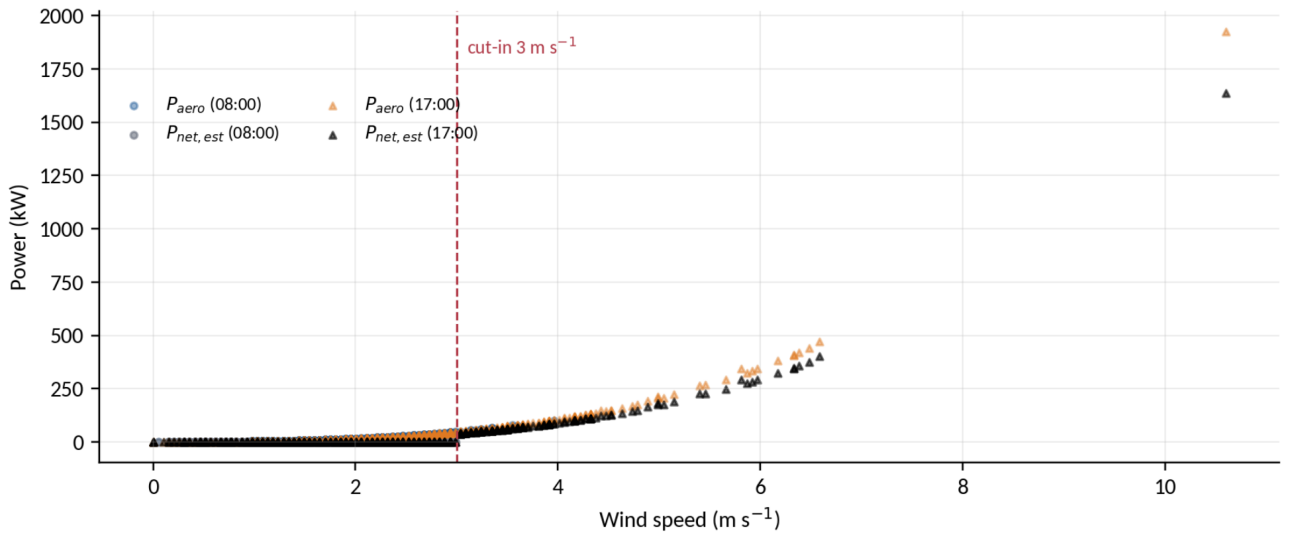


Figure 10. Aerodynamic power P_{aero} and modelled net power against wind speed for every valid monthly record (the legend label $P_{net,est}$ denotes $P_{net,mod}$ of the text). Net power is zero below the 3 m s⁻¹ cut-in and 0.85 P_{aero} above it.

