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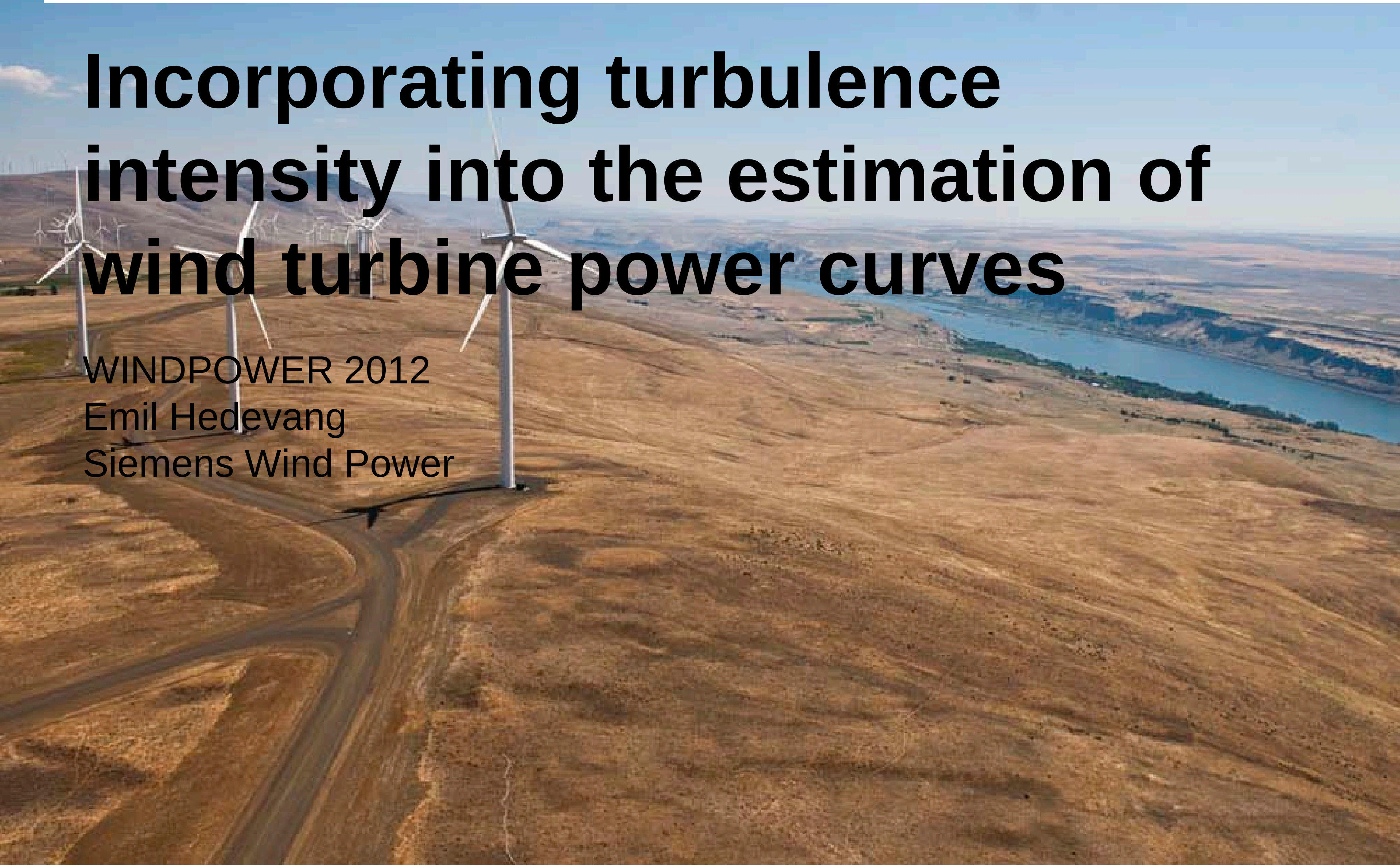
Incorporating turbulence intensity into the estimation of wind turbine power curves



WINDPOWER 2012
Emil Hedevang
Siemens Wind Power

Purpose: Reduce uncertainty

Uncertainty = Risk

- Did the wind turbine not produce as expected?
- Blame the wind turbine?
- Blame the wind?

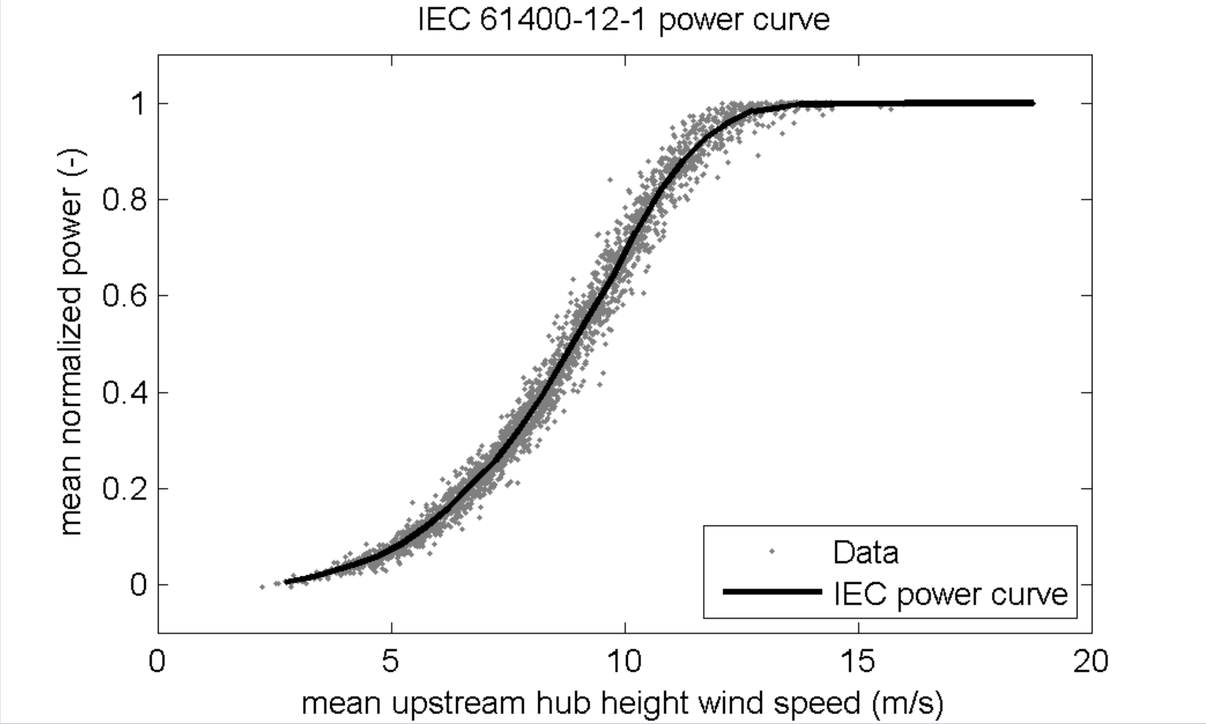
- Did the wind turbine produce as expected?
- How can you be sure?
- Was it a coincidence?

