Havsnäs Pilot Project

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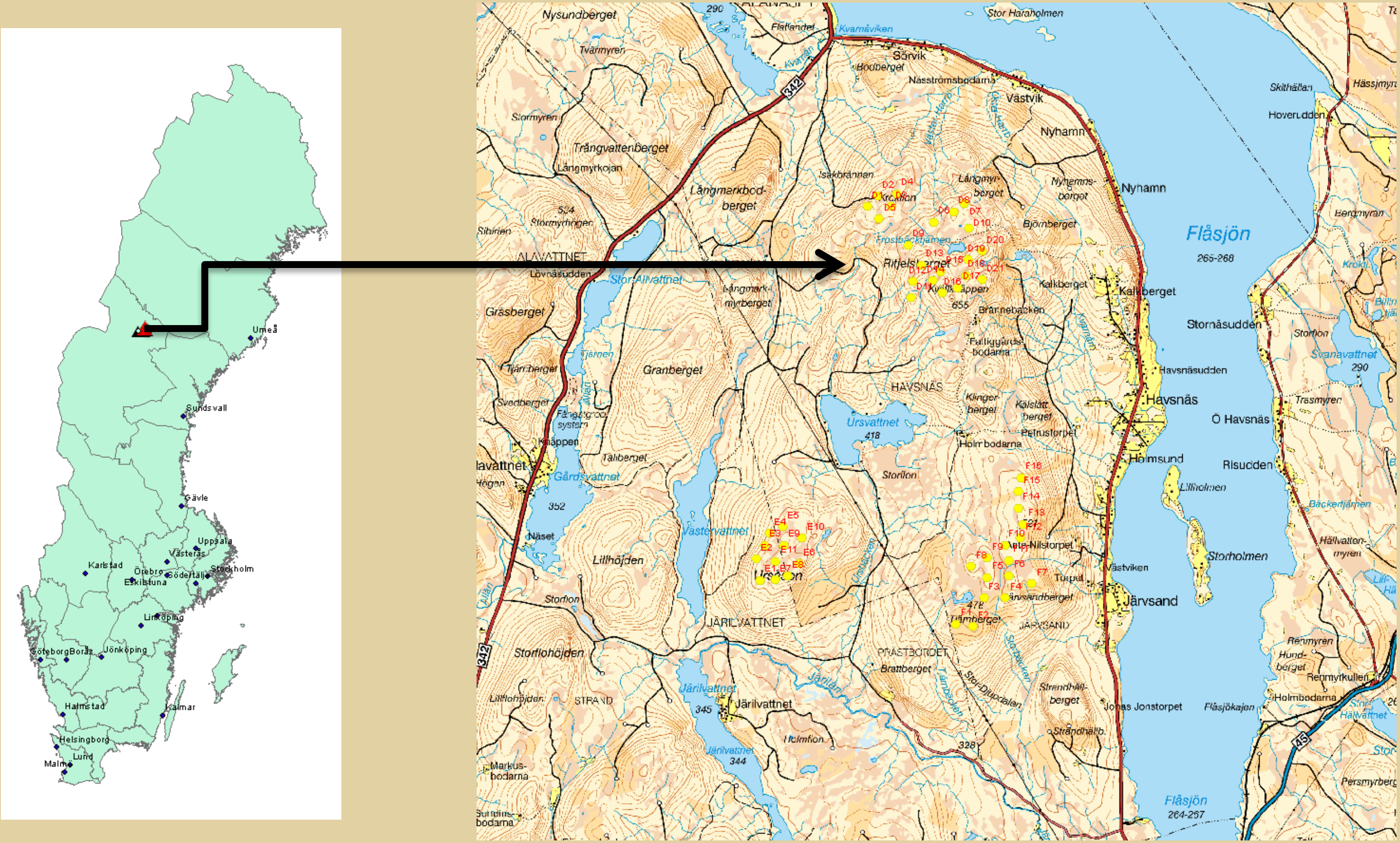
Winterwind, Östersund February 2013

power for good

Havsnäs Site Location



- 110 km North of Östersund, Jämtland (240km West of Umeå)
- Area of national interest for wind power.
- Spread over 3 hills occupying 20km x 10km .
- 510 to 650m asl
- Surroundings are lakes, marsh and forest.
- 48 x Vestas V90 on 95m towers
  - 45 x 2.0 MW + 3 x 1.8 MW
  - Largest onshore windfarm in Sweden
- Commission Summer 2010.

NV Nordisk Vindkraft Awarded a Pilot Project grant by Swedish Energy Agency in 2009.

Pilot Grant Key Information

- Purpose
  - To help remove barriers to future large scale on shore wind farm development in northern Sweden
- Havsnäs Project Non-Technical Research Areas
  - Nature value (impact on forest birds and reindeer)
  - Project finance (not common in Sweden)
  - Foundation (design for cold climate and wet ground)
- Establishment of Havsnäs Grid Company (connection to national grid)

- Havsnäs Project Technical Research Areas
  - High Hub Heights (uncertainties of shear extrapolation)
  - Cold Climate (instruments, wind flow modelling, icing, power curves)
- Timescales
  - 20/04/2009 to 31/12/2011 – extended to March 2013 due to wind farm operational issues.

