Power Curve Working Group

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Agenda

- Shear Coefficient and Hub Heights
- Power Curve Testing: Height Definitions and AEP
- Power Curve Testing: Uncertainty
- Predicting AEP

Shear Coefficient and Hub Heights

Theory

- Shear Coefficient Calculation:

Definition of the wind shear exponent α:

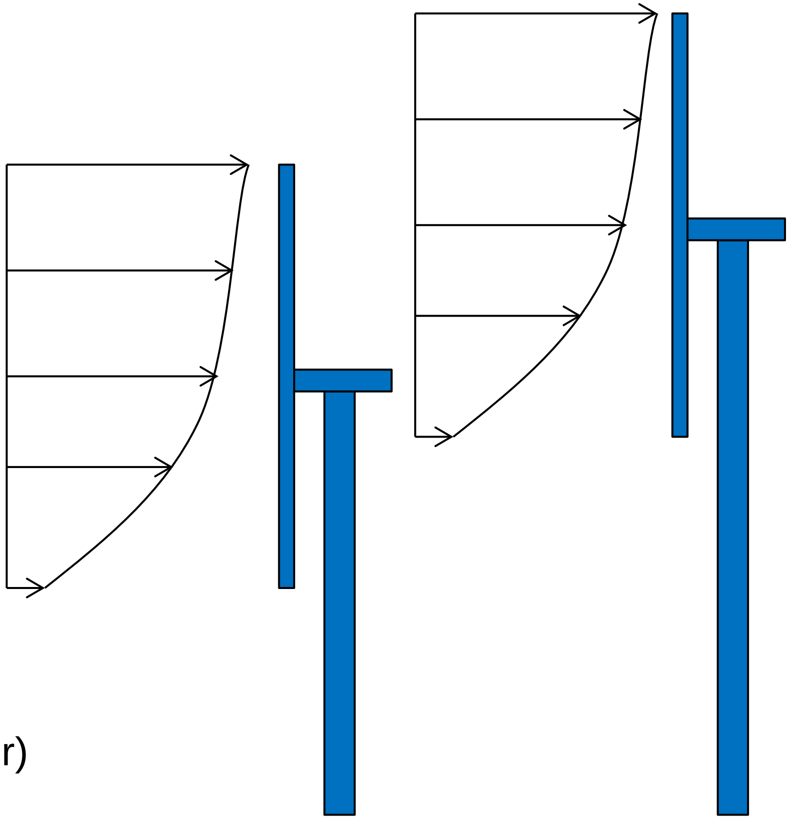
$$\alpha = \frac{\ln\left(\frac{V_{hub}}{V_{tip}}\right)}{\ln\left(\frac{Z_{hub}}{Z_{tip}}\right)}$$

Variables:

- V_{hub}: wind speed at hub height (measurement height)
- V_{tip} : wind speed at lower blade tip (measurement height)
- Z_{hub}: hub height (measurement height)
- Z_{tip} : height of lower blade tip (measurement height)

- Wind speed change over rotor area is important.
- Identical wind profiles should result in identical shear coefficients.
- Problem:
  - Shear Coefficient = f (Wind Profile, Hub Height)
- Better:
  - Shear Coefficient = f (Wind Profile),
    f (Wind Profile, Rotor Diameter)

- Identical WEC type
- Identical Wind profile
- Only Increase Hub Height
- Different shear coefficient



Shear Coefficient and Hub Heights
Real-world Impact and Consequences

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- Assumption of certain wind profile
- Calculation of shear coefficient
  for identical wind profile but larger towers
- For typical range of hub heights, impact is
  up to factor two
- affects contractual filter criteria
  - unnecessary many data filtered
  - measurement duration extended
- Never mix shear coefficient data of different hub heights

MM92	
hub height	max. shear
[m]	[-]
68.5	0.30
80.0	0.39
100.0	0.54

MM100	
hub height	max. shear
[m]	[-]
80.0	0.30
100.0	0.43

3.2M114	
hub height	max. shear
[m]	[-]
93.0	0.30
123.0	0.46
143.0	0.56

3.4M104	
hub height	max. shear
[m]	[-]
80.0	0.30
100.0	0.43
128.0	0.60

Doubled shear coefficient

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Power Curve Testing: Height Definitions and AEP
Height Impacts

