

Power Curve Turbulence Normalisation for Wind Resource Assessments

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Contents

- Turbulence normalisation of measured power curves according to draft of IEC 61400-12-1, Ed.2
- Application for wind resource assessments
- Pitfalls of procedure

Turbulence Normalisation of Power Curve Measurements (CD IEC 61400-12-2, Ed.2)

- Only effect of 10-minute averaging of power and wind speed data on measured power curve is considered
- Key assumption: turbine output follows instantaneous changes of wind speed, i.e. turbine always follows a certain power curve $P_{I=0}$:

$$\Rightarrow \text{mean power output over 10 min.: } P_{\text{simulated}} = \int_0^{\infty} P_{I=0}(v) f(v) dv$$

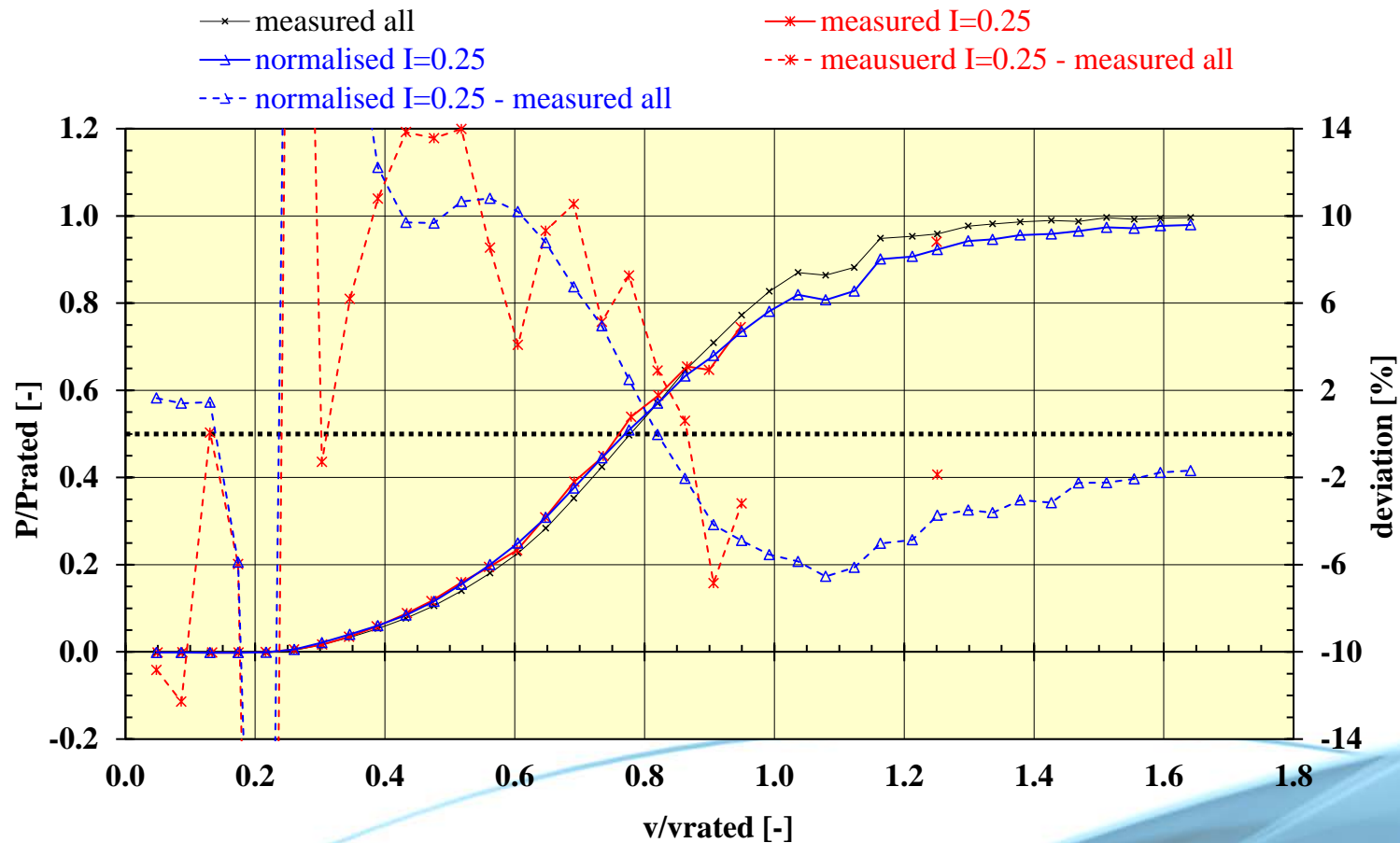
$f(v)$: wind speed distribution measured over 10 minutes, determined by $v_{H,\text{cup}}$ and I