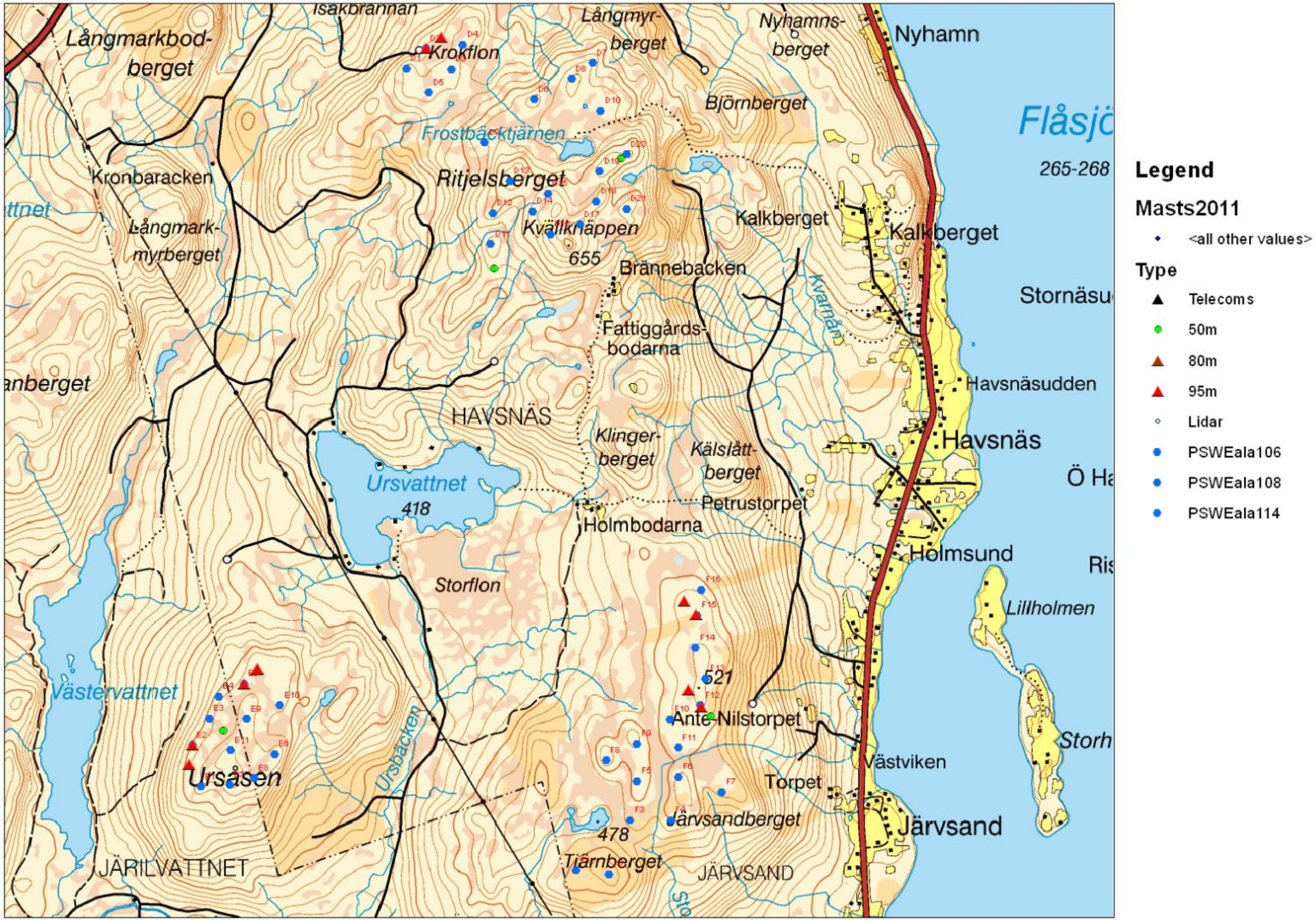
Technical Scope – From Resource Assessment to Operational Performance

- Cold Climate Instrumentation Reliability
- Lidar Measurements in a Cold Climate
- Mast Dispersal
- Mast Height vs High Hub Heights
- Shear & Vertical Extrapolation of Wind Speed
- Shear & Energy Content through Rotor
- Atmospheric Stability – Measurement and Implications
- Wind Flow Modelling – Linear vs Coupled Mesoscale/CFD
- Power Performance Measurements – Equivalent Wind Speed Power Curves
- Predicted vs Actual Wind Farm Performance
- Energy Lost Due to Icing
- Ice Throw Simulation – Health & Safety Implications (& Validation)

