Impact of “non-standard” inflow

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(with input from more LAC colleagues)

(**L**oads-**A**erodynamics-**C**ontrols)

Siemens Wind Power

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Contents

- The present IEC standard and the energy in the turbine rotor
- Aeroelastic simulations: Influence of wind shear and turbulence intensity on the power curve and the AEP of a w/t.

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- Cup vs. LIDAR lidar equivalent wind speed campaign: European flat terrain
- Cup vs. LIDAR lidar equivalent wind speed campaign: Midwest USA flat terrain

- The next step: TI normalization

- Conclusions and discussion

Back to basics:
C.J. Christensen et al: ”Accuracy of power curve measurements”, Risø-M-2632, 1986

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”… The power curve is then seen as the relation between the power P(v) produced by this undisturbed wind v .

This definition is, however, of very doubtful value for a windmill in the natural wind. The main difficulty is that it assumes a smooth laminar flow of high degree of homogeneity and symmentry”

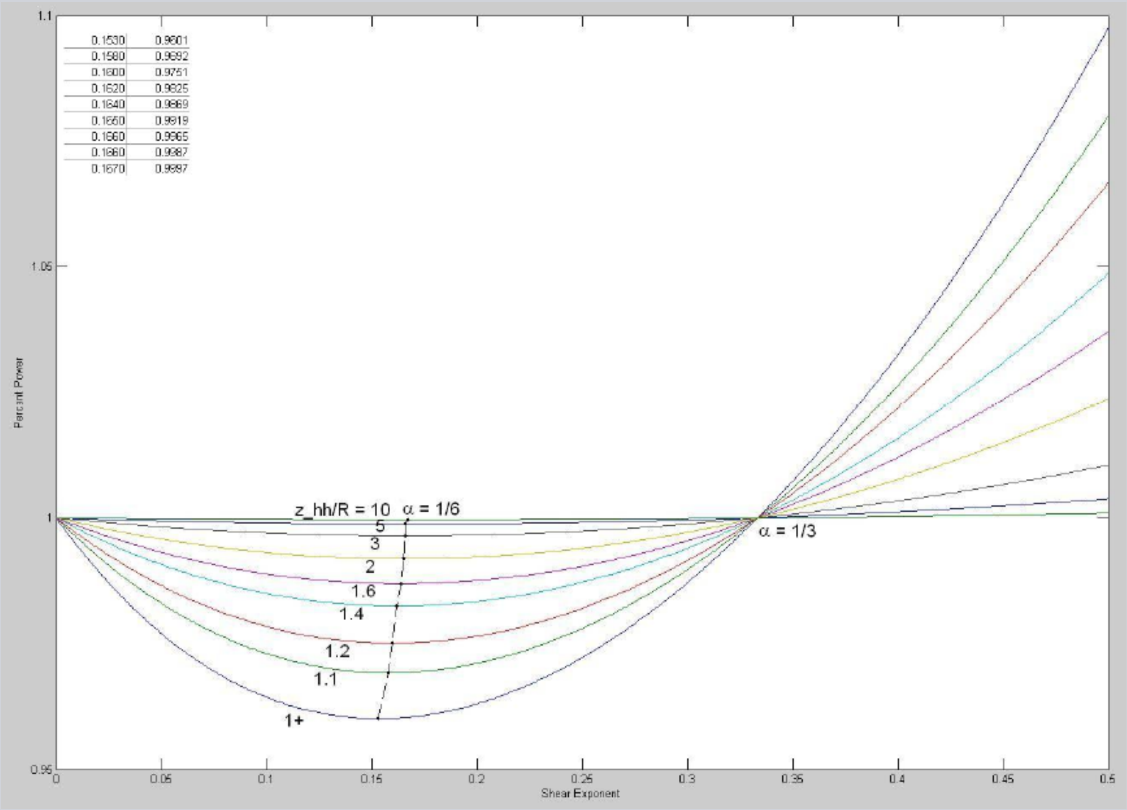
…

”In the case of a linear shear and with negligible turbulence, the driving wind speed is equal to the virtual speed at hub height”

$$\boxed{P = \tfrac{1}{2}\rho\pi R^2 v_{HH}^3}$$

Analytic solution: Energy flux through the rotor (case: exponential wind profiles)

$$P = \frac{1}{2}\rho \pi R^2 v_{HH}^3$$



- Relative to a flat profile the % of the available power varies with the shear exponent.
- Formula valid for flat profiles (shear exponent equal zero) or shear exponent a=1/3.
- Even in the case of well-defined shear profiles, the HH wind speed relation to the power available within the rotor disk varies.
- Conclusion: The wind shear influence the power available and needs to be measured.

Aeroelastic simulations using exponential profiles and varying TI levels

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		Shear.x						
	MAWS=6m/s	**0.05**	**0.1**	**0.15**	**0.2**	**0.25**	**0.3**	**0.4**
TI(%)	**2**	101.15	100.69	100.36	100.27	100.01	**100.00**	100.23
	4	101.20	100.74	100.40	100.30	100.03	100.02	100.23
	6	101.33	100.86	100.53	100.43	100.16	100.14	100.35
	8	101.53	101.07	100.73	100.63	100.36	100.34	100.55
	10	101.80	101.35	101.01	100.91	100.64	100.62	100.82
	12	102.17	101.71	101.37	101.27	101.00	100.98	101.17
	14	**102.62**	102.16	101.83	101.73	101.46	101.43	101.62

		Shear.x						
	MAWS=10m/s	**0.05**	**0.1**	**0.15**	**0.2**	**0.25**	**0.3**	**0.4**
TI(%)	**2**	**100.93**	100.72	100.56	100.51	100.37	100.34	100.40
	4	100.89	100.67	100.50	100.44	100.29	100.26	100.31
	6	100.84	100.62	100.45	100.39	100.24	100.21	100.26
	8	100.78	100.56	100.39	100.33	100.19	100.16	100.21
	10	100.72	100.50	100.33	100.27	100.13	100.10	100.15
	12	100.67	100.45	100.28	100.22	100.08	100.05	100.10
	14	100.61	100.40	100.23	100.17	100.03	**100.00**	100.06

- **Limited average AEP variations, decreasing as mean annual wind speed increases**
- **Logarithimic wind shear profiles used for aeroelastic simulations**
- **No wind veer**
- **Varying turbulence vs. wind speed**

The measurement method influence on the conclusions: Midwest site power curve vs. the HH wind speed (1)