$P_{I=0}$: Zero turbulence power curve (more later)

- Power curve normalisation to reference turbulence:

$$P_{\text{corrected}} = P_{\text{measured}, I\text{-measured}} - P_{\text{simulated}, I\text{-measured}} + P_{\text{simulated}, I\text{-reference}}$$

Examples of Turbulence Normalisations of Power Curve Measurements



- Increase of turbulence intensity leads to higher power at maximum c_p and lower power at knee of power curve

Examples of Turbulence Normalisations of Power Curve Measurements

- 2nd Example:
WT with 382W/m²

| I | cp_{max} | effect on cp_{max} | AEP/AEP_{I=10} v_{avg}=6.0m/s | AEP/AEP_{I=10} v_{avg}=7.5m/s | AEP/AEP_{I=10} v_{avg}=9.0m/s |
|----------|-------------------------|-----------------------------------|--|--|--|
| [%] | [-] | [%] | [-] | [-] | [-] |
| 0 | 0.450 | -2.9 | 0.998 | 1.006 | 1.008 |
| 5 | 0.454 | -2.2 | 0.999 | 1.005 | 1.007 |
| 10 | 0.464 | 0.0 | 1.000 | 1.000 | 1.000 |
| 15 | 0.480 | 3.6 | 1.002 | 0.993 | 0.990 |
| 20 | 0.504 | 8.7 | 1.006 | 0.985 | 0.977 |

Turbulence Correction in Case of Wind Resource Assessment (Time Series Approach)

- P is calculated for each 10-minute period:

$$P_{\text{corrected}} = P_{\text{given_PC,I-reference}}(v) - P_{\text{simulated,I-reference}}(v) + P_{\text{simulated,I-measured}}(v)$$