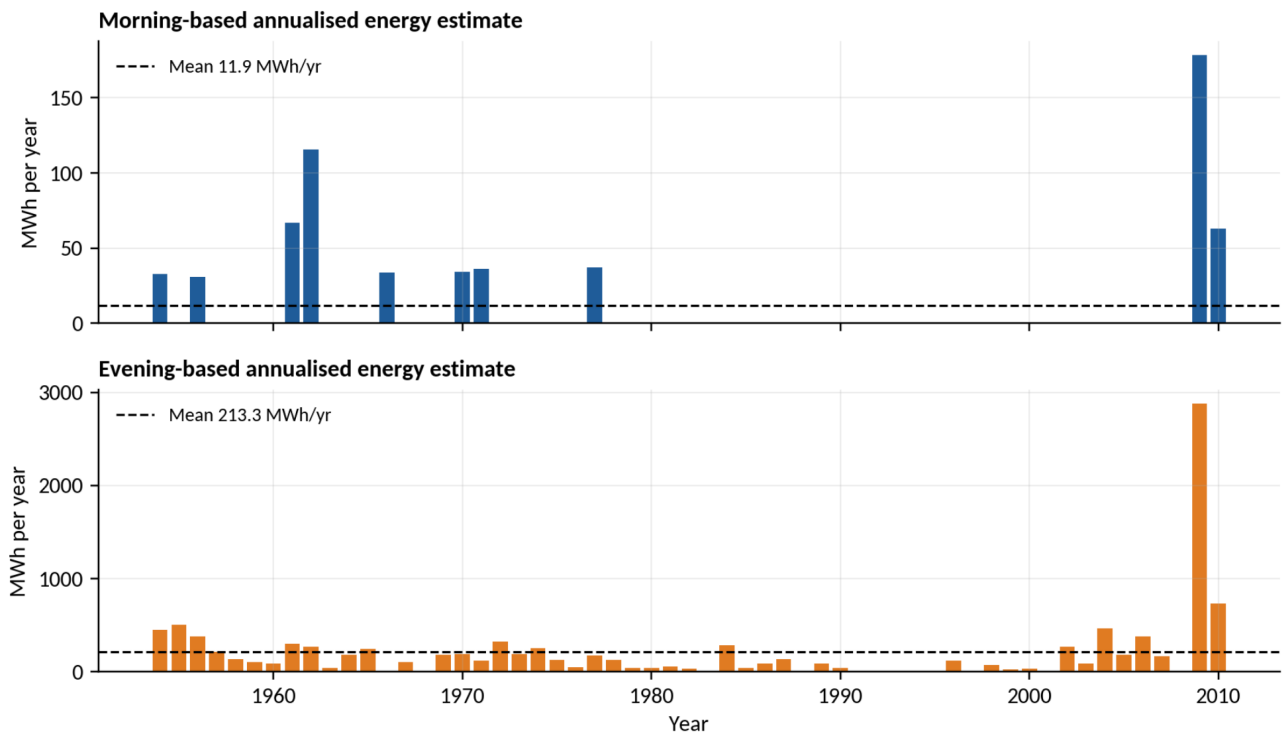


Figure 11. Annualised estimated energy (mean monthly energy $\times 12$) by year; the dashed line is the mean of the years shown. Years with fewer than six valid months are omitted.

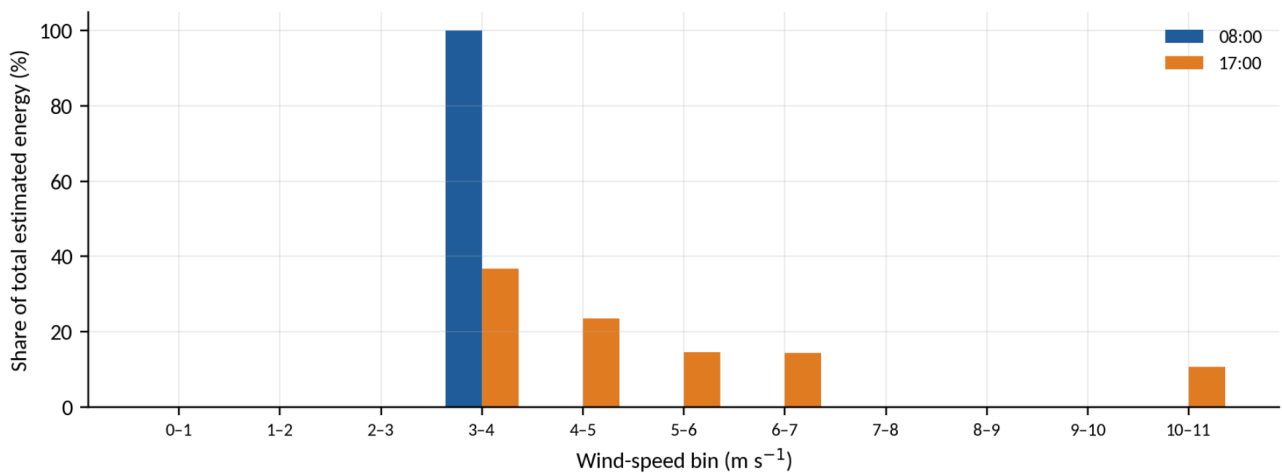


Figure 12. Share of total estimated energy by wind-speed class. Most energy comes from the few months with speeds above 5 m s^{-1} .