Wind Measurements at Havsnäs

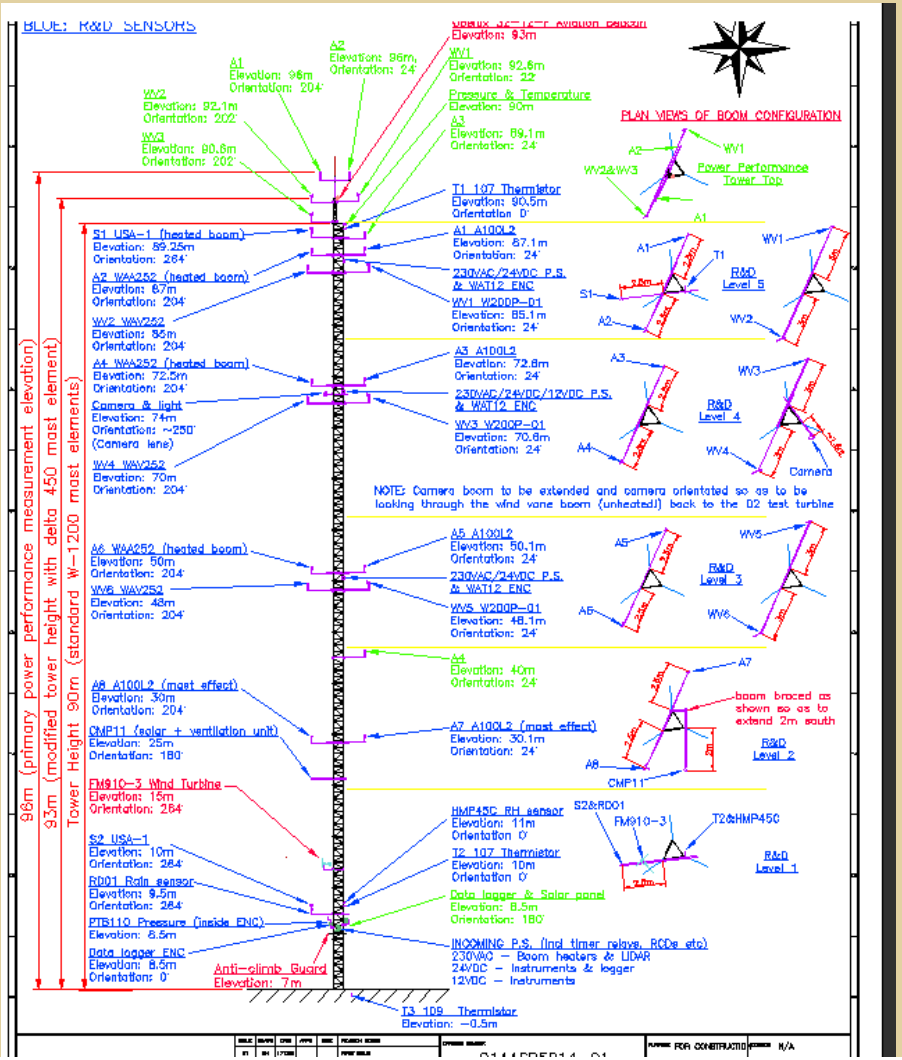
- Wind measurements started November 2003
  - 4 x 50m masts, 1 x 80m mast
  - 1 x off-site telecoms mast with heated reference instruments from 2003 to present day.
- 10 x 95m masts installed Summer 2008 for site calibration
  - 5 removed pre-construction
  - 5 remain for power performance and R & D
  - 3 of 5 masts fully instrumented for research purposes Summer 2010.
- Leosphere Windcube Mark 1 lidar deployed for R & D.

Measurement Locations



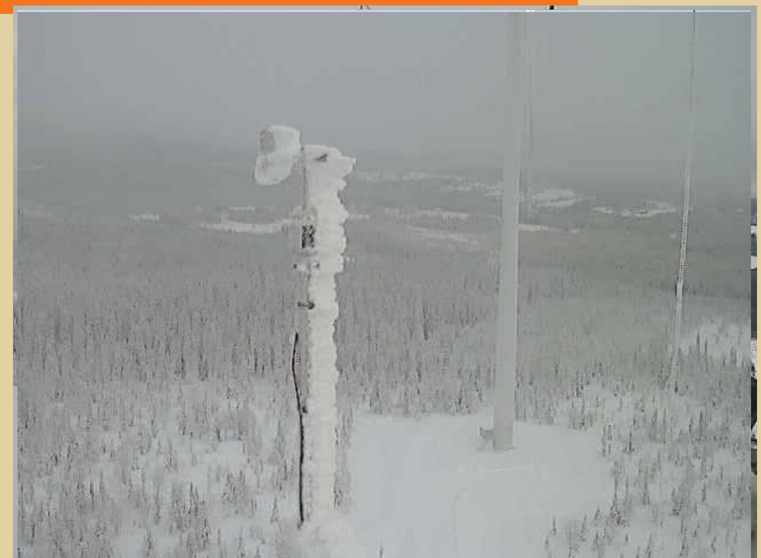
95m R & D Measurement Mast (3 – off)

- Pairs of heated (WAA252) and un-heated (A100) Ano's at 3 elevations (with heated booms)
- Pairs of heated (WAV252) and un-heated (W200P) wind vanes at 3 elevations
- Ultrasonic aneometers at 2 elevations.
- Mast blockage anemometer pairs at one elevation.
- Temperature, pressure, humidity, solar radiation and rain sensors
- Web cam
- Permanent Mains Power!