The problem with power curves

The notion of a power curve

The IEC 61400-12-1 power curve:
Mean power as a function of **mean hub height wind speed** corrected for **air density**

Estimation:
Method of binning



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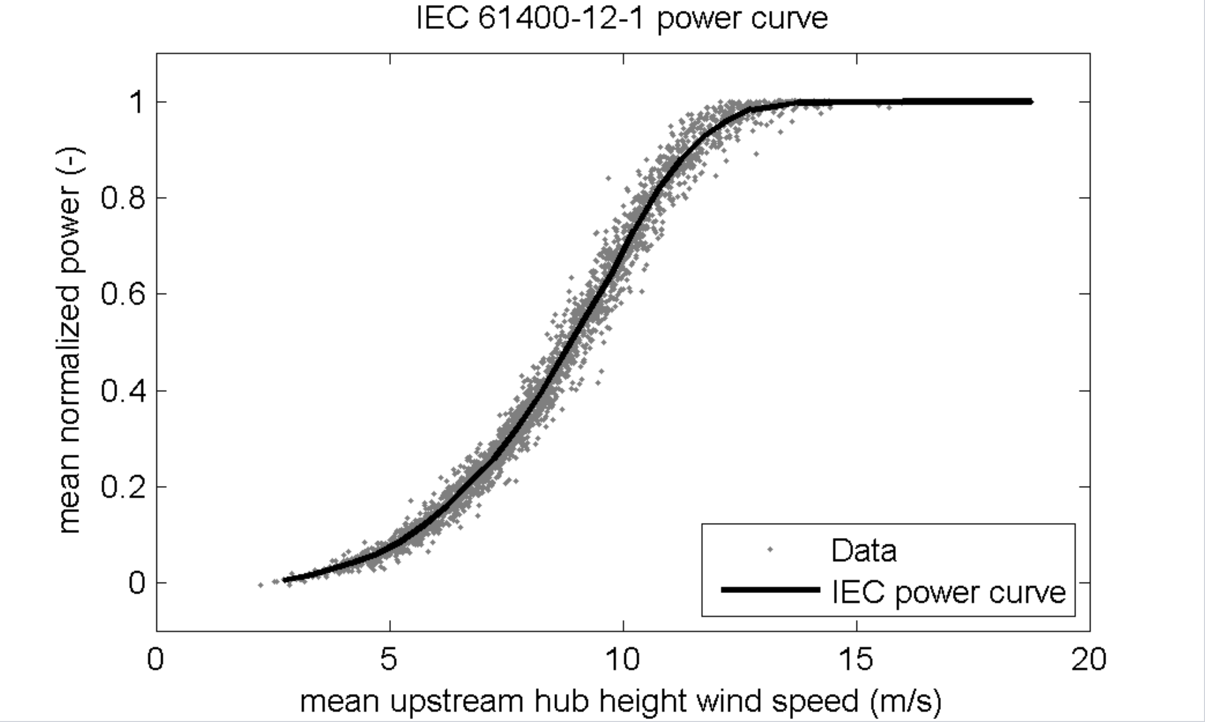
The mean power depends on more