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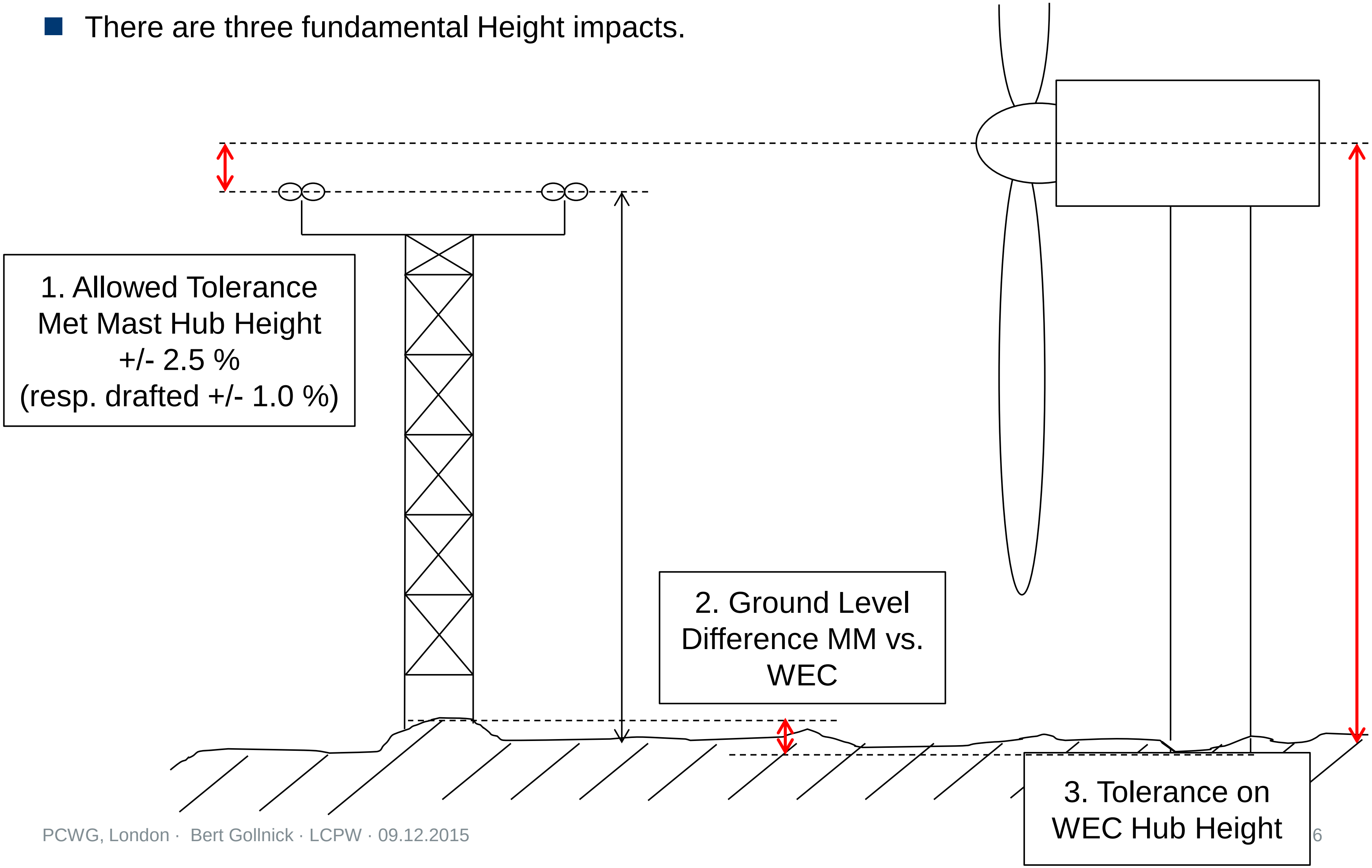
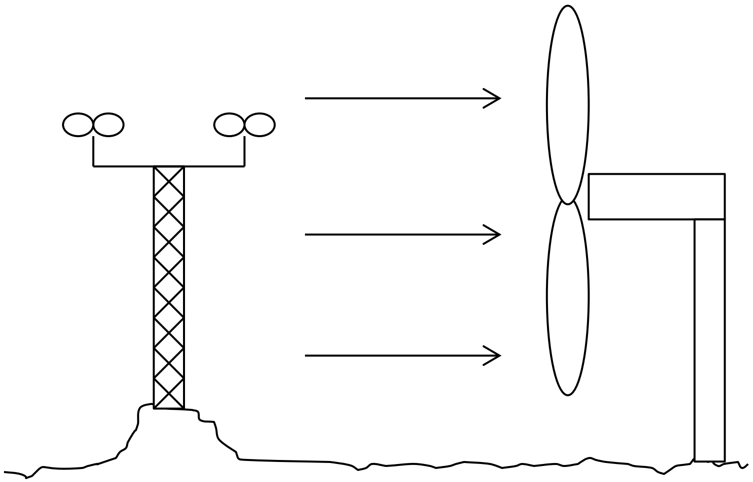
- There are three fundamental Height impacts.