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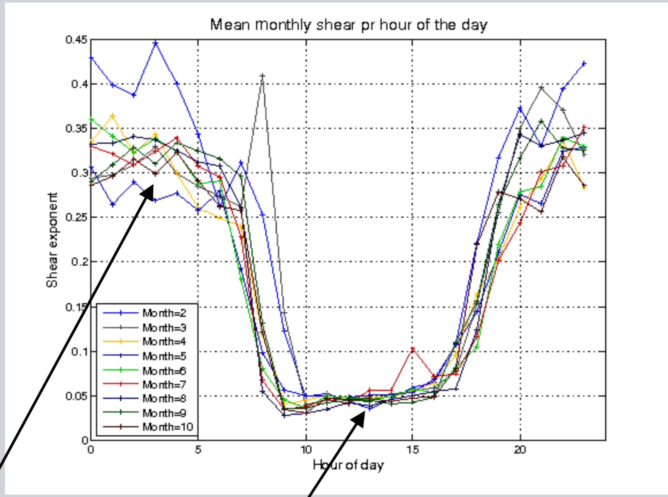
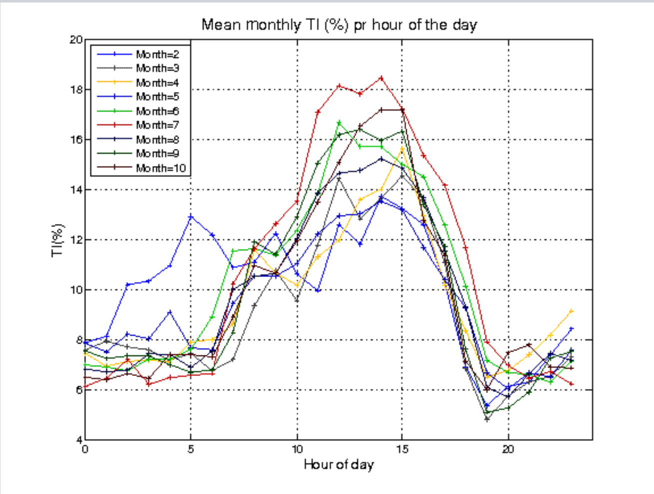
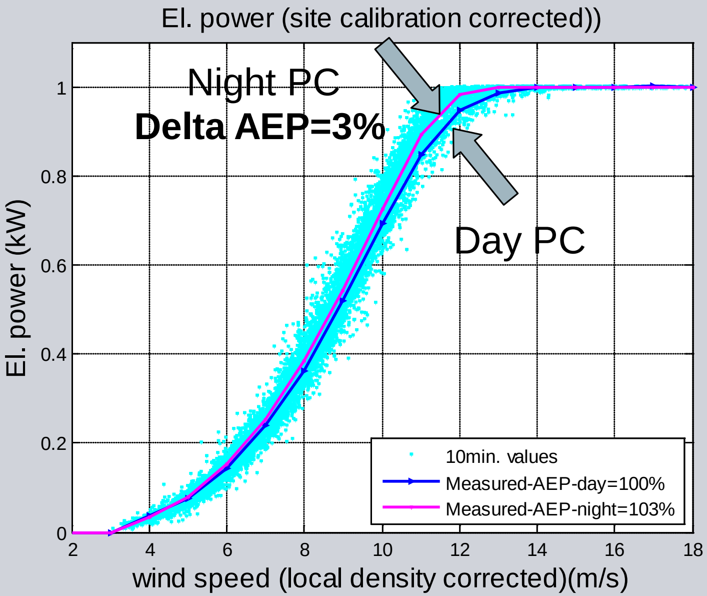




Predominantly stable

Predominantly unstable



Possible conclusion:

Wind turbines perform better during stable conditions

The measurement method influence on the conclusions: Midwest site power curve vs. the HH wind speed (2)

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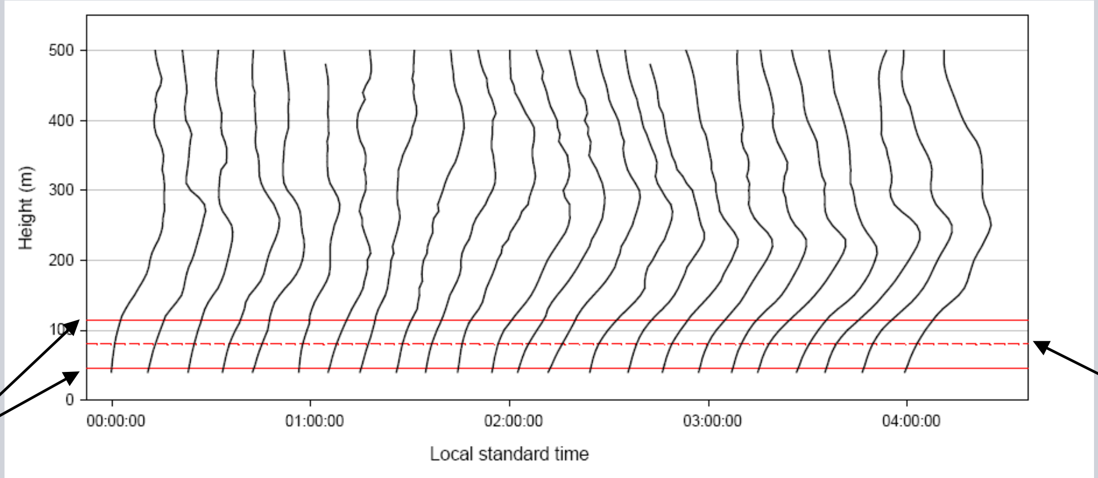

Courtesy N. Kelley

Rotor limits

Turbine HH

OR
is it maybe the measurement method playing games with us?

Answer: YES

The influence of an advantageous wind profile due to a LLJ during night hours is not registered by the wind speed measurement at HH.

Question:

Is there a more consistent method which can describe the turbine response vs. the wind profile properties ?

