Experience of Rotor Averaged Power Curve Measurements in Cold Climates

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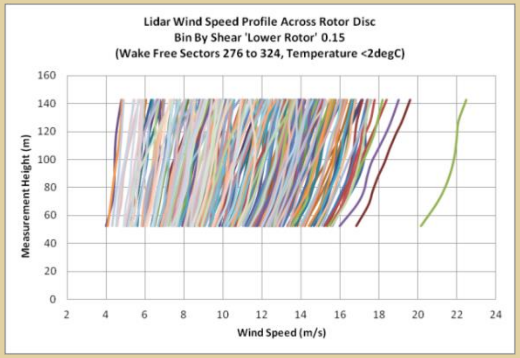
Overview

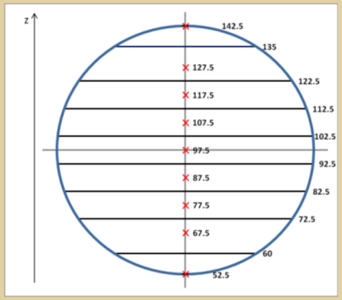
- Background
- Test Set Up
- Analyses
  - Power Curve
  - Site Effects
- Conclusions

Practical Experience of Equivalent Wind Speed Power Curves on a Cold Climate Site

Background

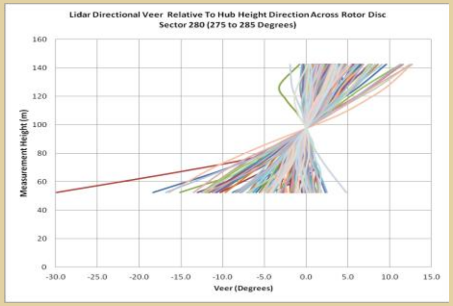
- IEC 61400 12-1 CDV introduces alternative definition of wind speed
  - Shear corrected rotor equivalent wind speed (normative)

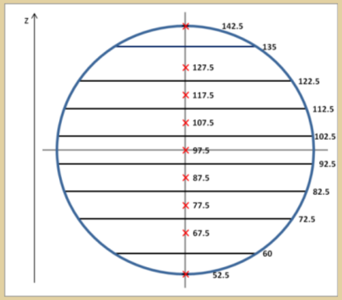




$$v_{eq} = \left(\sum_{i=1}^{n} v_i^3 \frac{A_i}{A} \right)^{\frac{1}{3}} \quad (1)$$

  - Veer (and shear) corrected rotor equivalent wind speed (informative)



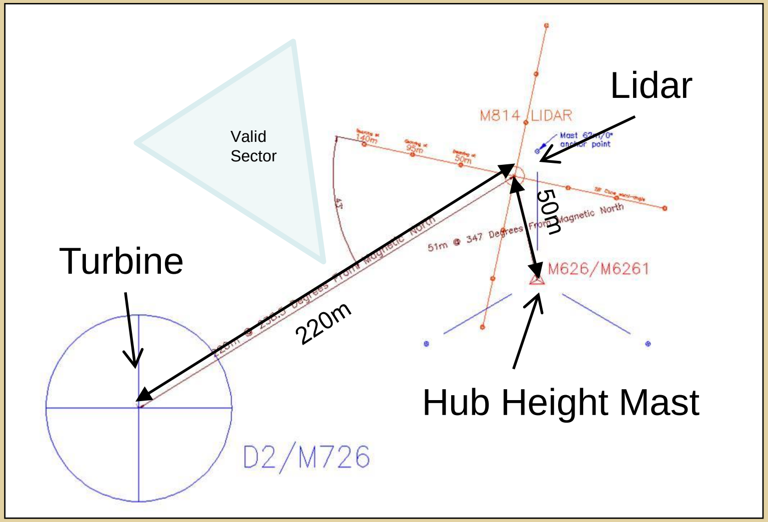


$$v_{eq} = \left(\sum_{i=1}^{n} (v_i \cos(\varphi_i))^3 \frac{A_i}{A} \right)^{\frac{1}{3}} \quad (2)$$

  - Equivalent-to-hub height wind speed correction factor $f_{r,X} = v_{eq,X} / v_{h,X}$