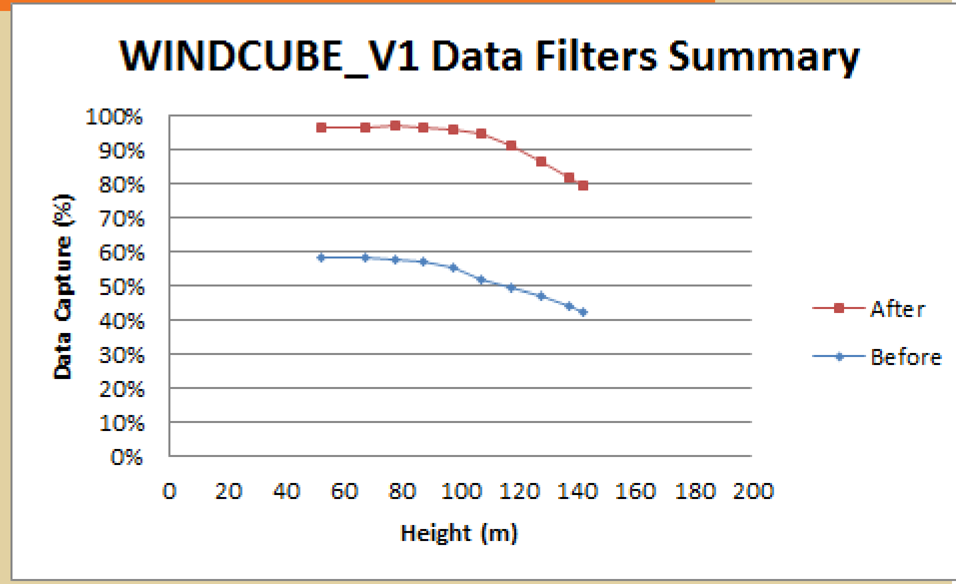
Mast Instrumentation Key Results

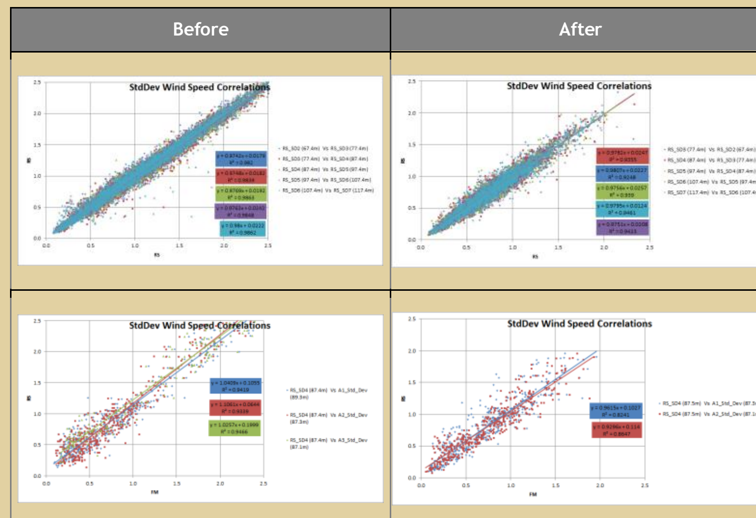
- Heated anemometers are not completely immune to icing – ca 1% to 2% data loss compared to 20% to 30% unheated.
- Heated instruments only as good as their power supply – 12% to 35% data loss due to power supply issues.
- Impact of ice load on instrument and boom static and dynamic loading to be assessed at design stage.
- Wind vanes are less prone to sticking in icing condtions – 8% to 27% lost – little difference heated or unheated > care needed interpreting data.
- Robust ultrasonic anemometer required for severe ice climate.



WindCube V1 Lidar Key Results

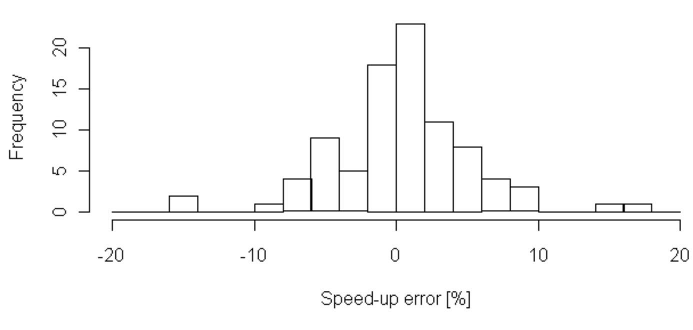
- Scans per line of sight quadrupled due to low aerosol density at this northern latitude > fewer measurements per 10-minute average.
- Extra heating/insulation required.
- Snow protection required.
- Significantly more data passing quality filters after modifications.
- Mean wind speed well correlated with fixed mast.
- Wind speed standard deviation well correlated with fixed mast.
- Validation of lidar against fixed mast on the site of interest is necessary.