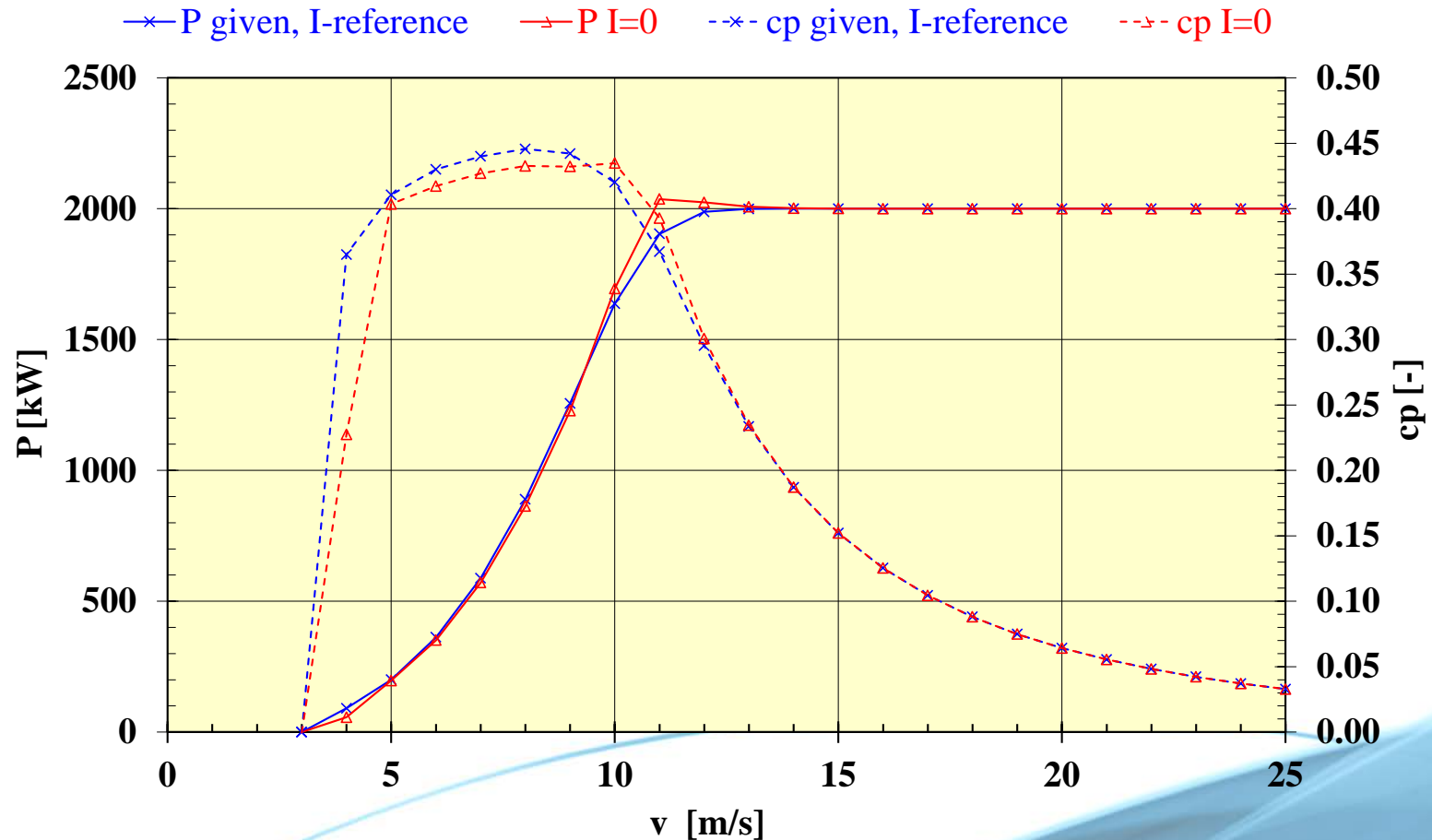
$$P_{\text{simulated}} = \int_0^{\infty} P_{I=0}(v) f(v) dv$$

where

- $P_{\text{given_PC,I-reference}}$: given power curve for reference turbulence
 v : 10-minute mean value of wind speed
 σ_v : standard deviation of wind speed within 10 min.
 $f(v)$: Gaussian distribution determined by v and σ_v

- Zero turbulence power curve $P_{I=0}$ is determined from given power curve under consideration of reference turbulence intensity

Zero Turbulence Power Curve



- $P_{I=0}$ (Zero turbulence power curve) is determined from $P_{\text{given_PC, I-reference}}$ according to the procedure outlined in CD IEC 61400-12-1

Combination of Rotor Equivalent Wind Speed and Turbulence Correction

- Rotor equivalent wind speed and turbulence correction are independent from each other
 - both methods can be combined
 - order of application does not matter (effects add linearly)
- Which v and σ_v is to be used if the given PC refers to the rotor equivalent wind speed?
 - Be **consistent**: v and σ_v used in $f(v)$ must match $P_{I=0}$
 - Don't apply $P_{I=0}$ referring to rotor equivalent wind speed (REWS) with HH wind speed when integrating over the Gaussian distribution! Instead use REWS!
 - Don't apply $P_{I=0}$ referring to HH wind speed with REWS. Instead use HH wind speed.