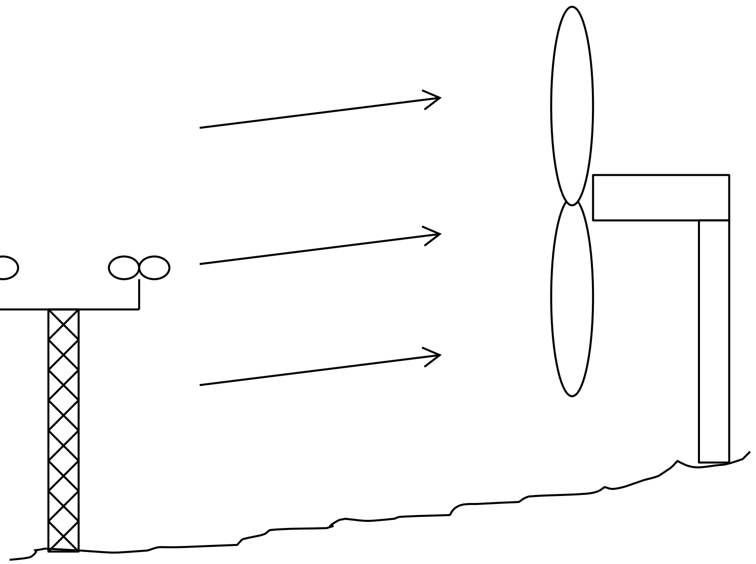


Power Curve Testing: Height Definitions and AEP
2. Ground Level Difference

- Different types of ground affect AEP result differently.
- Parallel flow to ground might be assumed.



Large Impact



Small Impact

Power Curve Testing: Height Definitions and AEP
2. Ground Level Difference

- Definition for Non-Complex Terrain in Appendix B

Distance	Sector	Maximum slope %	Maximum terrain variation from plane
<2 L	360°	<3*	<0,04 $(H+D)$
≥2 L and < 4 L	Measurement sector	<5*	<0,08 $(H+D)$
≥2 L and <4 L	Outside measurement sector	<10**	Not applicable
≥4 L and <8 L	Measurement sector	<10*	<0,13$(H+D)$

* The maximum slope of the plane, which provides the best fit to the sectoral terrain and passes through the tower base.

** The line of steepest slope that connects the tower base to individual terrain points within the sector.

- Assumptions:
  - 3.2M114 @ 143 m Hub Height

- Max Ground Level Difference Met Mast vs. WEC
  - 2D: 6.8 m
  - 4D: 8.0 m

→ There might be a height difference of 6.8 - 8.0m and site is still considered non-complex!