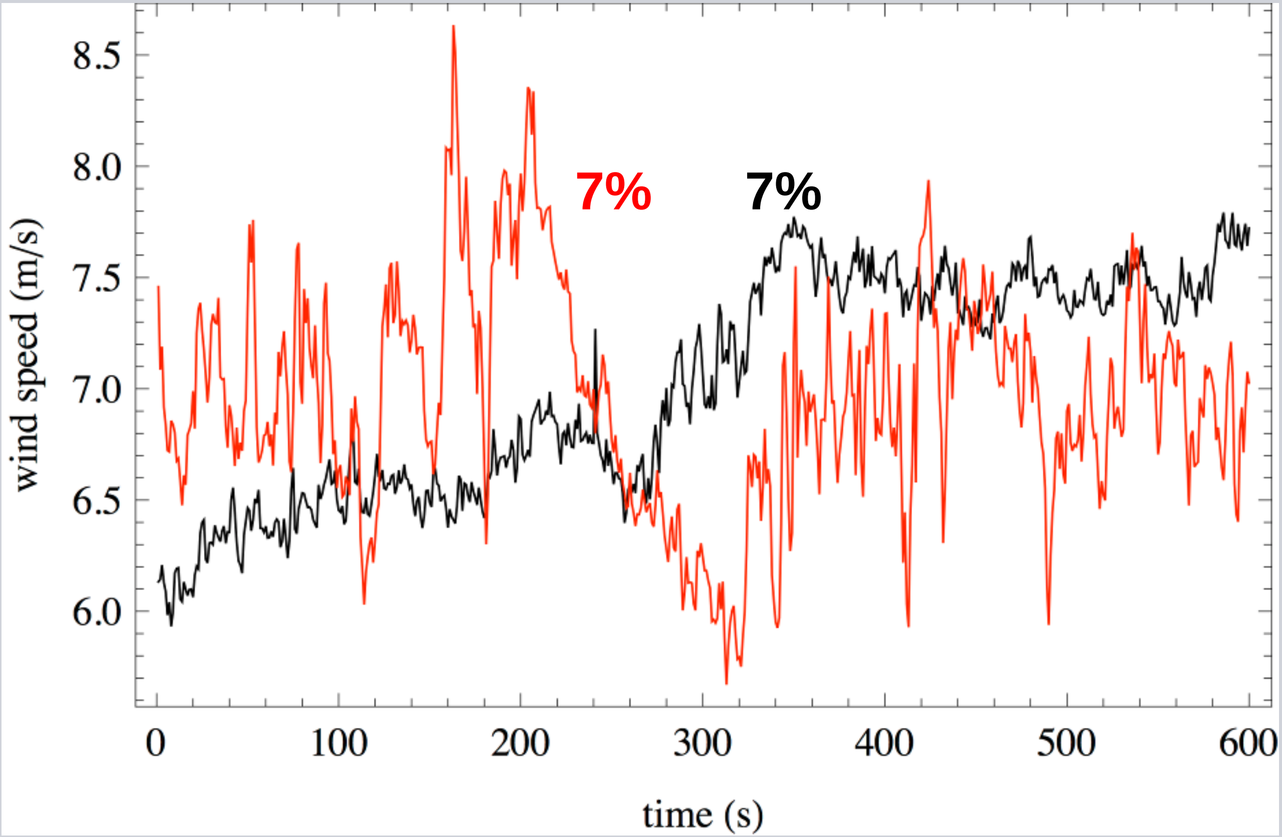
- **turbulence intensity** [1-4]
- vertical wind profile [5-6]
- atmospheric stability [7-8]
- dynamic response [2,9]

[1] Christensen et al. (1986)
[2] Sheinman et al. (1992)
[3] Kaiser et al. (2003)
[4] Albers (2009)
[5] Elliott et al. (1990)
[6] Wagner et al. (2009)
[7] Sumner et al. (2006)
[8] Wharton et al. (2012)
[9] Gottschall et al. (2007)

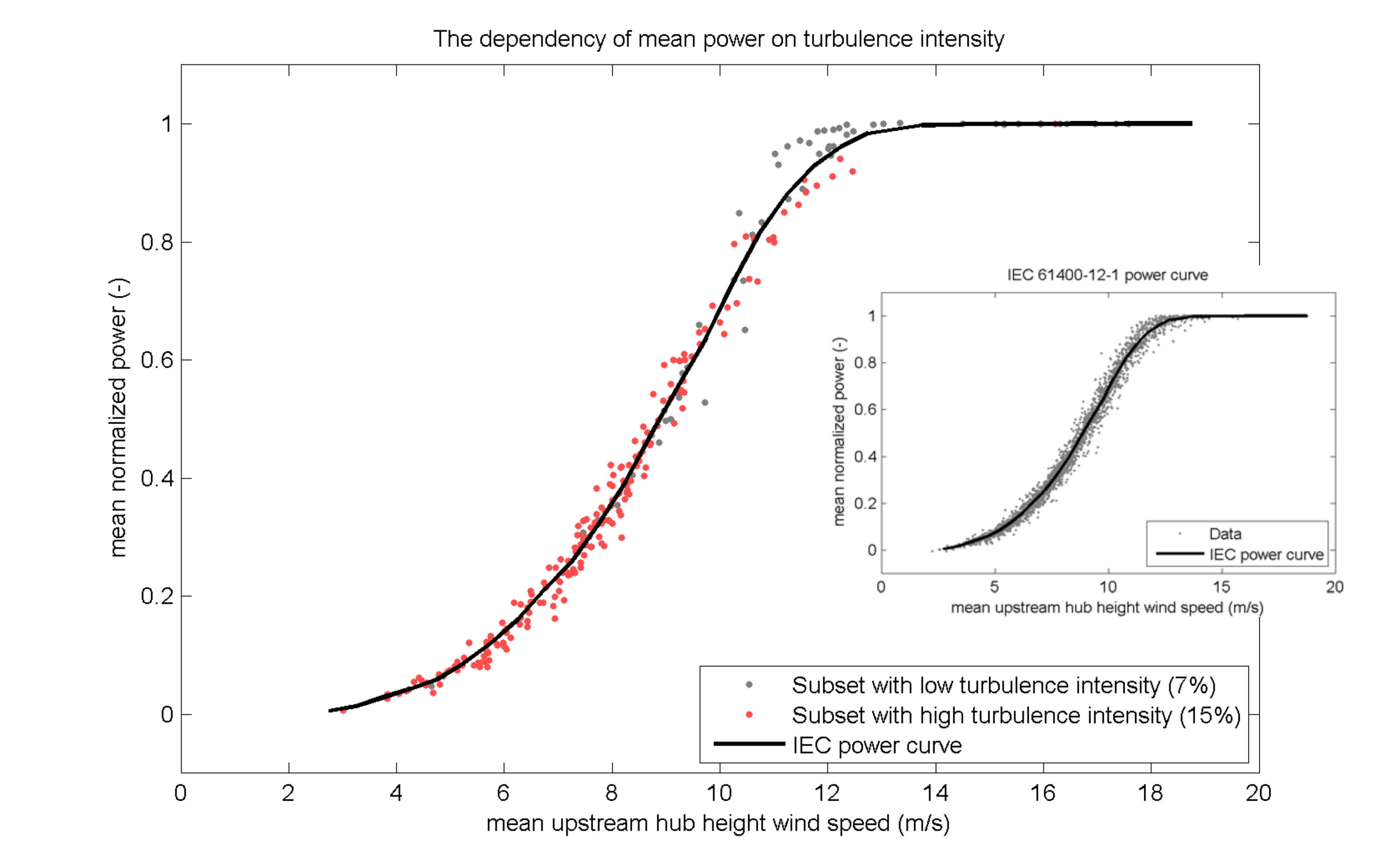


The notion of turbulence intensity

$$\text{turbulence intensity} = \frac{\text{spread of wind speeds}}{\text{typical wind speed}} = \frac{\text{standard deviation}}{\text{mean}}$$