Wind shear, wind veer and TI filtering influence the turbine response

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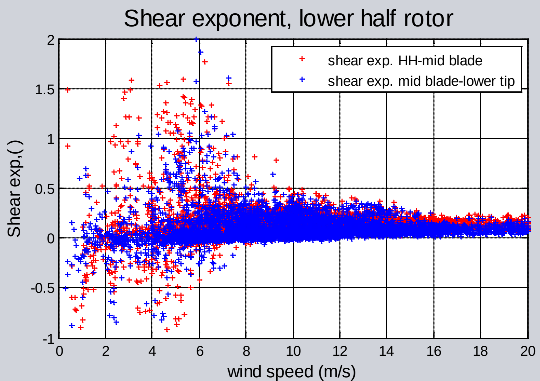

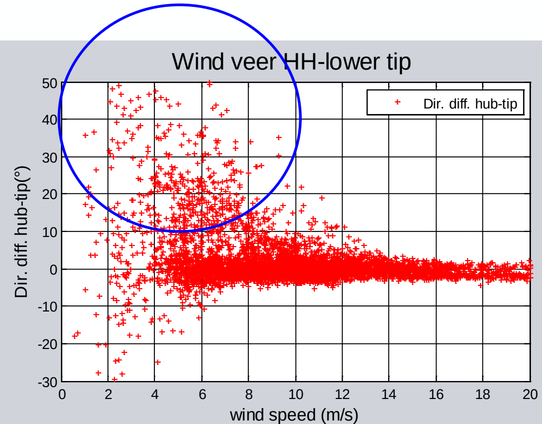

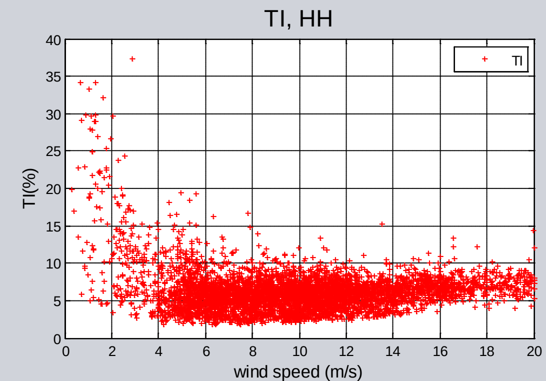

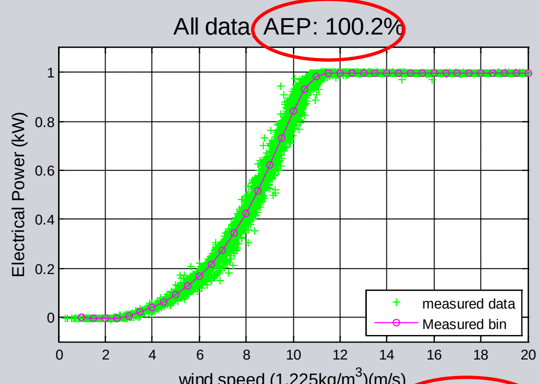

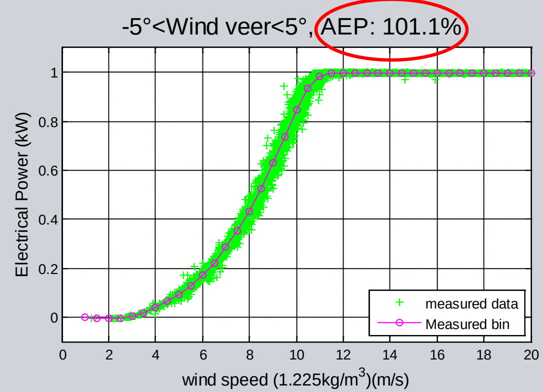

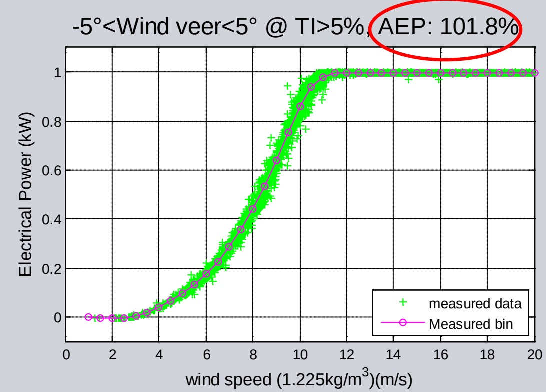

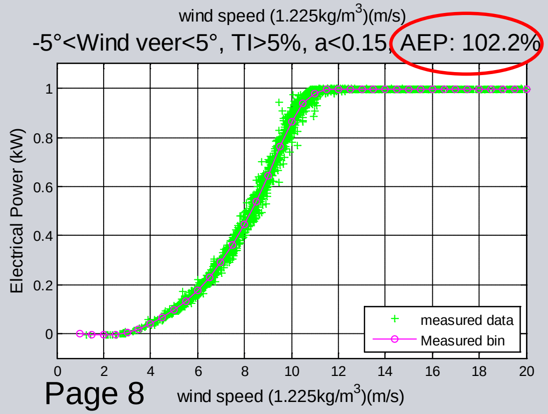

Question:

Does the turbine produce better during low shear, low veer and higher TI conditions?

OR:

Has our filtering, modified the energy contents of the wind profile ? (without our measurement method being able to register it!)