Test Set Up

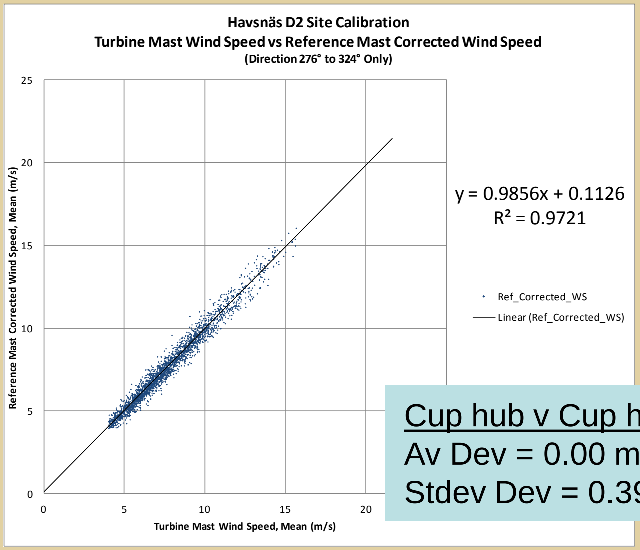
- Retrospective application of remote sensing
  - Vestas V90 2MW on 95m hub height in northern Sweden
  - Moderate terrain and surface roughness complexity
  - Large seasonal variation in climate
  - Pre-existing IEC 61400 12-1 (2005) test set-up with site calibration
  - Leosphere Windcube V1 installed for R&D after completion of power curve warranty tests.



- Limitations
  - Site not flat (IEC requirement)
  - Valid sector perpendicular to mast-to-turbine axis
  - Two stage site calibration
    - Turb Mast > Ref Mast > Lidar
  - Assumption that lidar measured shear profile represents profile at turbine
- However
  - Still likely to be informative

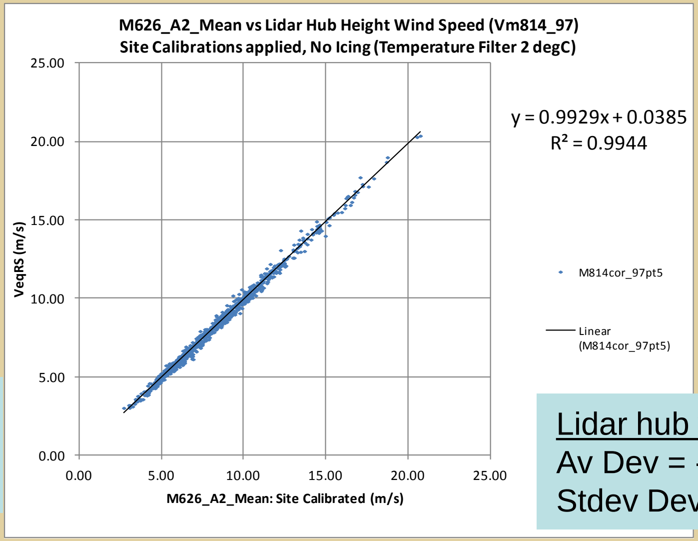
- Two step hub height site calibration (by 10 degree direction sector)
  1. V_c = Hub height ref mast w/s corrected to turbine mast hub height w/s
  2. V_{cL} = Lidar hub height w/s corrected to V_c

1.



Cup hub v Cup hub
Av Dev = 0.00 m/s
Stdev Dev = 0.39 m/s

2.