Power Curve Testing: Height Definitions and AEP

3. WEC Hub Height

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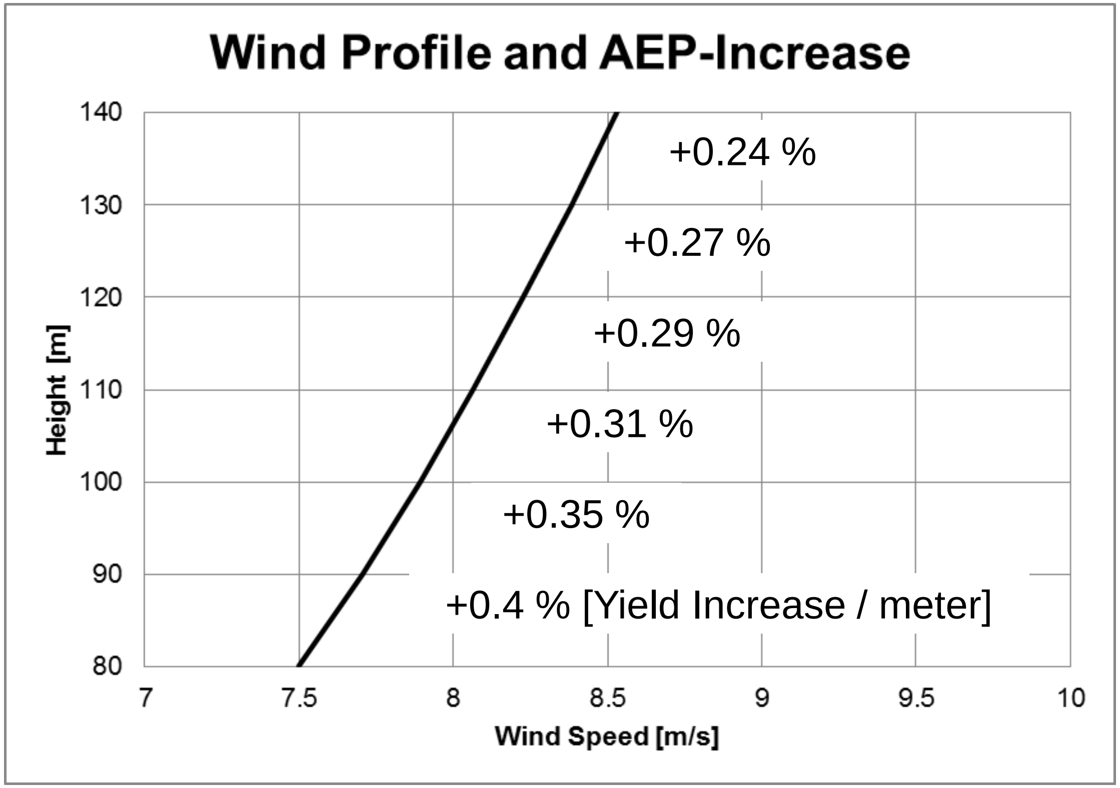
- Installation tolerance of WEC w.r.t. natural site reference height within a few cm
- BUT natural site reference height difficult to obtain
- Natural Site Reference Height
  - Customer installs peg, which is reference for us
  - Site types
    - marshes:
      - flat terrain
      - often surface of crane pad used, which is 20 – 40 cm above surrounding land
    - geest:
      - less flat than marshes
      - sometimes land survey institute averages up to four different reference points
    - low mountain range:
      - site height variations up to 1 m
      - requires agreement of all stake holders (customer, surveyer, officials)

→ Tolerance of natural site reference of 20 – 40 cm assumed

Power Curve Testing: Height Definitions and AEP
Yield Increase and Height

- Result is derived from LiDAR study on different sites.



- AEP-Increase reduces with Height due to Wind Profile.