Using a LIDAR to measure inflow:
The equivalent wind speed concept

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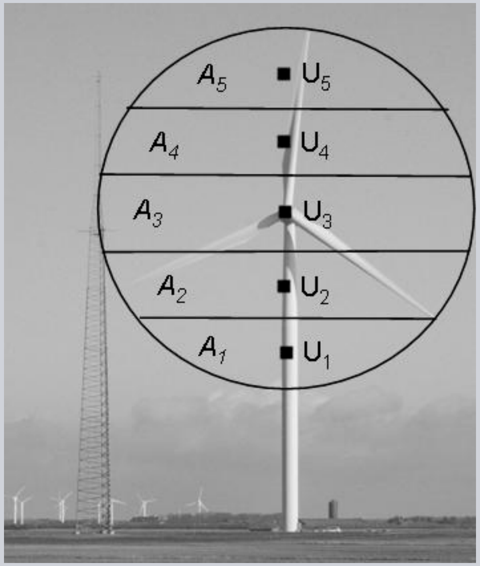
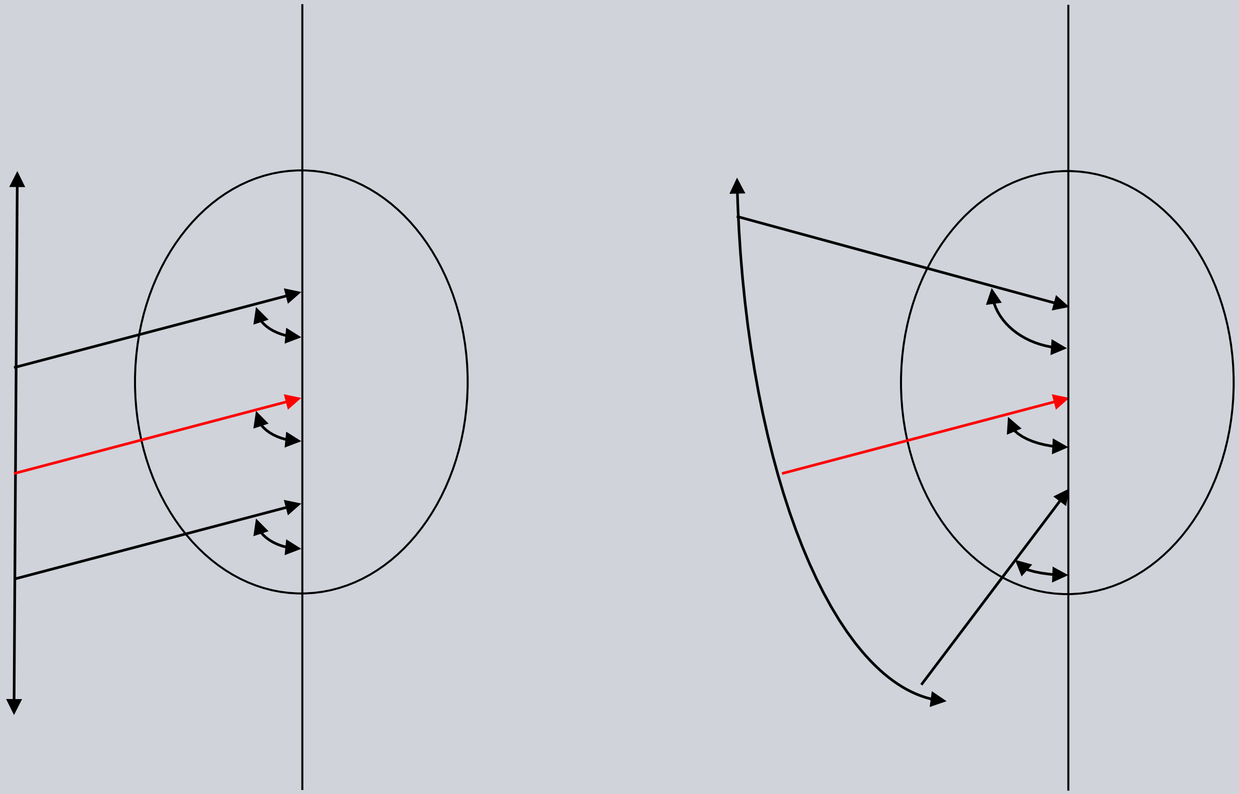
$$V = \sqrt[3]{\frac{1}{A}\int_{H-R}^{H+R}\left(v(z)\cos(\varphi(z))\right)^{3} dA}$$



- **A LIDAR is deployed next to a met mast**
- **The LIDAR can measure the wind speed and direction at more heights regularly distributed over the rotor**
- **The wind speeds at all heights are normalized by dividing with the LIDAR wind speed at hub height.**
- **The LIDAR wind directions at all heights are subtracted from the direction at hub height (wind veer relative to hb height).**
- **The normalized LIDAR wind speeds at all heights are multiplied with the cosine of the direction angle relative to hub height**
- **Subsequently all wind speeds are multiplied with the cup wind speed at hub height.**

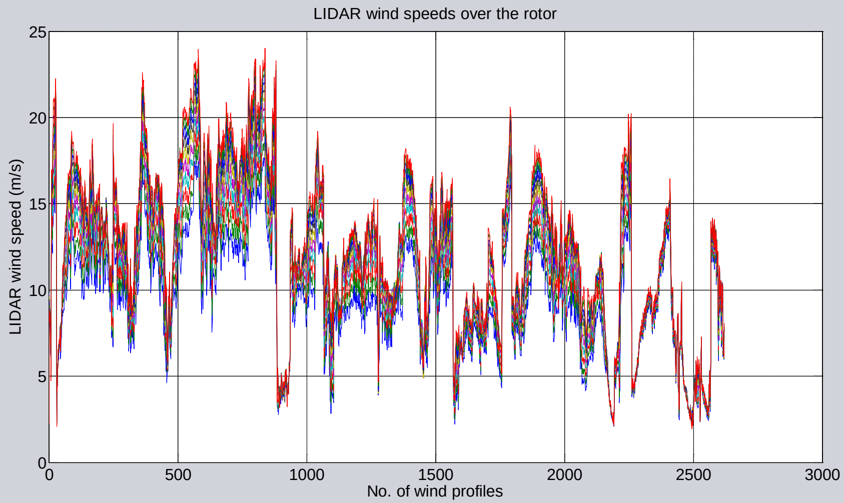
The importance of wind veer

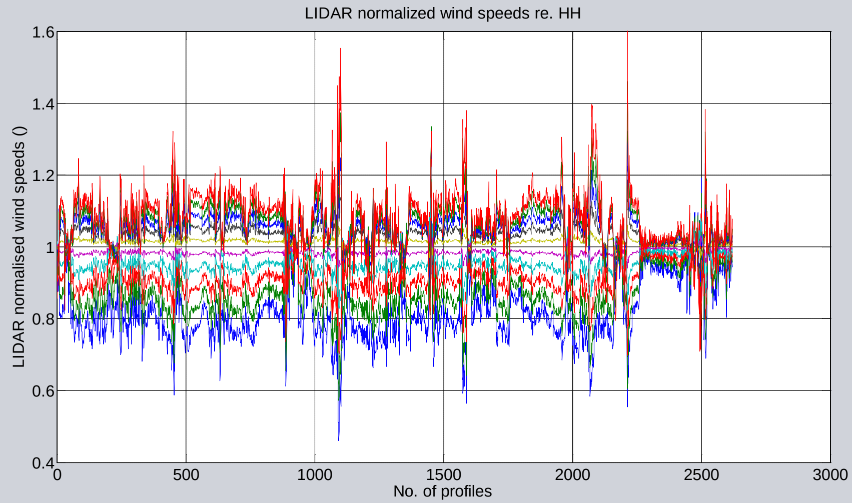


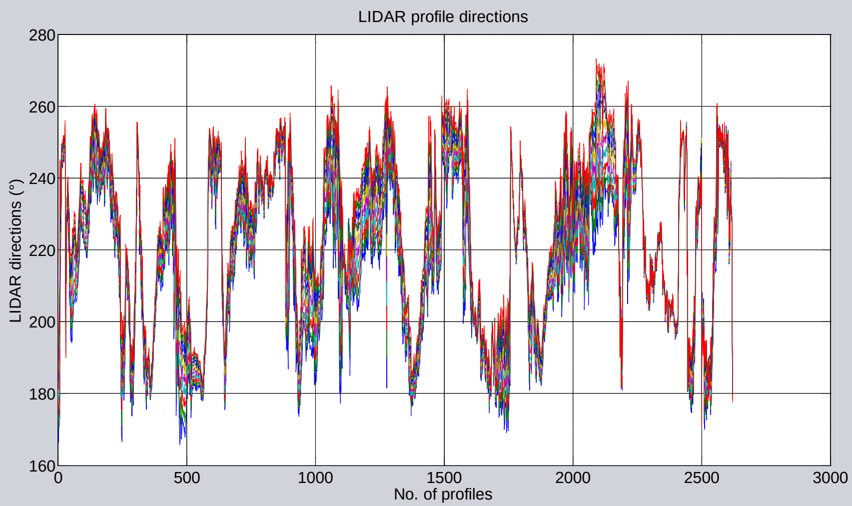
Assuming the same wind speed magnitudes within the rotor disk:

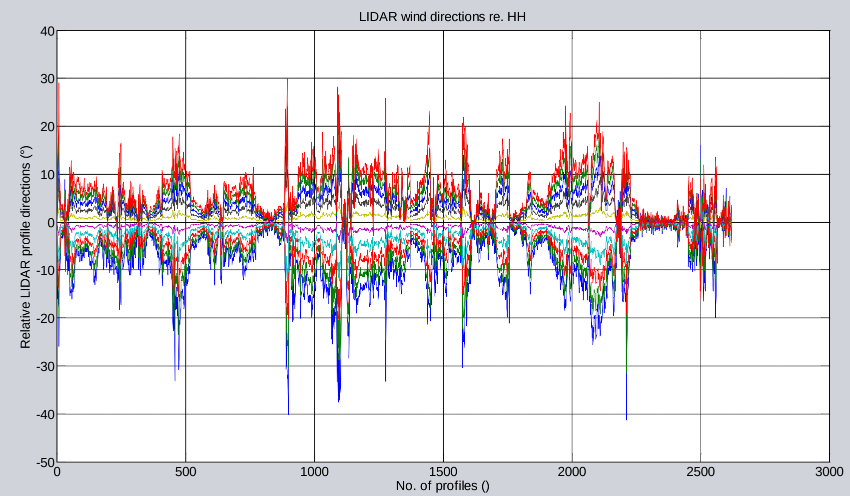
Larger veer is equivalent with lower available energy through the turbine rotor

PC and load measurement campaign in EU flat terrain: Using a HH cup and a LIDAR to measure inflow (1)

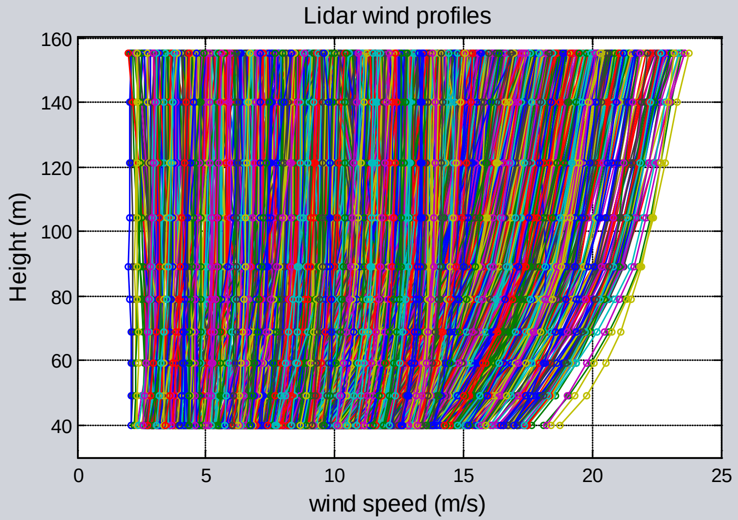


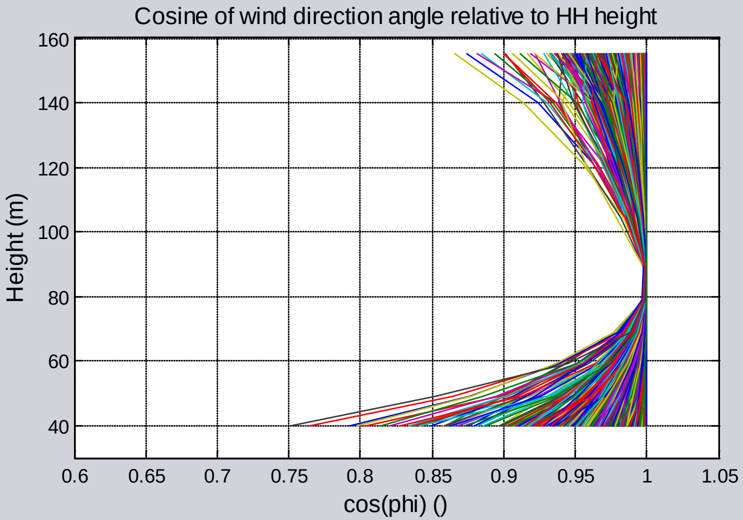


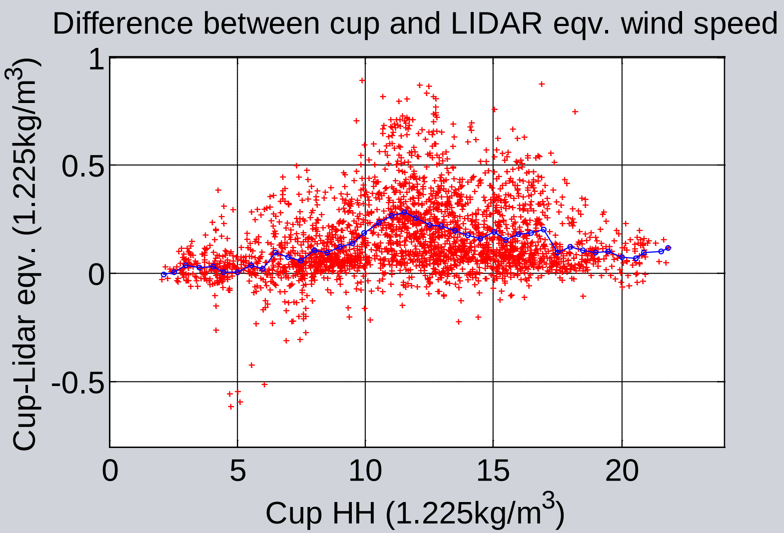




PC and load measurement campaign in EU flat terrain
Using a cup and a LIDAR to measure inflow (2)