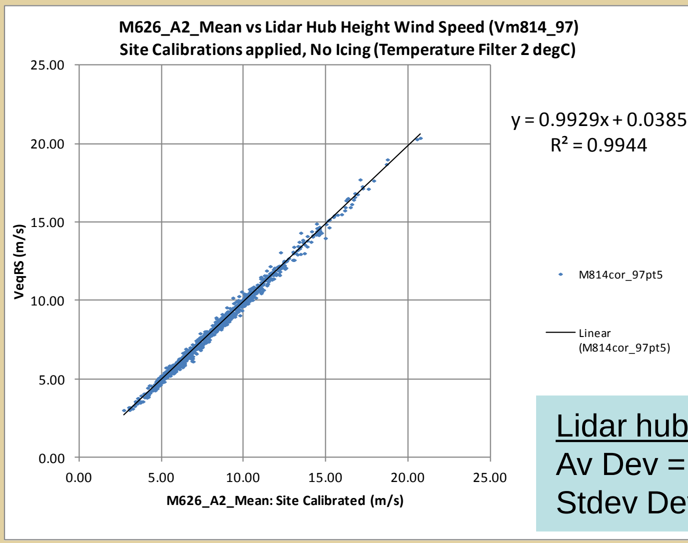


Lidar hub v Cup hub
Av Dev = -0.02 m/s
Stdev Dev = 0.21 m/s

- 1st step site calibration (over 220m distance) lower correlation quality (r^2) than 2nd step (over 50m distance) as expected.
- confident that 2nd step site calibration is at least as valid as 1st step despite different measuring principles (cup anemometer v lidar)

Analyses – Equivalent Wind Speed (Rotor Averaged)

- Equivalent wind speed
  - 10-minute lidar w/s profiles at 10 heights normalised to lidar hub height w/s
  - 10-minute lidar profiles corrected to V_{cL}
  - V_{eq} derived from lidar profiles according to Formula (1) or (2)



Lidar hub v Cup hub
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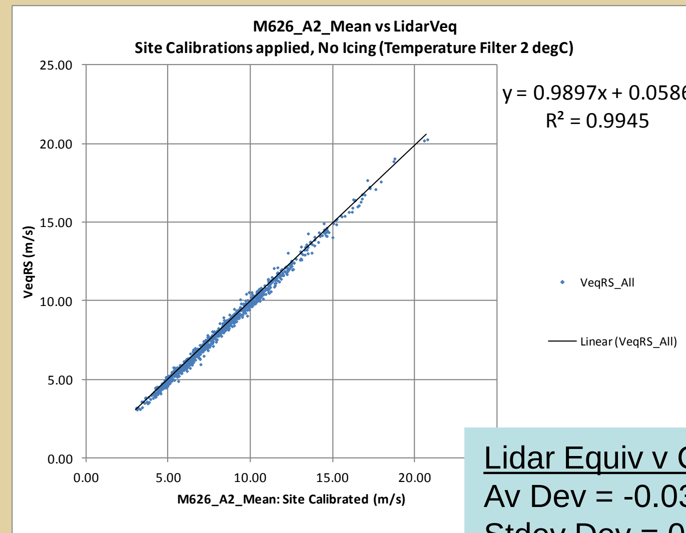
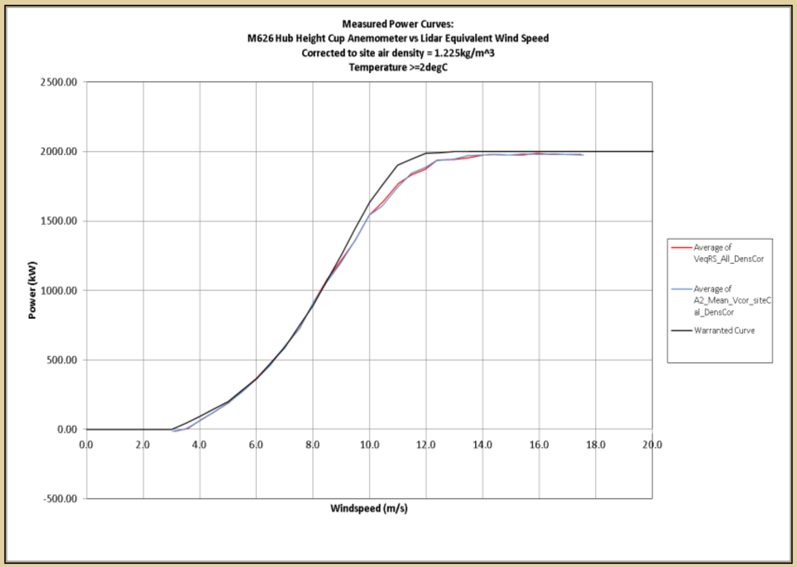