The mean power depends on turbulence intensity



The new method is able to quantitatively account for the influence of turbulence intensity

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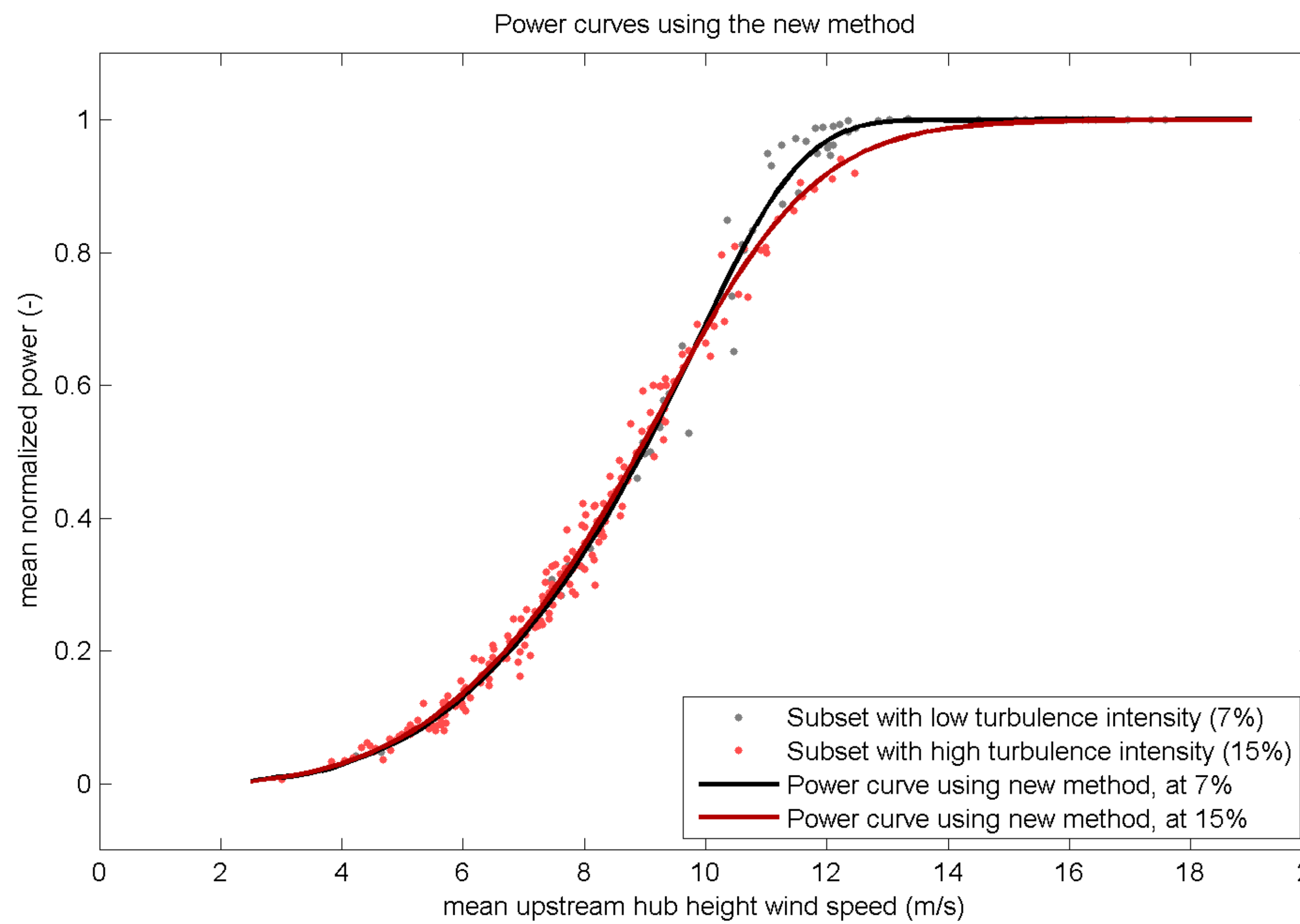
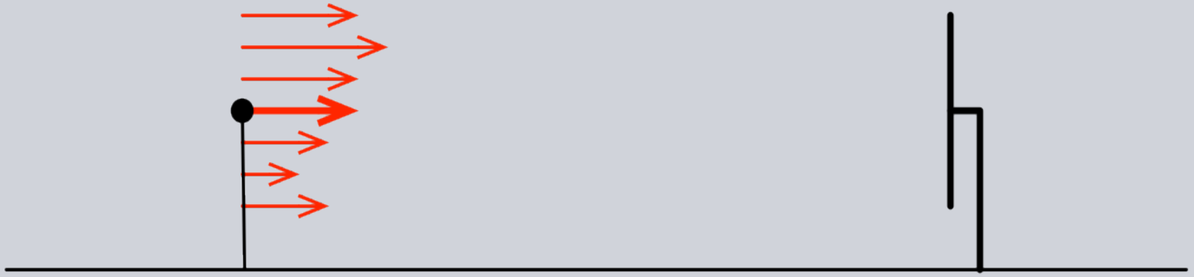


Solution

Power as a function of wind speed



The wind is measured at the meteorology mast **upstream**.

Perhaps only the wind speed at hub height is measured.

The wind turbine extracts power from the **whole wind field** around it.