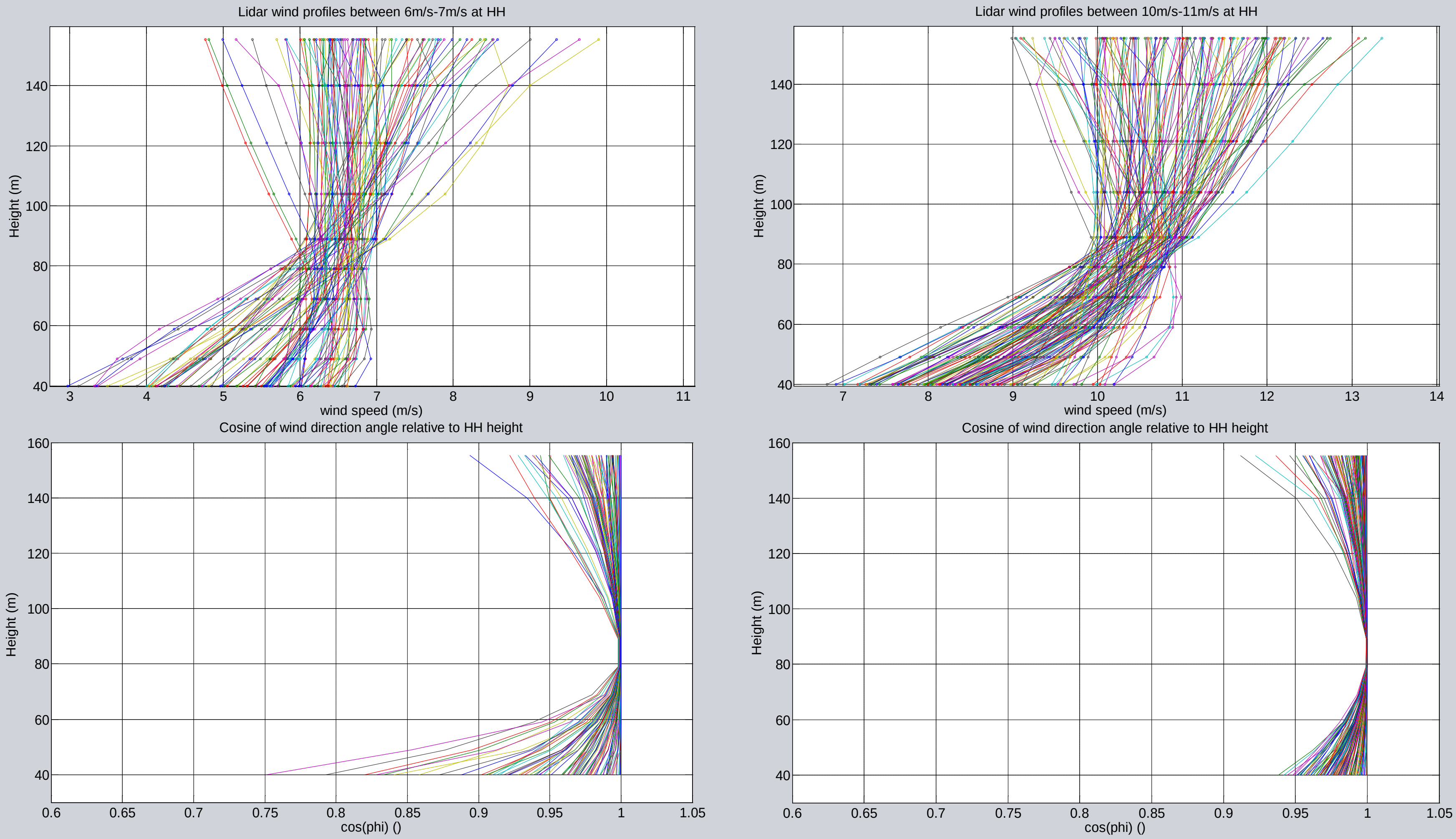






- **Significant wind shear and veer over the rotor height**
- **Both negative and positive differences of the equivalent wind speed relative to HH cup**

PC and load measurement campaign in EU flat terrain
Using a cup and a LIDAR to measure inflow (2)



6m/s-7m/s at HH

10m/s-11m/s at HH

EU flat terrain:
Measured and calculated equivalent loads using a HH cup and a LIDAR to measure inflow (3)

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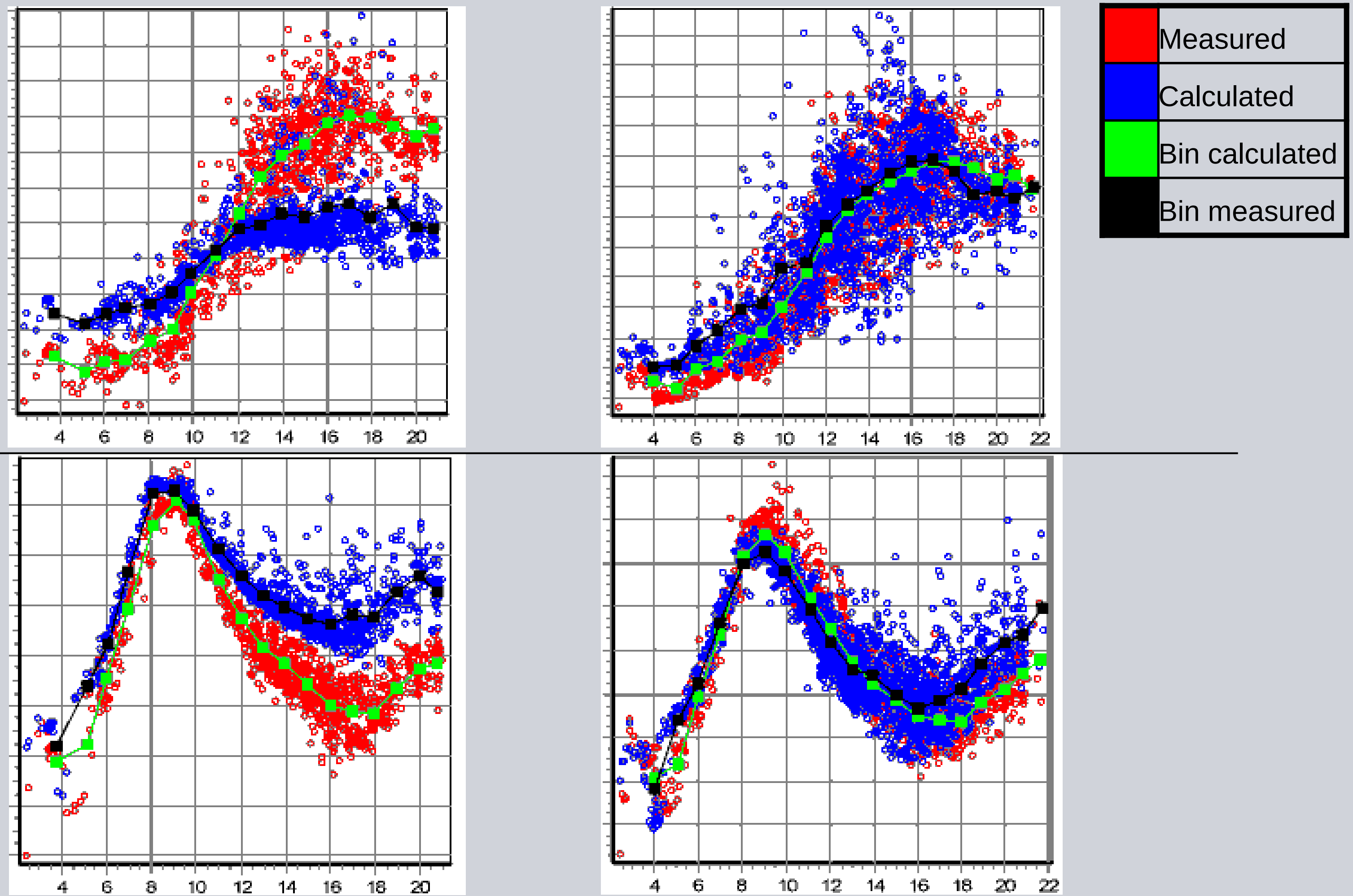
Flap-root bending