Lidar Equiv v Cup hub
Av Dev = -0.03 m/s
Stdev Dev = 0.21 m/s

  - Equivalent wind speed well correlated to hub height wind speed
  - Small negative bias on corrected lidar wind speeds compared to cup anemometer – perhaps vacet of volumetric lidar measurement

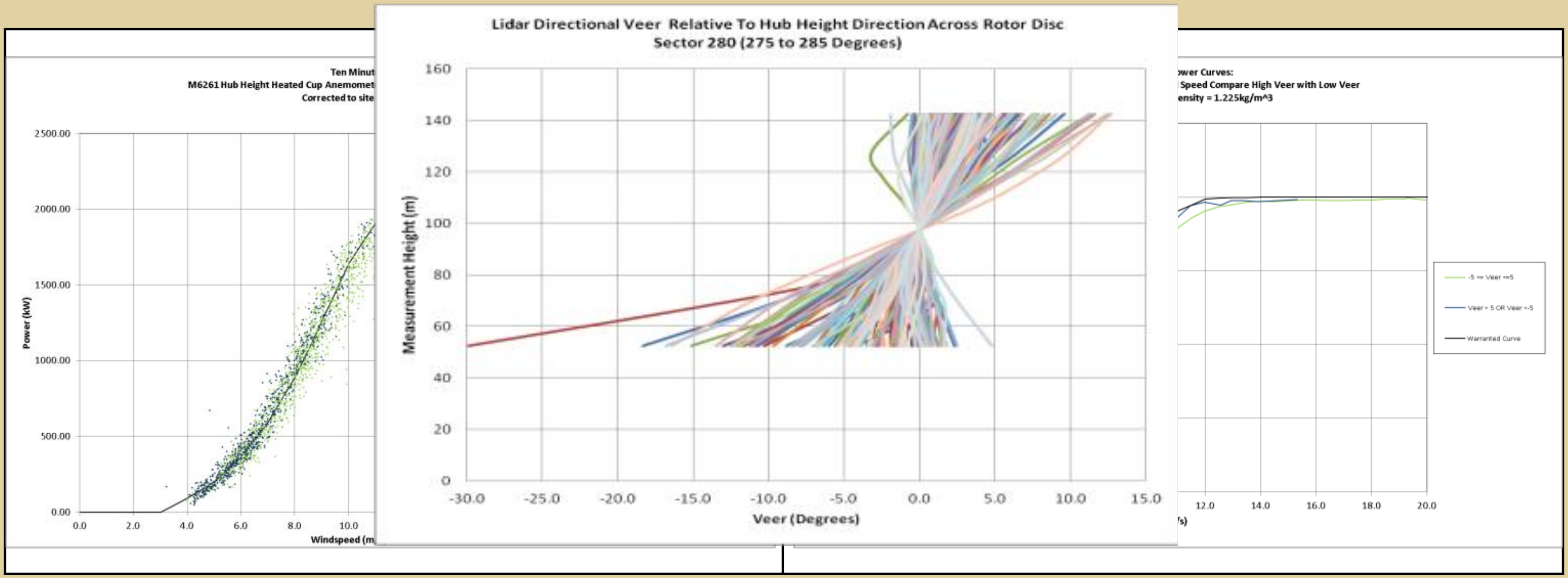
- Power curves derived using hub height and equivalent w/s definitions
  - Energy production derived for site specific wind speed distribution
  - Results presented wrt production from warranted power curve



Test	Anemometer	AEP Diff.
Test A	Cup 1 V_{m626}	-0.10%
	Cup 2 V_{m6261}	
Test B	Cup 1 V_{m626}	+0.61%
	Lidar V_{m814_97}	
Test C	Cup 1 V_{m626}	+0.59%
	Lidar V_{eq}	

- Lidar derived hub height and equivalent w/s power curves
  - Positive energy bias wrt cup anemometer power curve. As expected from negative bias in lidar w/s >>> Power curve shifted to left.
  - Suggest that hub height w/s is representative of energy through rotor on this specific test.

Data filtered into High and Low Veer Cases



Low veer is considered to be a value between -5 and +5 degrees. High veer is considered to be any value outside this range.