Thus we must acknowledge at least

- the distance between the meteorology mast and the wind turbine
- the spatial extension of the rotor

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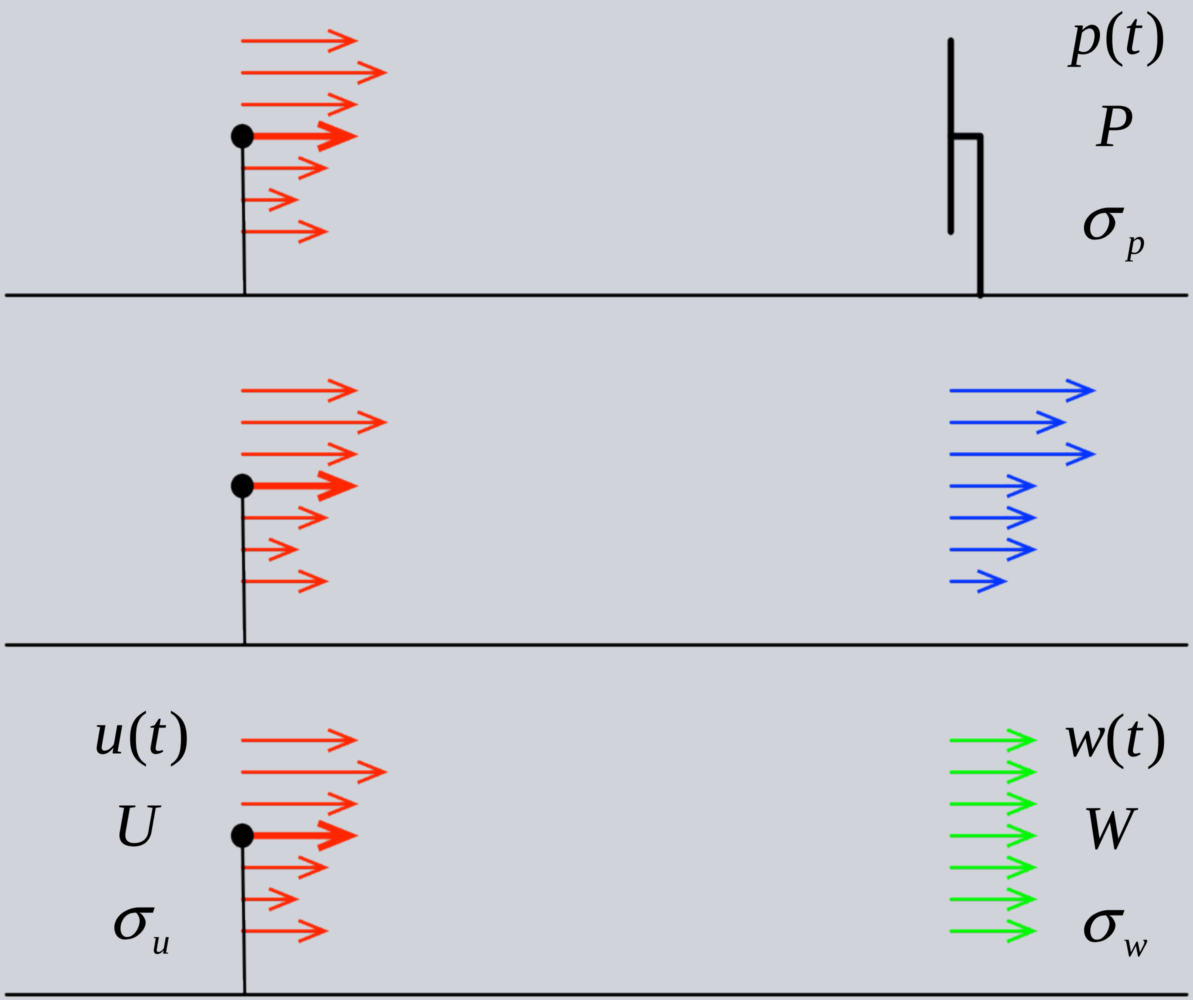
Three notions of wind to get started [1]



Upstream wind field at the meteorology mast. (Measured).

Virtual wind field at the location of the wind turbine if the wind turbine was not there to disturb the wind flow. (Fictive)

Driving wind, the common wind speed of a homogeneous wind field that yields the same power output as the virtual wind. (Fictive).

[1] Christensen et al. (1986)

Modelling the wind from scarce data

Ten minute statistics:

mean, **standard deviation**, min, max

Assumption:

normally distributed wind speeds

The method works with better data.

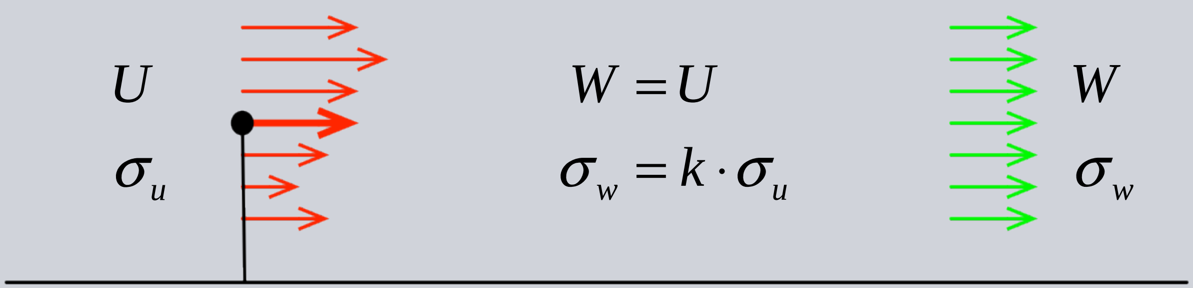
From upstream wind to driving wind:

$$W = U, \quad \sigma_w = k \cdot \sigma_u$$

In the presense of shear, apply the correction of [6].

k is needed due to:

- influence of turbulence on turbine
- influence of turbulence on anemometer
- size of rotor
- integral length scales of turbulence
- dynamic response of turbine



[6] Wagner et al. (2009)

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Modelling the power

Quasi static model: $p(t) = f(w(t))$

(instantaneous power is a function of instantanous driving wind speed)