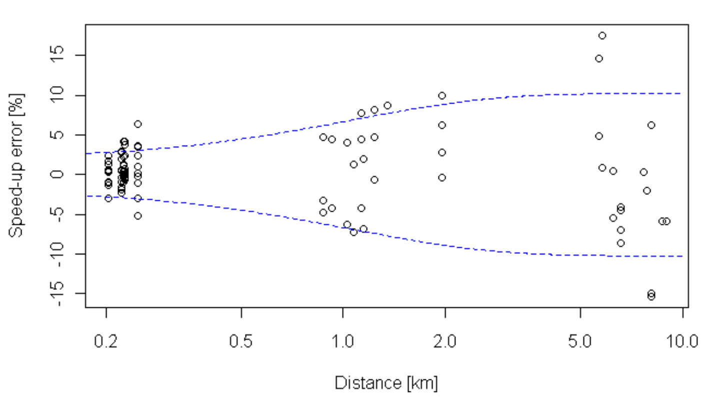




Mast Dispersal and Wind Flow Modelling Uncertainty

- Compare inter-mast wind speed ratios with linear flow model speed ratios by direction (30 degree sectors).
- 90 mast pair/direction sector cases possible from the quality controlled Havsnäs met mast data set.
- MS3DJH linear flow model used to derive modelled speed ratios.
- Standard deviation of speed ratio error = 5% (top right)
- Strong correlation of speed up error and mast separation.
- Havsnäs findings consistent with wider RES study of masts across many RES sites
- Flow modelling introduces significantly higher uncertainties if initialisation masts separated by more than 1km in complex flow environment.



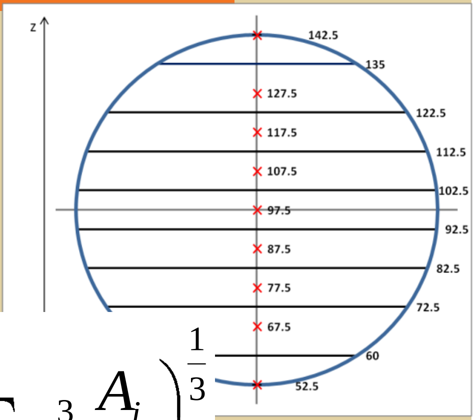


Mast Height compared to Very High Hub Heights

- Performance of common shear profile models evaluated with regard to extrapolating wind speed from lower measurement heights compared to actual hub height measurements.
- Assess ability of models to
  - Characterise profile; i.e. Goodness of fit to measured profile
  - Represent continued profile above measurement height; i.e quality of extrapolation.
- Multi-point shear method (3 or more measurement heights) was best overall performer and relatively insensitive to forest canopy height errors (i.e. Displacement height effects).
- Two point power law also performs well although sensitive to choice of measurement heights.
- Remote sensing campaigns adjacent to long-term masts recommended to validate profile behaviour above mast measurement heights.
- More detail in presentation by Iain Campbell later in this Winterwind session

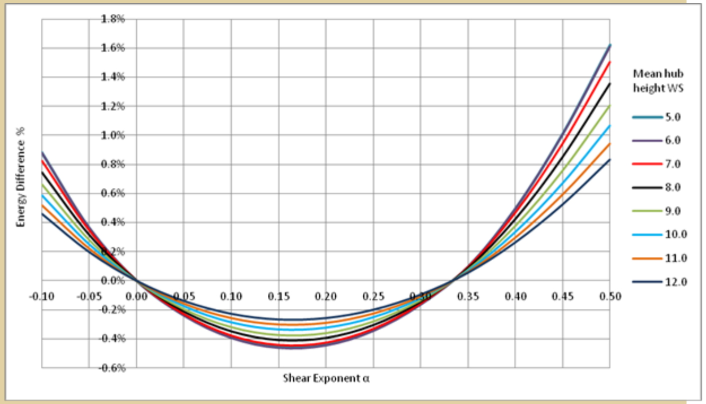
Shear Profile and Energy Content through Rotor Disk

- Remote sensing can provide knowledge of profile across entire turbine rotor disk height range.
- Energy Content through rotor uses concept of rotor “Equivalent Wind Speed” V_{eq}
- Theoretical and lidar measured profiles compared.
- Shear profile can impact:
  - Energy Available to the turbine
  - Aerodynamic Efficiency of the turbine
  - Predicted v Actual energy error dependent on both components.
- Sensitivity Analysis of lidar profiles at Havsnäs turbine D5 suggests that Available Energy is 0.8% greater than the theory suggests.
- However, uncertainties in measurements large.