Times Series Approach, Case 1

- Given PC refers to:
 - rotor equivalent wind speed v_{eq}
 - a certain turbulence intensity I-ref
 - a certain air density, ρ -ref
- Consistent turbulence correction:
 - Derive zero turbulence power curve $P_{I=0}$ for rotor equivalent wind speed and for ρ -ref
 - Calculate I-measured from wind speed measurement at HH:

$$I_{\text{measured}} = \frac{\sigma_{v_{HH,\text{measured}}}}{V_{HH,\text{measured}}}$$

- apply Gaussian distribution with density corrected v_{eq} and adjusted σ_v :

$$\sigma_{v,\text{adjusted}} = I_{\text{measured}} v_{eq,\rho\text{-ref}}$$

Times Series Approach, Case 2

- Given PC refers to:
 - HH wind speed
 - a certain turbulence intensity I-ref
 - a certain air density, ρ -ref
- Consistent turbulence correction:
 - Derive zero turbulence power curve $P_{I=0}$ for HH wind speed and for ρ -ref
 - Calculate I-measured from wind speed measurement at HH:

$$I_{\text{measured}} = \frac{\sigma_{v_{\text{HH,measured}}}}{V_{\text{HH,measured}}}$$

- apply Gaussian distribution with density corrected v_{HH} and adjusted σ_v :

$$\sigma_{v,\text{adjusted}} = I_{\text{measured}} V_{\text{HH},\rho\text{-ref}}$$

Distribution Approach

- Bin measured turbulence intensity at HH against density corrected v (to which the given PC refers)
- Turbulence correct given PC bin by bin:

$$P_{\text{corrected}} = P_{\text{given_PC, I-reference}}(v) - P_{\text{simulated, I-reference}}(v) + P_{\text{simulated, I-measured}}(v)$$

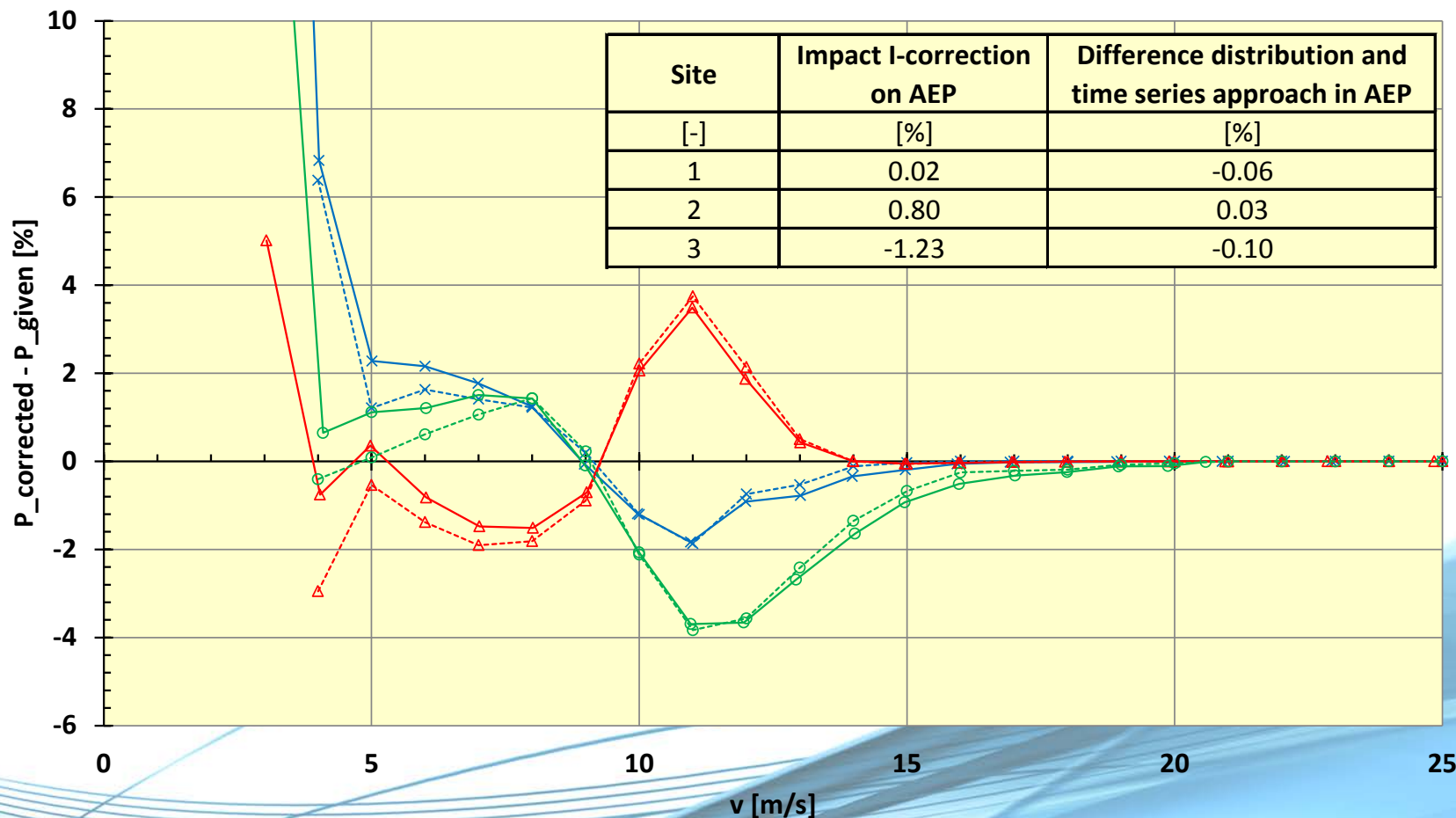
$$P_{\text{simulated}} = \int_0^{\infty} P_{I=0}(v) f(v) dv$$