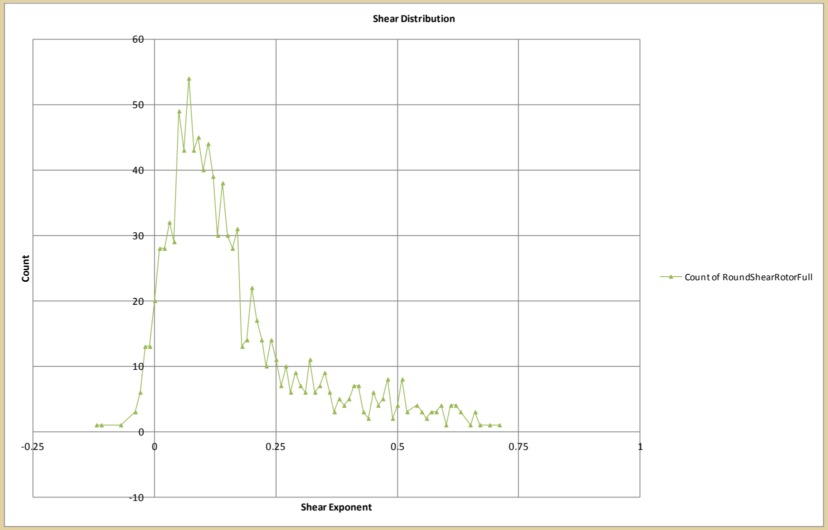
Applying Veer correction Formula (2)

Test	Anemometer	AEP Diff.
Test C	V_{eq}	
Test D	V_{eq_VEER}	+0.14%

Power Curve Measurement Conclusions

- Consistent equivalent wind speed power curve measurements possible
- Measurement method bias apparent in lidar based results despite calibration against adjacent hub height anemometer
- On this site (and another in France), hub height and equivalent wind speed power curves agree closely (compared to measurement uncertainties)
- Power curve measurement inflow conditions were not representative of the site average conditions.
- Turbulence impact on measured power curve dominates over shear and veer.

- Shear distribution of power curve data
  - T > 2 deg C => ice free conditions for anemometer to lidar comparison
  - Not typical of seasonal distribution of shear on this site
  - Practical difficulties in measuring power curve in Swedish Winter conditions
  - What do we expect impact of Winter conditions