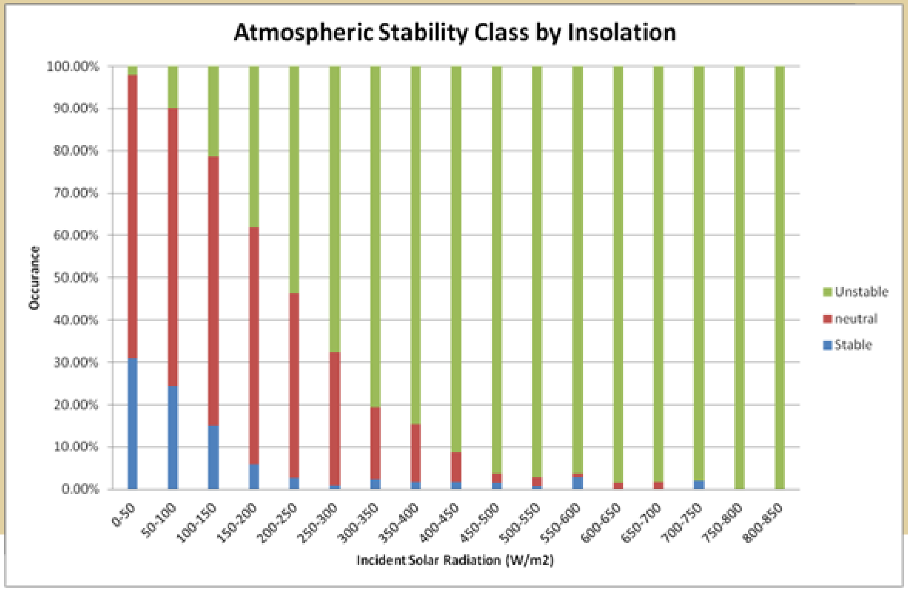


$$v_{eq} = \left(\sum_{i=1}^{n} v_i^3 \frac{A_i}{A} \right)^{\frac{1}{3}}$$

$$\delta\alpha = \delta\alpha_A + \delta\alpha_P$$



- Atmospheric Stability Defines:
  - Mixing of vertical layers in atmosphere
  - Turbulence
  - Shear profile
  - Temperature Gradient
- Measurements at two masts evaluated:
  - Flux methods
  - Gradient methods

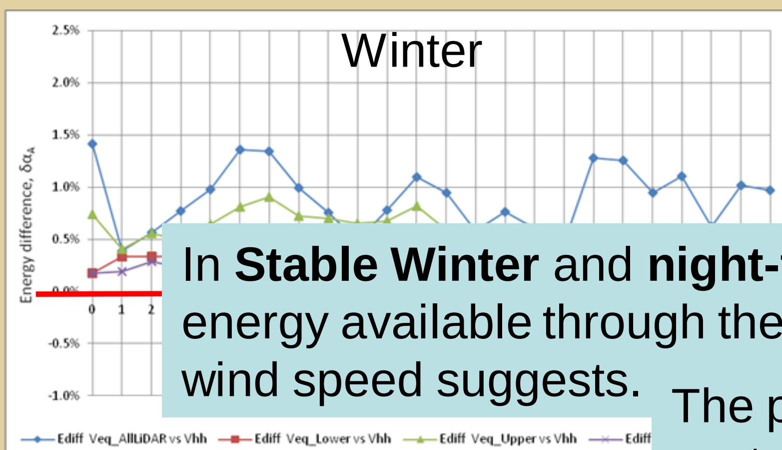


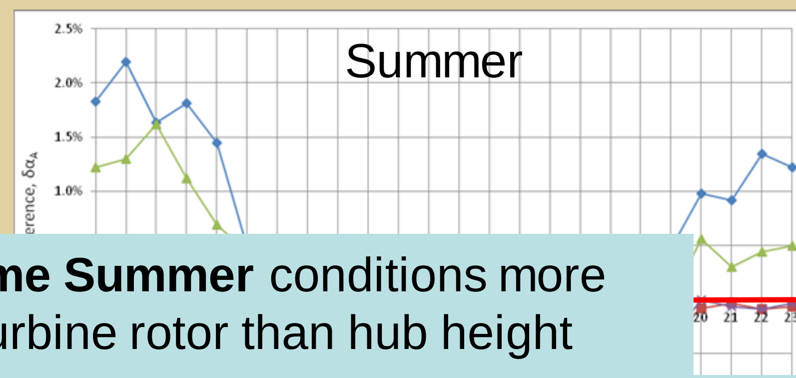
- Flux methods
  - More costly instrumentation required
  - Instruments not robust
  - Ultimately generated little data
- Gradient methods
  - Simple instrumentation
  - Relatively successful data capture
  - Higher uncertainty in stability results.

- Sufficient measured evidence to suggest that stability dependent:
  - Shear models
  - Turbulence models
  - Energy Conversion Methods (rotor equivalent wind speed)
  - Wind Flow Models