where $f(v)$: Gaussian distribution determined by v and I
 v : bin averaged wind speed (to which given PC refers)
 I : bin averaged turbulence intensity
 $P_{I=0}$: zero turbulence power curve as determined from given PC and reference turbulence

- Use turbulence corrected PC for wind resource assessment

Example: 3 Round Robin Test Sites of EWEA Power Curve Expert Group

- x— site 1: I correction time series approach - -x- - site 1: I correction binned PC
- △— site 2: I correction time series approach - -△- - site 2: I correction binned PC
- site 3: I correction time series approach - -○- - site 3: I correction binned PC



Other Pitfalls

- Integrate over very large wind speed range, e.g. 0-100 m/s

$$P_{\text{simulated}} = \int_0^{\infty} P_{I=0}(v) f(v) dv$$

- not only over +/-5m/s around measured v!

- Use fine enough intervals for integration: $dv \leq 0.1 \text{ m/s}$
- Extend PC by power of highest bin to upper limit of integration
 - don't set power to zero at 25m/s!
- Consider site specific turbulence as function of wind speed:
 - don't consider just mean turbulence intensity at the site or normal turbulence model of IEC 61400-1!
- Leave zero turbulence power curve $P_{I=0}$ enough degrees of freedom:
 - follow 3-step process given in CD IEC 61400-12-1 strictly
 - don't determine $P_{I=0}$ by minimising sum of differences of given PC and simulated PC!

Conclusions

- Effect of 10-minute averaging explains a significant part of observed turbulence effects on power curves:
 - correction helps for wind resource assessments
 - but direct impact of I on turbine power not covered
 - Large deformations of power curves by turbulence effect
 - Often relative small impact on AEP as effects around maximum c_p and at knee of the PC partly cancel out
 - Turbulence correction and rotor equivalent wind speed can be combined linearly
 - Turbulence correction of binned power curve leads to same results as time series approach
 - Normalisation method given in CD of IEC 61400-12-1 is robust due to self-stabilising elements, despite simplifying assumptions
 - Normalisation method has many pitfalls, details given in CD of IEC 61400-12-1 important
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