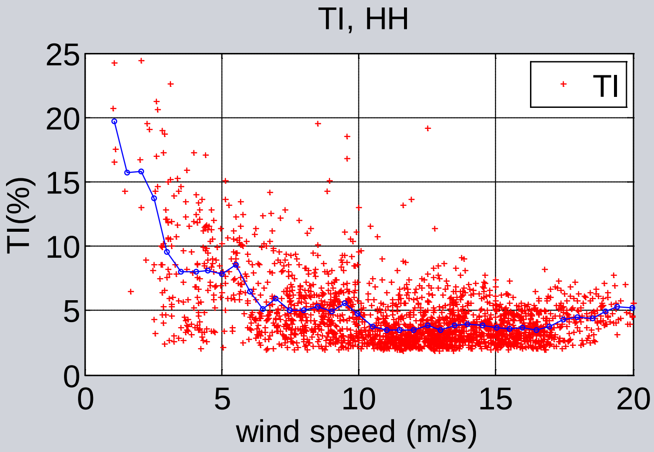
Edge-root bending



Cup at HH

LIDAR wind profile +veer re. HH

EU flat terrain:
AEP using a HH cup and a LIDAR to measure inflow (3)



	AEP (cup HH)	AEP (eqv. LIDAR)
All data	100%	101.4%
TI>=5%	100.8%	101.5%
TI<=5%	99.2%	101.2%
TI>=6%	100.9%	101.3%
TI<=6%	99.4%	101.2%
TI>=7%	100.7%	101.3%
TI<=7%	99.6%	101.3%
$Delta_{max-min}$ (%)	1.6%	0.3%

PC measurement campaign in flat terrain Midwest USA : Using a cup and a LIDAR to measure inflow (2)

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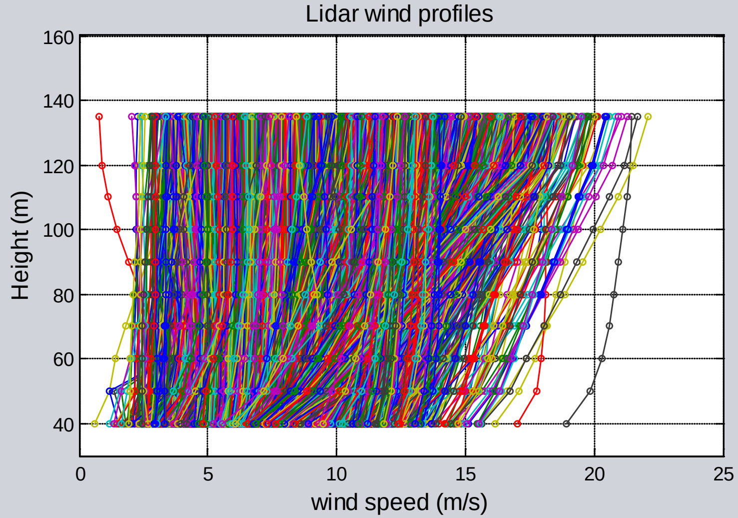
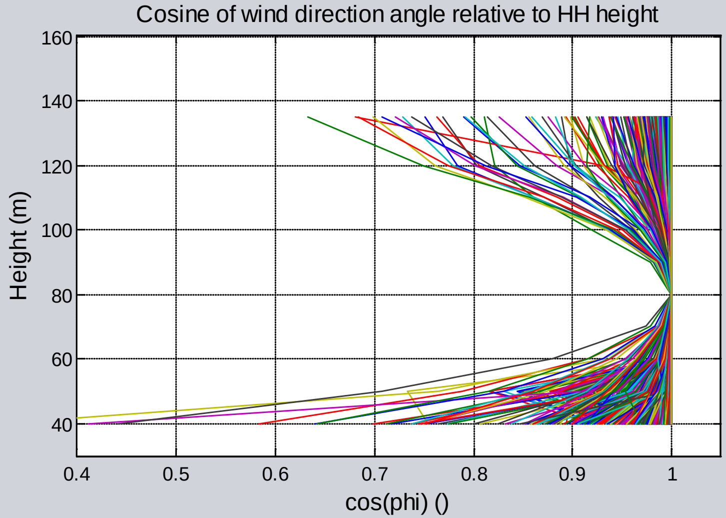
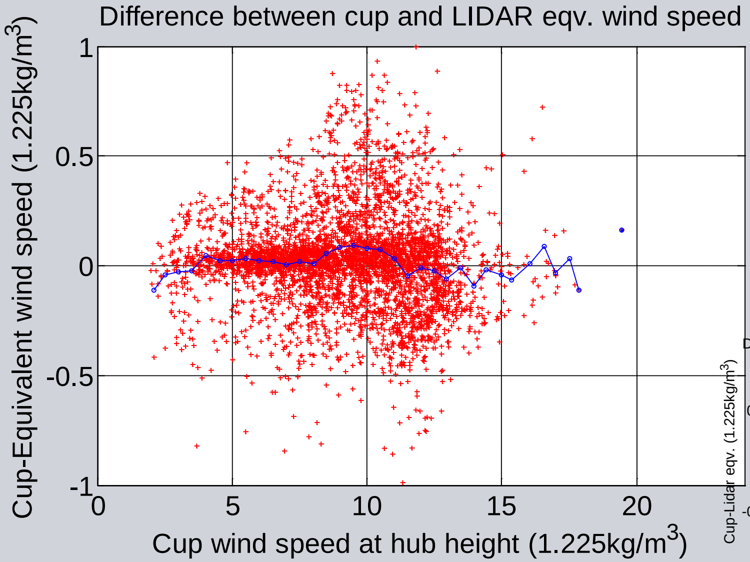
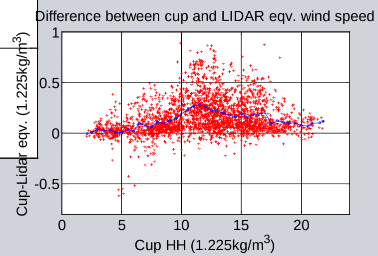






