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Power Curve Turbulence Normalisation for Wind Resource Assessments

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- 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 $P_{I=0}$:

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

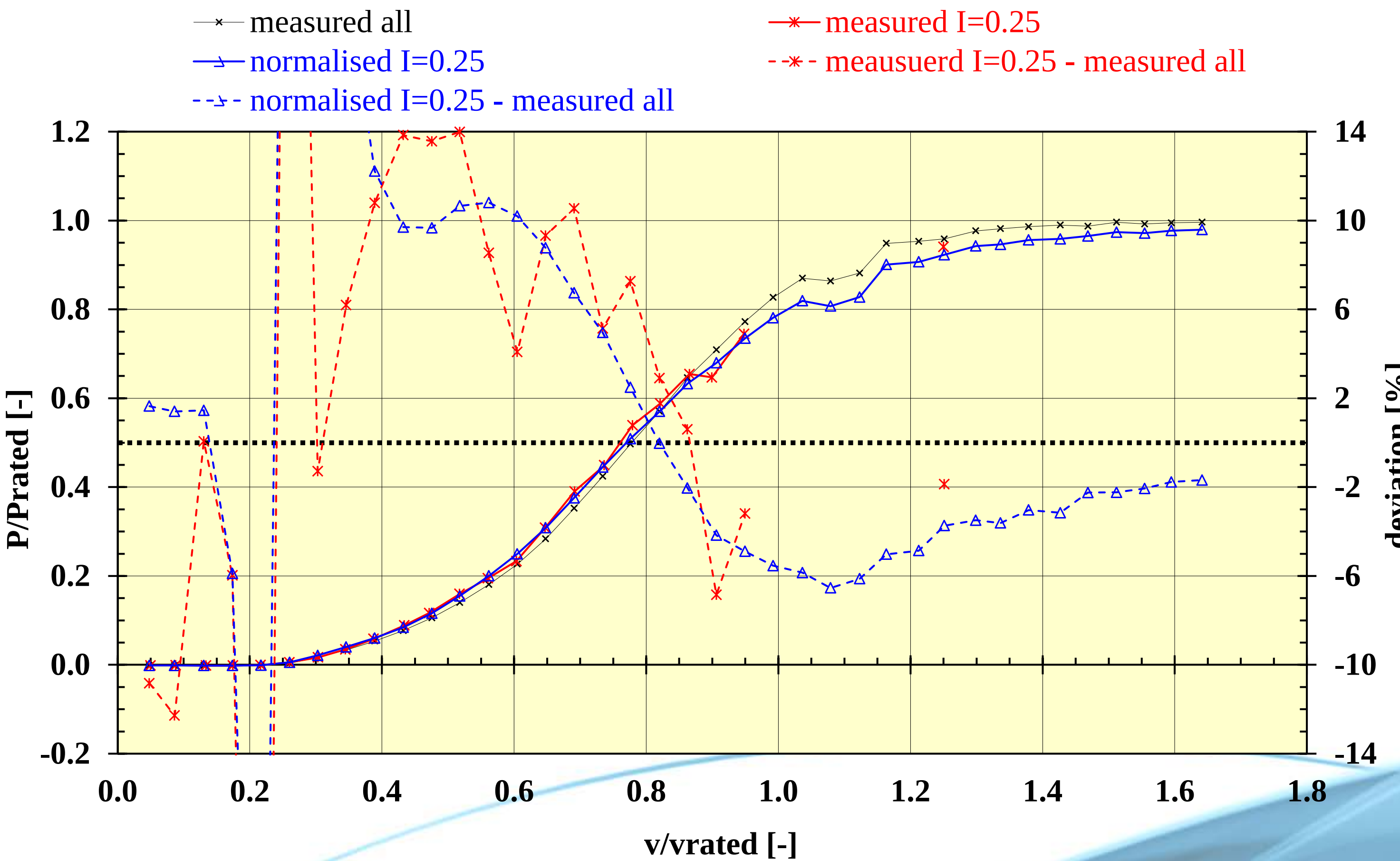
f(v): wind speed distribution measured over 10 minutes, determined by $v_{H,cup}$ and I

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

- Power curve normalisation to reference turbulence:

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

Examples of Turbulence Normalisations of Power Curve Measurements



mean measured turbulence intensity of all data about 0.15

- 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)