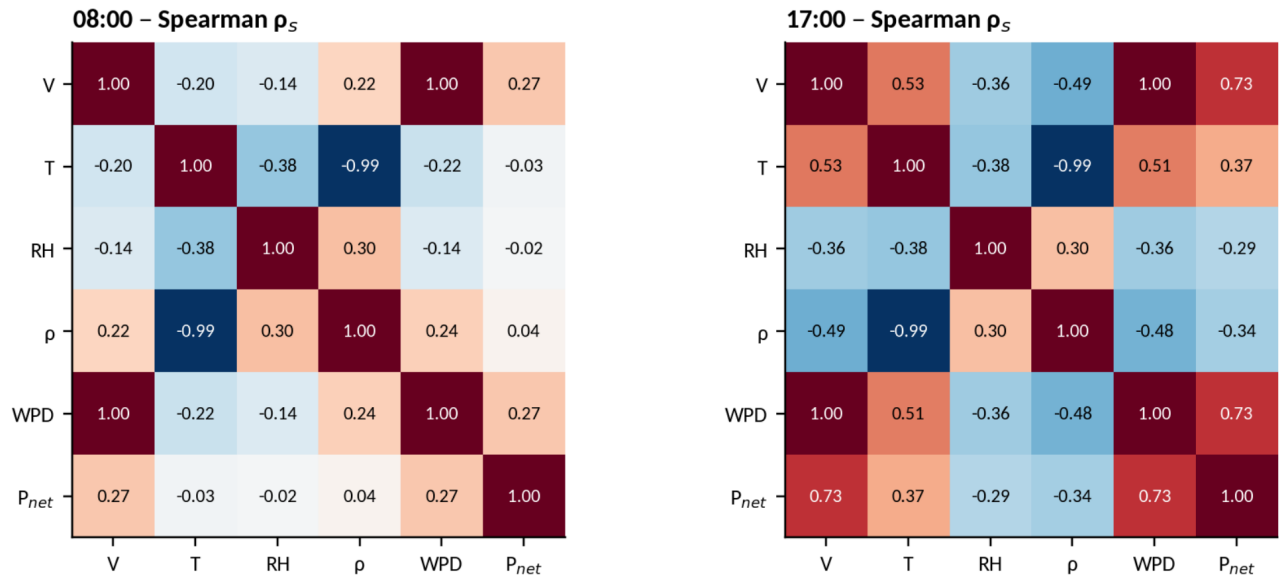


Figure 13. Spearman correlation matrices for the morning and evening series (V: wind speed, T: temperature, RH: relative humidity, ρ : air density, P_{net} : net power).

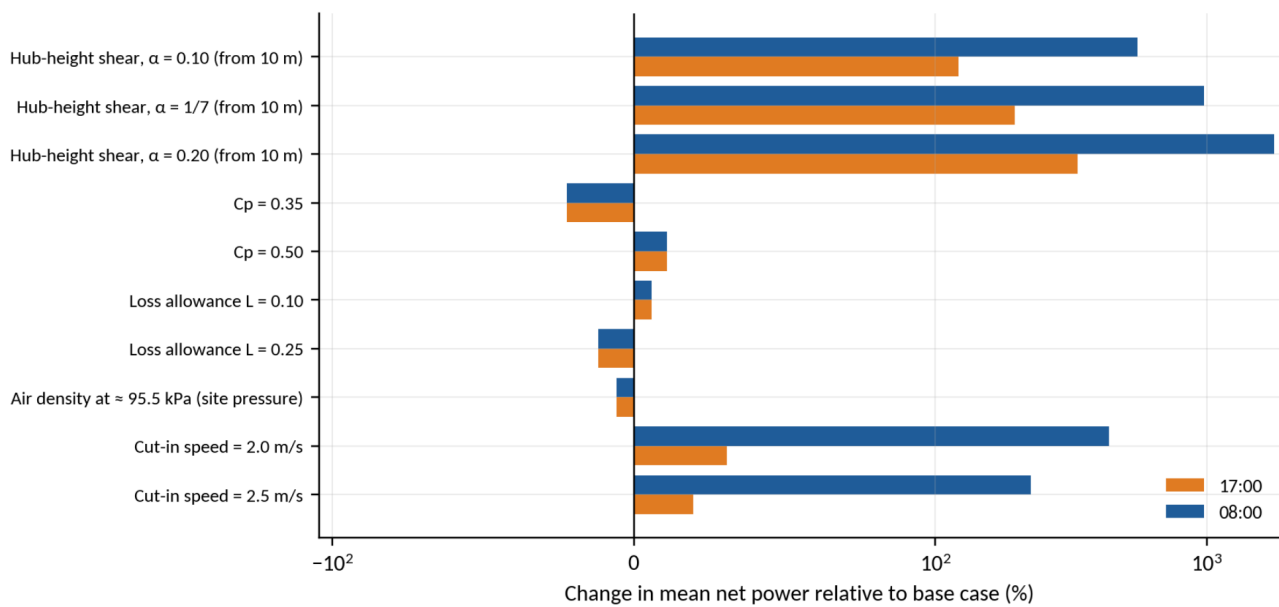


Figure 14. Change in mean modelled net power relative to the base case for each sensitivity scenario (symmetric logarithmic axis).