Consequence for ten minute statistics:

$$P = \int_0^\infty f(x) \cdot \mathrm{pdf}_w(x)\, dx$$

$$\sigma_p = \cdots f \cdots \mathrm{pdf}_w \cdots$$

f is the **zero-turbulence power curve**
(not the conventional power curve)

pdf*w* is the distribution of driving wind speeds
(incorporates the turbulence intensity)

Combining the quasi static model with the assumptions on the wind speed

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$$\left.\begin{aligned} p(t) &= f(w(t)) \\ W &= U \\ \sigma_w &= k \cdot \sigma_u \end{aligned}\right\} \Rightarrow \begin{cases} P = \int_0^\infty f(x) \cdot \mathrm{pdf}(x; U, k \cdot \sigma_u)\, dx \\ \sigma_p = \cdots \end{cases}$$

When ***f*** and ***k*** are known, we obtain the **conventional power curve** at any desirable turbulence intensity.

$$P(U, I) = \int_0^\infty f(x) \cdot \mathrm{pdf}(x; U, k \cdot U \cdot I)\, dx$$

Compare with the Normal Distribution Model [4].

[4] Albers (2009)

Conventional power curves at any desired turbulence intensity

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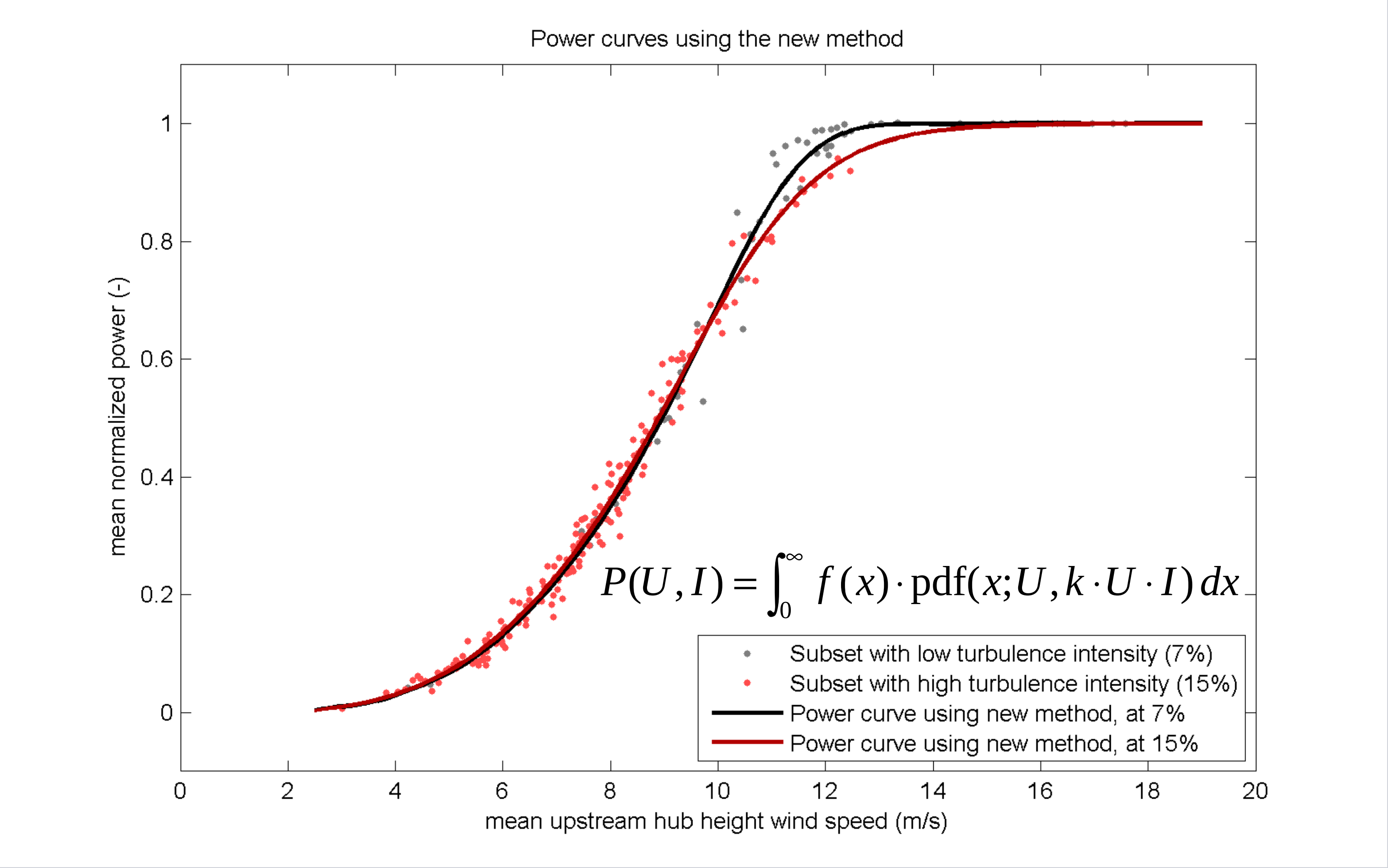


Estimation from data

Data: U, σ_u, P, σ_p

Model: $$P = \int_0^\infty f(x) \cdot \mathrm{pdf}(x; U, k \cdot \sigma_u)\, dx$$