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- P is calculated for each 10-minute period:

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

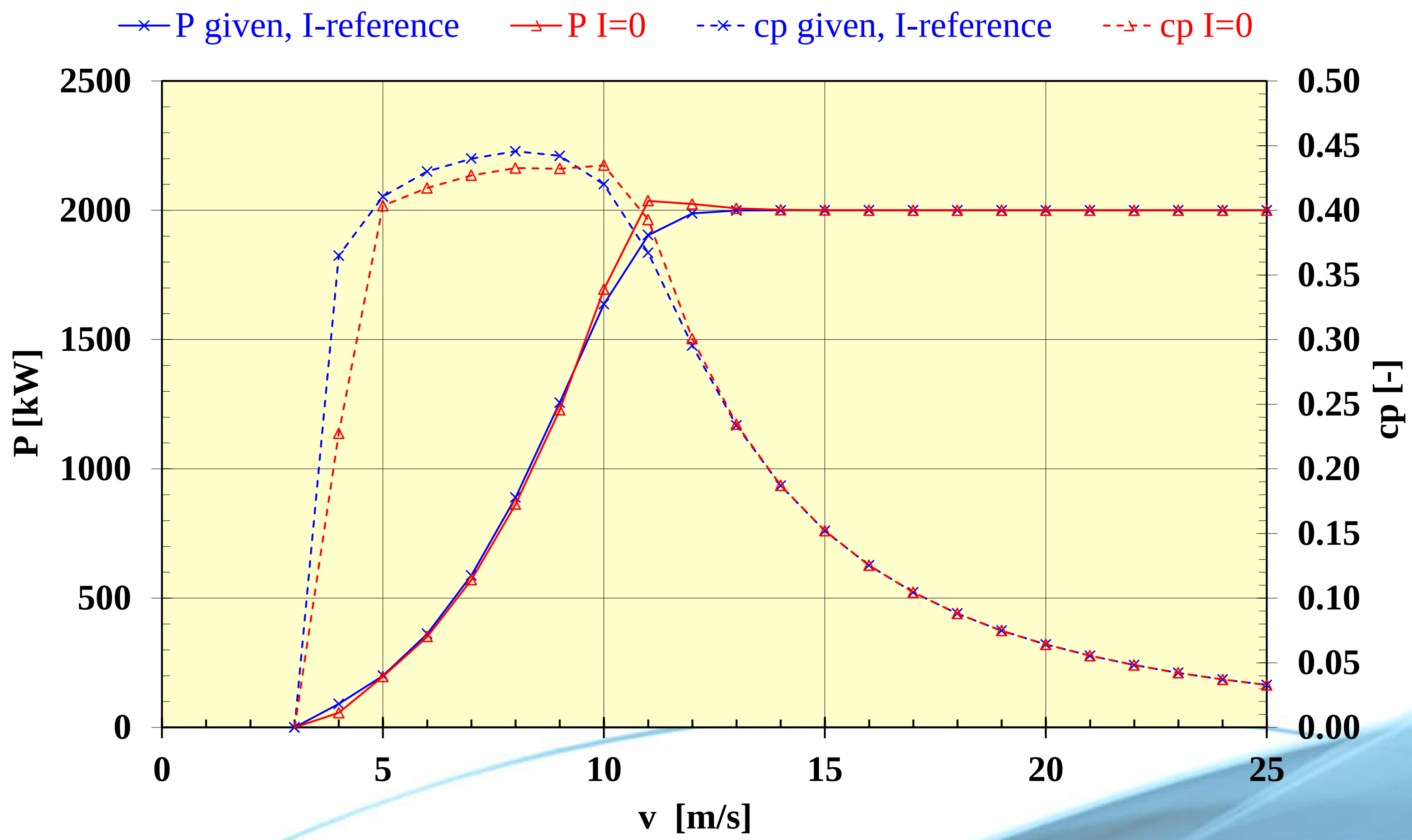
$$P_{simulated} = \int_0^\infty P_{I=0}(v) f(v) dv$$

where

$P_{given\_PC,I\text{-}reference}$:	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 $P_{given\_PC,I\text{-}reference}$ 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:

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

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

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

Times Series Approach, Case 2

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- 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:

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

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

where f(v): Gaussian distribution determined by v and I

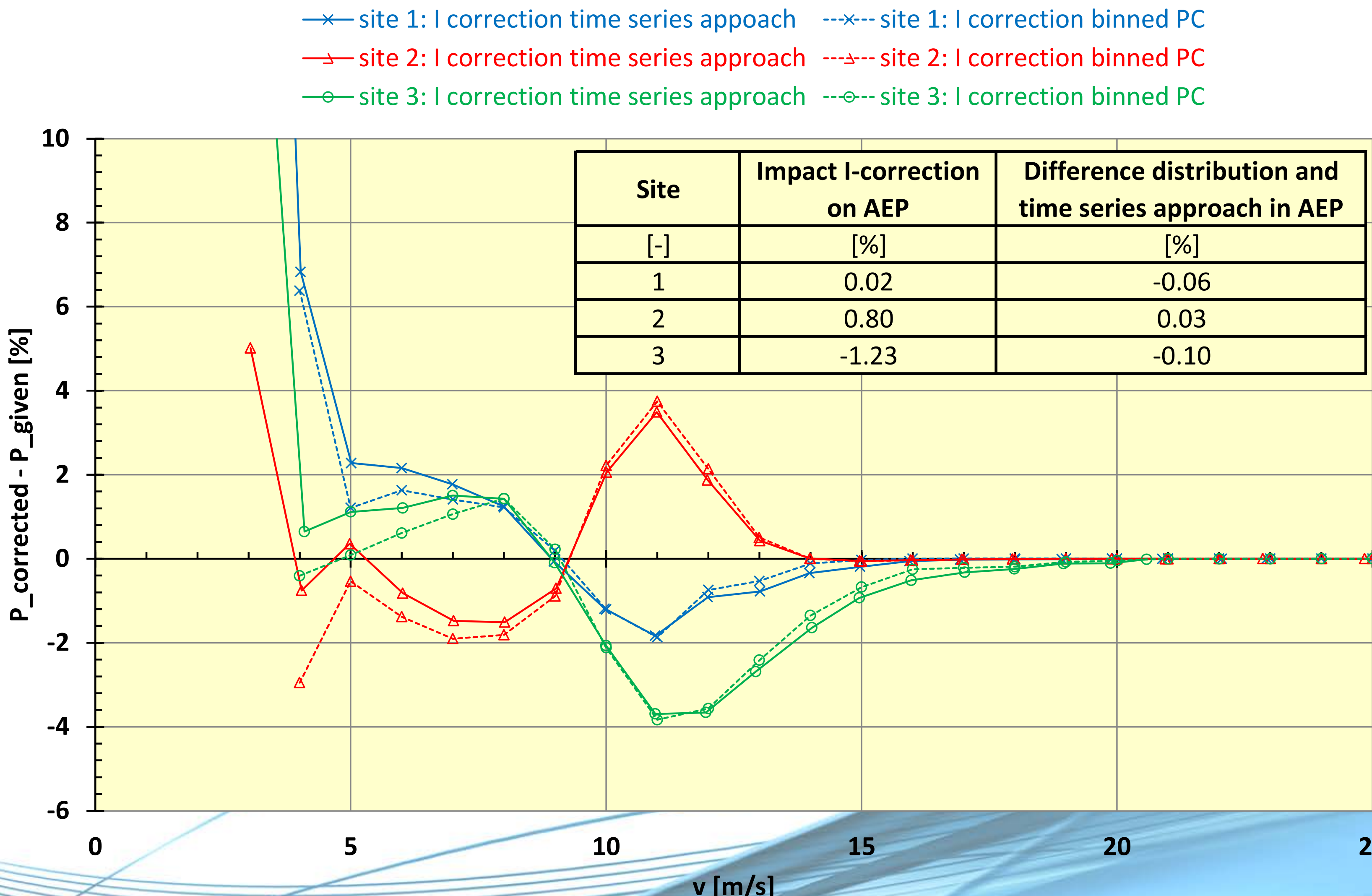
v: bin averaged wind speed (to which given PC refers)

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



Site	Impact I-correction on AEP	Difference distribution and time series approach in AEP
[-]	[%]	[%]
1	0.02	-0.06
2	0.80	0.03
3	-1.23	-0.10

Other Pitfalls

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

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

  - not only over +/-5m/s around measured v!
- Use fine enough intervals for integration: $dv \leq 0.1 m/s$
- 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