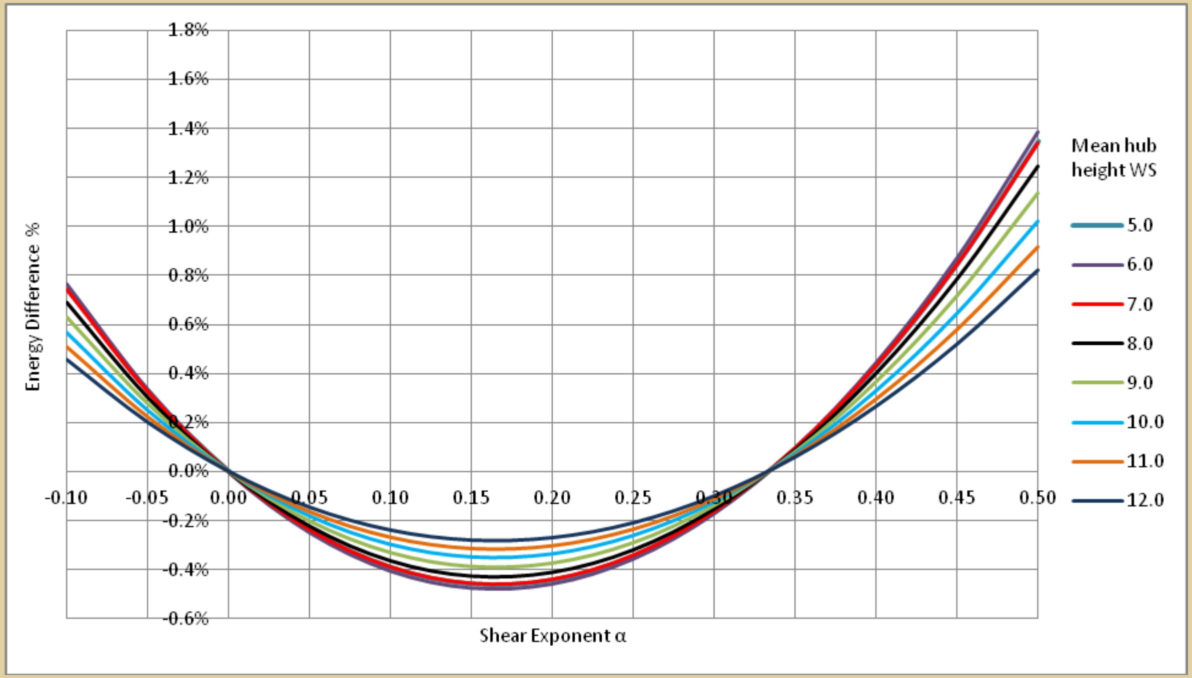
Power Curve Campaign Shear Distribution

Energy Difference

(Gain or Loss)

$\delta\alpha_A$ + ve, If use of V_{hh} underestimates energy yield

- ve, If use of V_{hh} overestimates energy yield

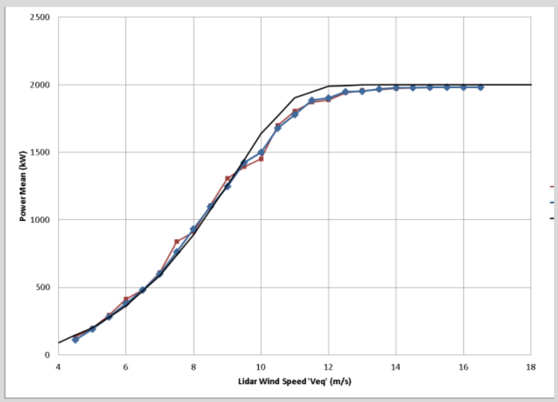
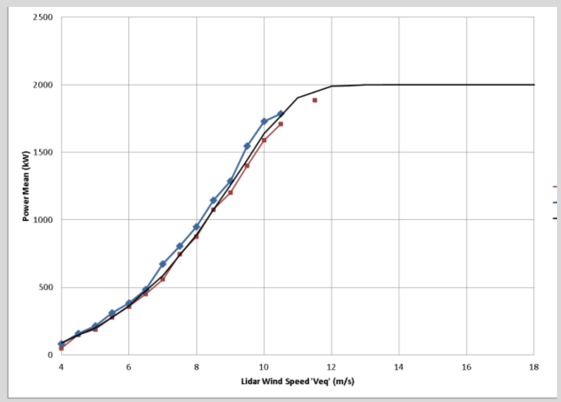
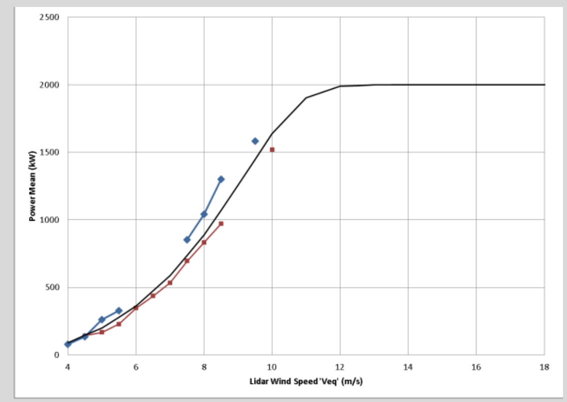


Measured shear statistics

Shear Case	Mean	Standard Deviation
α_Lower	0.236	0.225
α_Upper	0.304	0.309
α_RotorFull	0.262	0.216

Shear Filtered Power Curves

Divergence of hub height w/s measured power curves with progressively higher shear