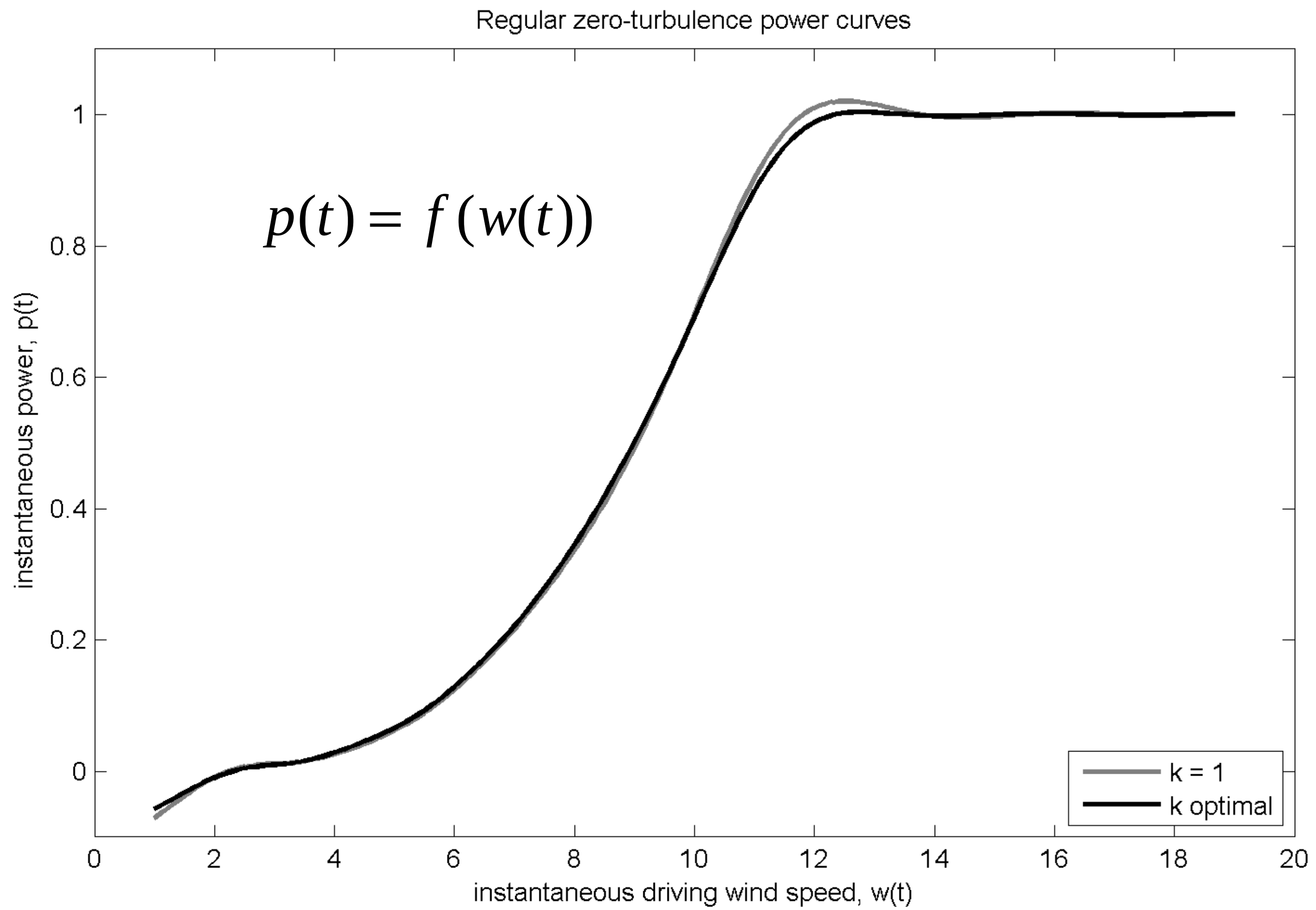
$$\sigma_p = \cdots U \cdots \sigma_u \cdots f \cdots k \cdots$$

Estimate ***f*** and ***k*** by matching the model with data (using least squares).

The estimation is

- essentially non-parametric
- computationally inexpensive

Estimated zero-turbulence power curve



Conventional power curves at any desired turbulence intensity

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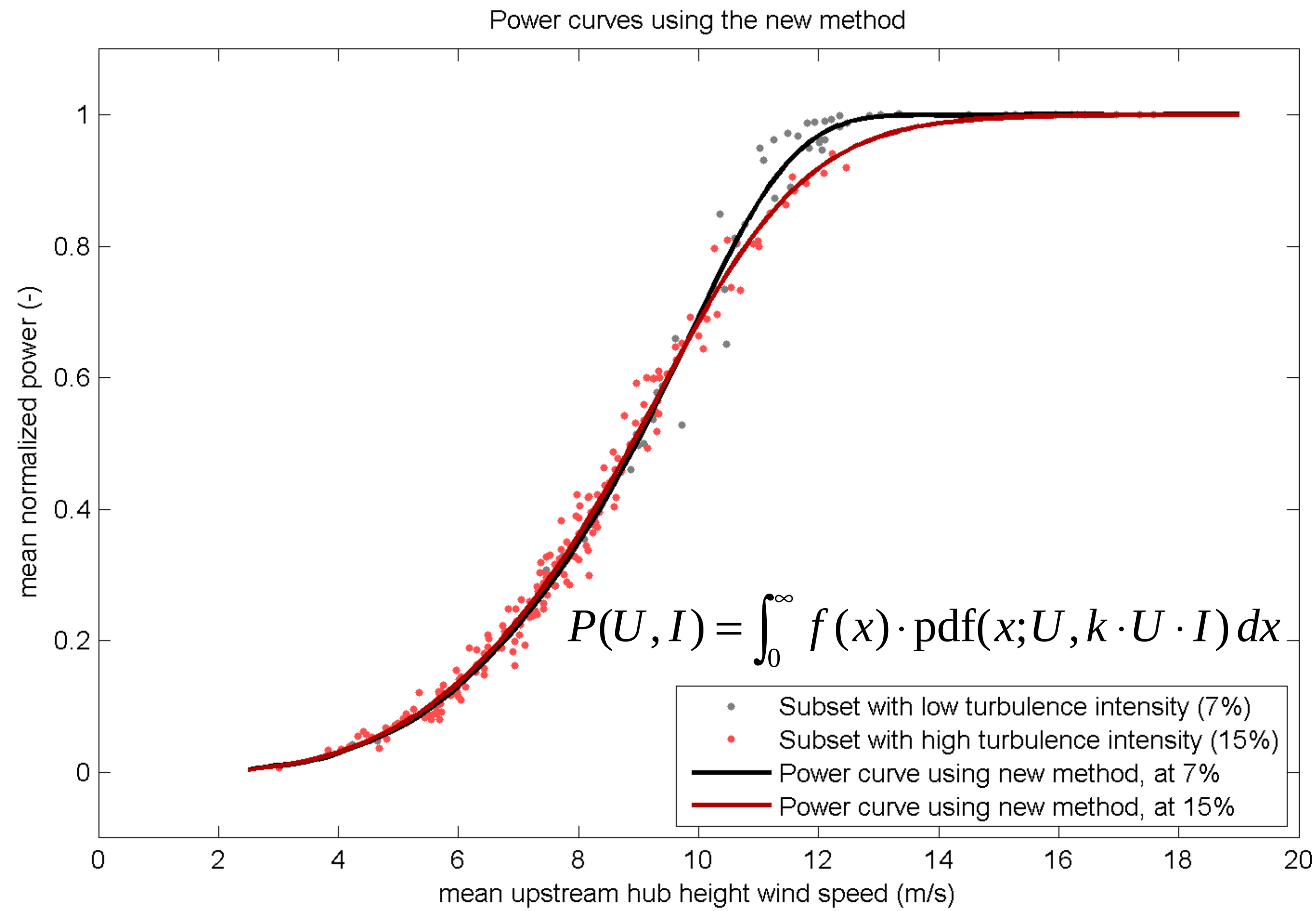