- **Significant wind shear and veer over the rotor height (more than in EU terrain).**
- **Both negative and positive differences of the equivalent wind speed relative to HH cup.**



Midwest USA flat terrain:
AEP using a HH cup and a LIDAR to measure inflow (3)

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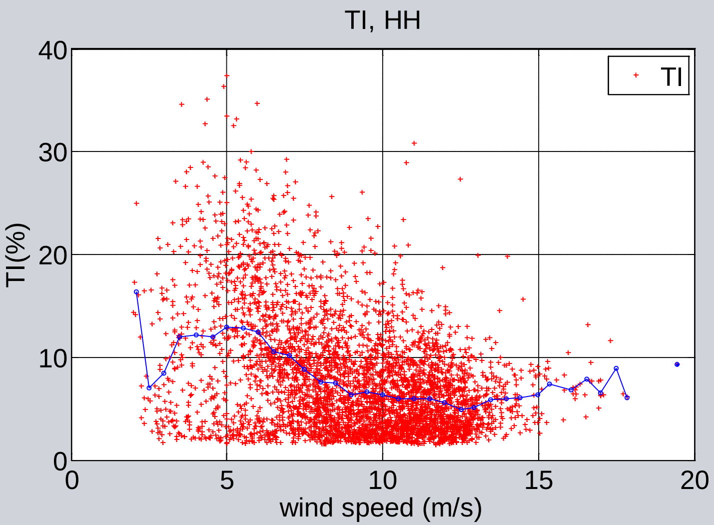


	AEP (cup HH)	AEP (eqv. LIDAR)
All data	100%	100.8%
TI>=4%	100.6%	100.7%
TI<4%	98.2%	100.5%
TI>=5%	100.6%	100.7%
TI<5%	98.5%	100.4%
TI>=6%	100.6%	100.7%
TI<6%	98.8%	100.4%
TI>=7%	100.4%	100.6%
TI<7%	99%	100.4%
$Delta_{max-min}$ (%)	2.4%	0.4%

The next step: Equivalent wind speed combined with TI normalization at a certain TI level.

Turbulence represents additional energy for the existing wind; depending on the curvature of the power curve this energy is added (concave part up) or subtracted (concave part down)

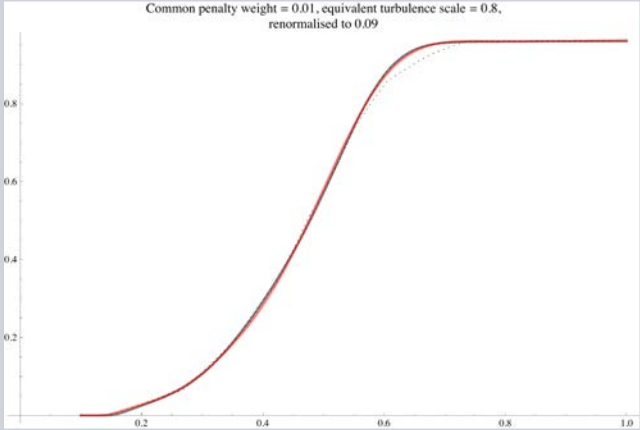
$$P(u) = P(\bar{u}) + \frac{dP(\bar{u})}{du}(u-\bar{u}) + \frac{1}{2}\frac{d^2P(\bar{u})}{du^2}(u-\bar{u})^2 + \ldots$$

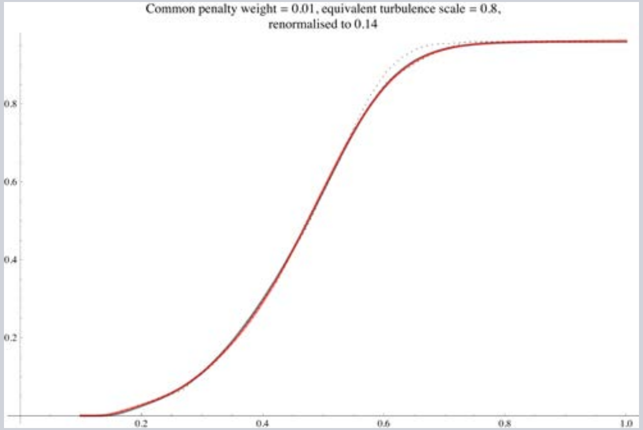
$$\overline{P(u)} = P(\bar{u}) + \frac{dP(\bar{u})}{du}\overline{(u-\bar{u})} + \frac{1}{2}\frac{d^2P(\bar{u})}{du^2}\overline{(u-\bar{u})^2} + \ldots$$

$$\overline{P(u)} = P(\bar{u}) + \frac{1}{2}\frac{d^2P(\bar{u})}{du^2}\sigma_u^2$$

TI varies with height

Challenge: Find a TI representative of the whole rotor





(work by Emil Sørensen)

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Conclusions

1. Wind shear, wind veer and TI contribute in the energy available within the rotor disk.
2. This makes the HH wind speed measurement a poor method for measuring a turbine's power curve, especially for larger turbine rotors.
3. The equivalent wind speed takes into account both wind shear and veer and seems more robust in delivering more consistent load and AEP results, compared to the HH wind speed.
4. Pseudo-dillema: Overprediction-Underperformance gap are two sides of the same coin! Improvements will only happen if:
   - New wind speed measurement methods are used for PC campaigns!
   - Siting measurements are upgraded; a combination of HH masts and remote sensing devices to measure both wind and direction at more heights both below and above HH
   - Flow modelling examines other than neutral conditions.

Thank you for your attention