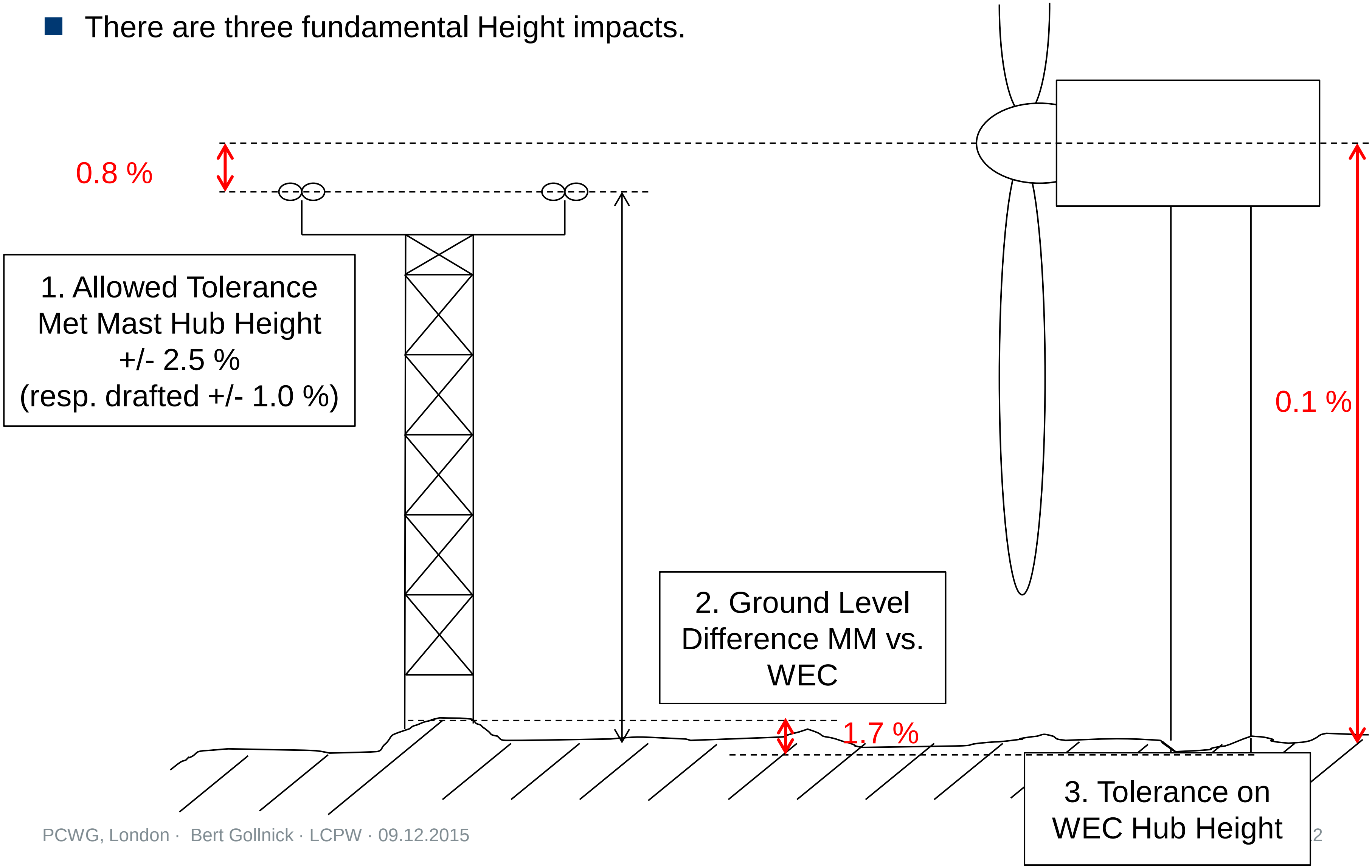
Power Curve Testing: Height Definitions and AEP
Impact on WS and AEP

- Worst Case Assumptions:
- Assumptions
  - 3.2M114 @ 143m Hub Height

Parameter	Value	WS Impact [m/s]	AEP Impact [%]
Tolerance Met Mast Hub Height	+/- 2.5 % = 3.6 m	0.05 m/s	0.8 %
Ground Level Difference Met Mast vs. WEC	6.8 to 8.0 m	0.11 m/s	1.7 %
Tolerance WEC Hub Height	0.4 m	0.01 m/s	0.1 %
Total (worst case)	12.0 m	0.16 m/s	2.5 %

Height Definitions and Tolerances
Revised

- There are three fundamental Height impacts.



Conclusion

- Three parameters define PCV measurement height

1. Tolerance on Met Mast Hub Height
2. Ground Level Difference Met Mast vs. WEC
3. Tolerance on WEC Hub Height

- Worst case study: 11.8 m difference between Met Mast Anemometer Elevation and WEC Hub Height Elevation.

- This impact equals approx. 2.5 % AEP

- Impacts 2 and 3 are not documented. Only impact 1 is documented.

- These height impacts might be as important as wind profile correction (shear and TI).