Residuals of mean power
No bias

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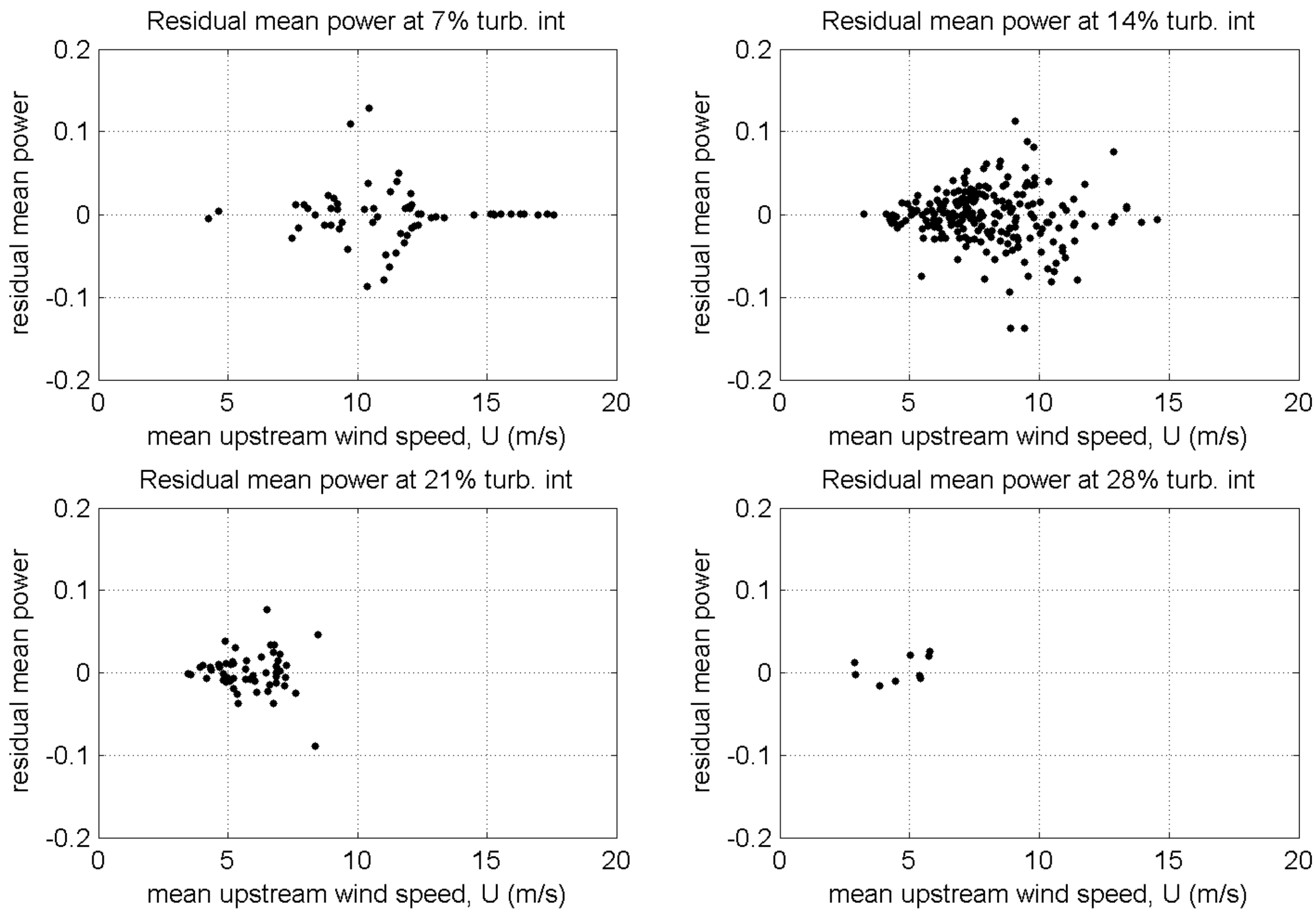

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Conclusion and further applications

- **Can account for the impact of turbulence intensity**
  Non-parametric, computationally inexpensive.

- **Can estimate a power curve with few data points**
  Each data point contributes with more information when the turbulence intensity is included.

- **Can estimate a power curve with gaps in data**
  When including the turbulence intensity, each data point contributes with information about range of wind speeds, approximately 4 m/s at U = 10 m/s and I = 10%.

- **Can predict performance at unobserved turbulence intensities**
  The model explicitly includes the turbulence intensity.

Some references (not an exhaustive list)

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