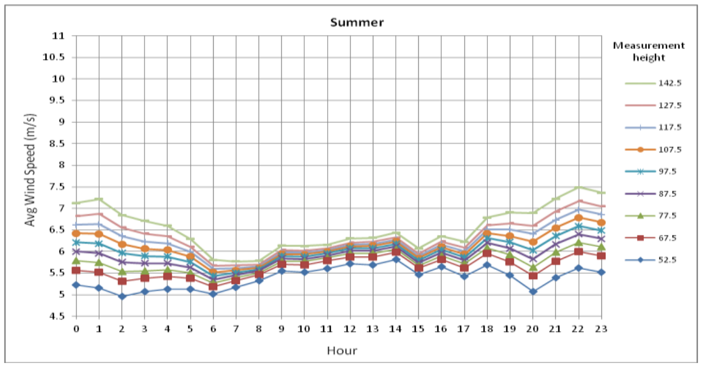
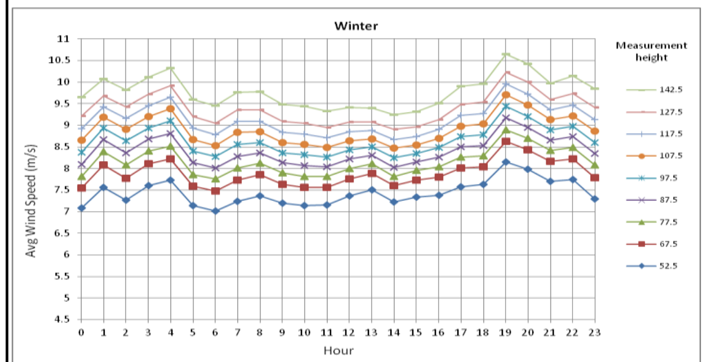
α = 0.15	α = 0.35	α = 0.5
		

Note: Shear measured over lower half of rotor

- Red represents wind speed = Veq
- Blue represents wind speed = Vm6261
- Black represents warranted power curve

V_{eq} power curve segments appear more consistent over a wide range of shear. Warranted power curve range of validity perhaps greater if redefined in terms of V_{eq}?

AVAILABLE ENERGY TIME SERIES ANALYSIS WITH LiDAR DATA

<table>
<tr><th>Hourly Means</th><th>Summer</th><th>Winter</th></tr>
<tr><td>LiDAR Wind Speed</td><td>
</td><td>
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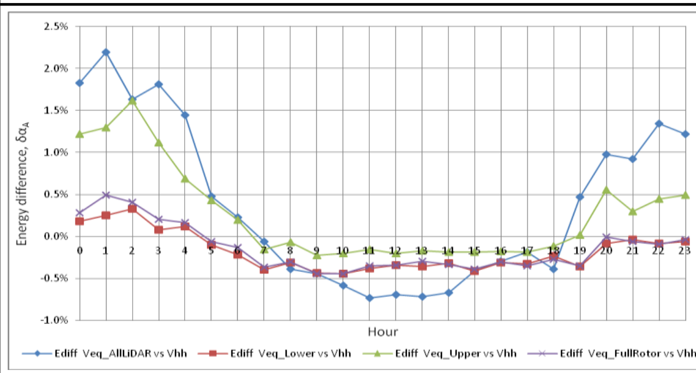
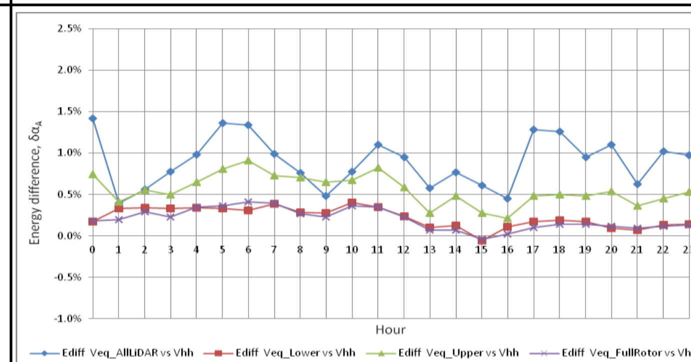
<tr><td>EY Difference
(2MW turbine at LiDAR location)</td><td>
</td><td>
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Hub height w/s likely to underestimate annual energy on this site.
Site wind regime defined in terms of Veq with Veq power curve may improve assessment

Conclusions

- IEC 61400 12-1 CDV Equivalent wind speed practical with lidar even in harsh, Swedish environment.
- Measurement bias not yet investigated but can be accounted for.
- Redefining wind speed in terms of V_{eq} appears to increase range (of shear) applicability of power curve.
- Only meaningful if site wind regime redefined to V_{eq}
- Turbulence impact on power curve not presented here but significant.

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