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PCV Uncertainty

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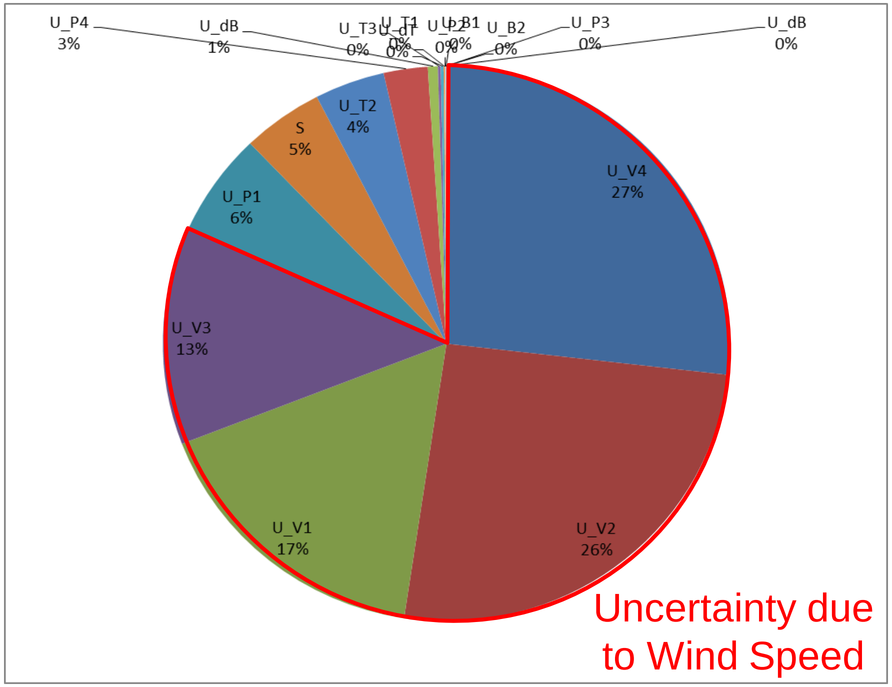
- PCV Uncertainty contractually as important as PCV-Result
- Many Factors affect Result

- Round Robin shows Large Deviation within Institutes
  - PCV-Uncertainty strongly varies: 2.6 % (Institute A), 4.2 % (B), 5.1 % (C) and 17.7 % (D)!

- Wind Speed Parameters most important

- Upcoming -12-1 will address many changes in Uncertainty calculation

- Interesting topic for PCWG???



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Predicting AEP

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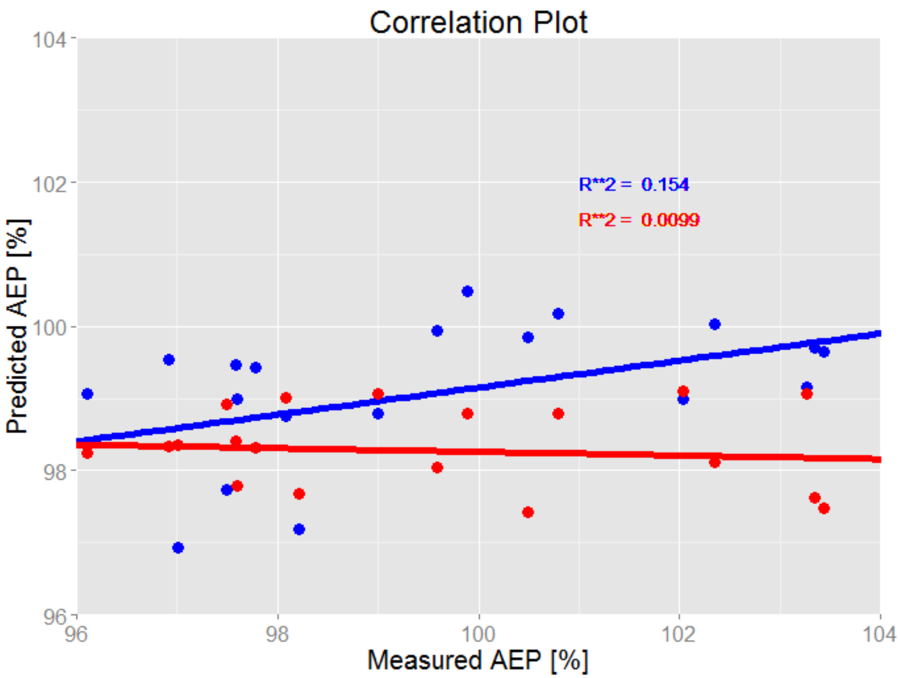
- Comparison of Matrix Approach (WS, TI Matrices for three different Shear Coefficient Ranges) and Multivariate Non-Linear Regression Approach

	Regression-Approach	Matrix-Approach
Parameters (Order)	WS (4), TI (4), Shear (2), Temp (2)	WS, TI, Shear
Complexity of Parameters	12 Parameters	3 Matrices a 15x20 → Up to 900 parameters
Scalability	Approach can easily be extended to cover more Parameters	Each paramete multiplies number of existing parameters



Thank you for your Attention.

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Bert Gollnick
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