are required for sites like Havsnäs

Available-Energy Deficit Based on Lidar Measured Wind Profiles



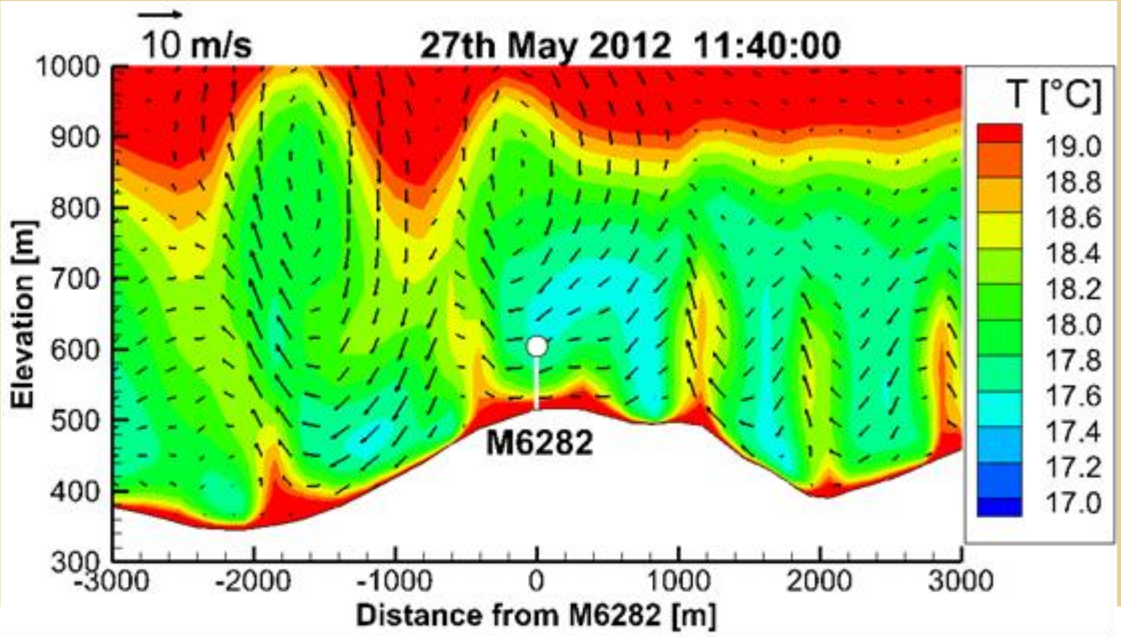


In **Stable Winter** and **night-time Summer** conditions more energy available through the turbine rotor than hub height wind speed suggests.

The problem is present day turbines **cannot** capture it all due to sub-optimal aerodynamic performance in high shear

Wind Flow Modelling – Coupled Mesoscale/CFD

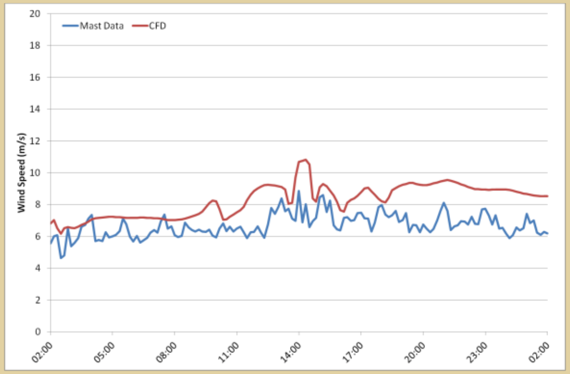
- Stability implications modelled via coupled Mesoscale/CFD VENTOS®/M
  - WRF Mesoscale
  - VENTOS® CFD
- 9 separate days between 17th November 2011 and 30th May 2012 simulated and compared with on-site measurements
- Range of stability, snow cover, wind speeds and temperatures covered.

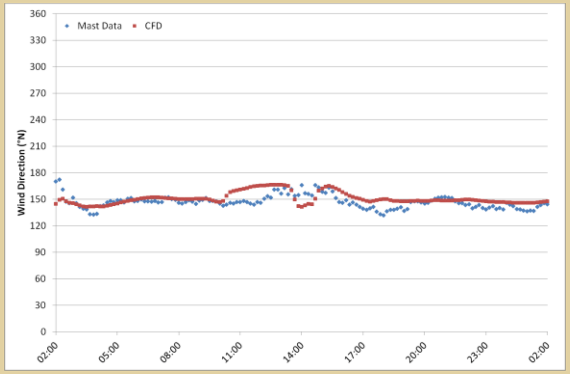


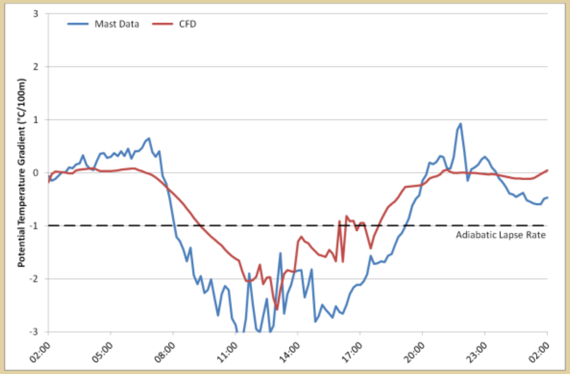
Unstable example showing daytime thermals rising and vertical mixing

Stable example showing night time temperature inversion and suppression of vertical mixing

- A larger number of days required to draw strong conclusions but:
  - Shows promise as illustrated here:







Wind Speed

Wind Direction

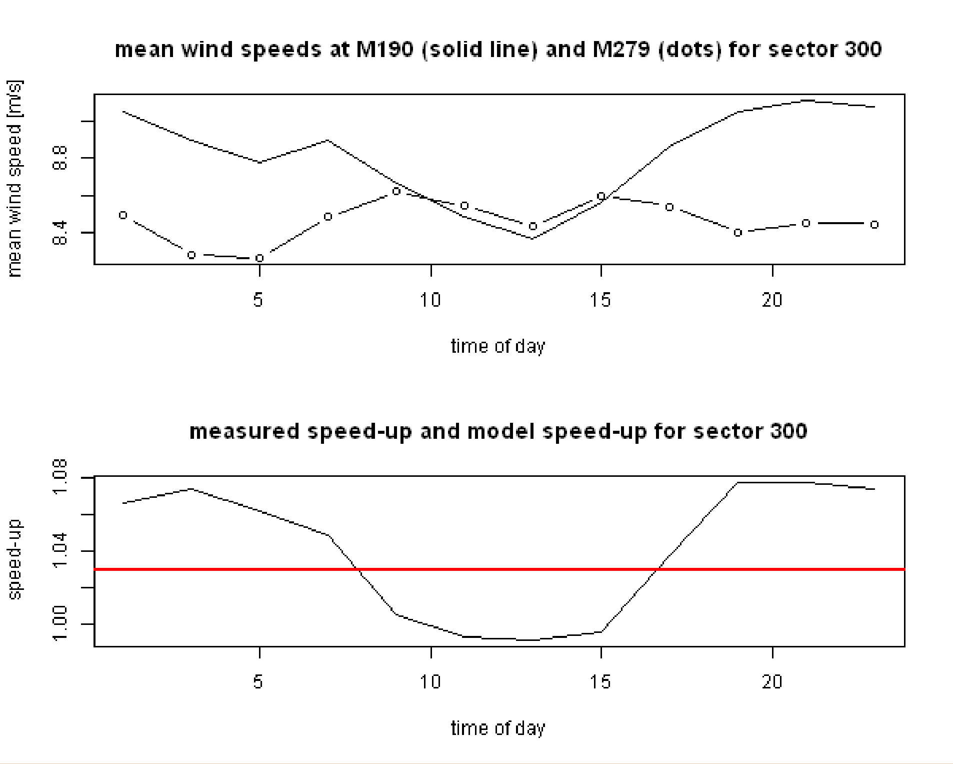
Temperature Gradient

Measured

Coupled Mesoscale/CFD

Reminder about Linear Flow Model Performance

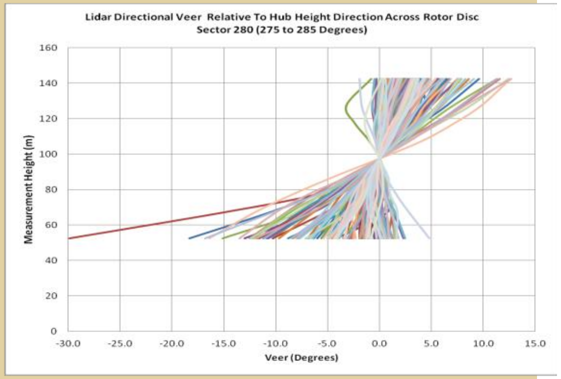
- Tuned for neutral conditions
- Does not model stability variations (without empirical tweaking)
- But may still be good enough on average



Pre and Post Construction Annual Energy Yield Estimates already agreed within 1% at Havsnäs.

Measured
Linear Flow Model

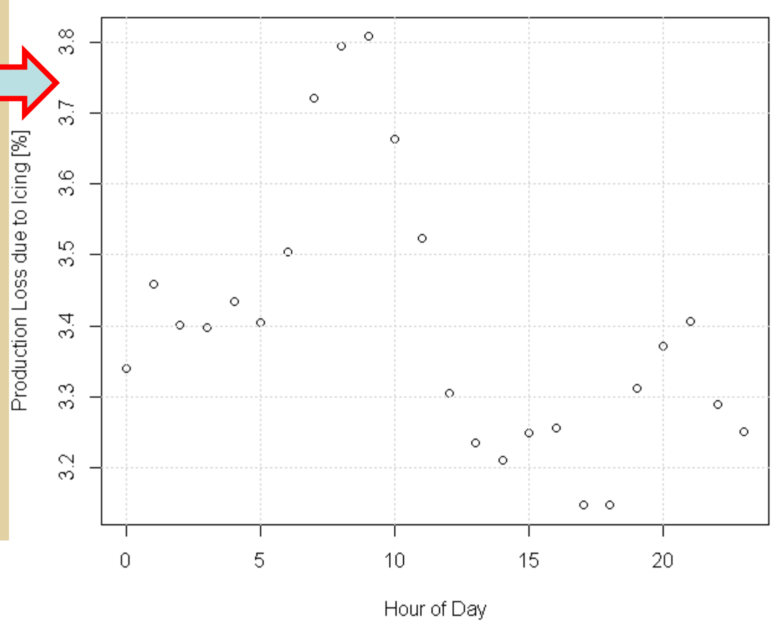
- New draft IEC 61400 12-1 Equivalent Wind Speed Power Curve procedure tested using lidar data at turbine D5.
- Turbulence normalisation procedure tested.
- Veer correction tested.
- Results completely site and turbine specific – not generic, but suggested that:
  - Hub height wind speed and equivalent wind speed power curves near identical.
  - Turbulence impact on 10-minute averaged power curve dominates distortion of measured power curve. Difficult to isolate shear and veer profile impact.
  - Significant veer measured across rotor.
  - Lidar is a practical supplement to a power performance test set-up, providing insight to the flow impacting the whole turbine rotor height.
  - Using lidar with a hub height mast has the potential to reduce power curve measurement uncertainty by 2 to 3%



Production Lost Due to Icing

- Evaluation of entire wind farm using SCADA data (Oct 2010 to Sep 2012).
- Comparison of nacelle power curves with expected nacelle power curve.
- Most icing loss occurs near 0°C
- Strong correlation between icing loss and turbine elevation.
- Strong correlation between reduction in icing loss and solar insolation, i.e. natural deicing – 0.6% reduction on average.
- Measured annual average icing loss =4.1%
- Agrees well with pre-construction estimate = 4.0%

Month	Icing loss as % of expected monthly yield
Jan	11.0%
Feb	13.3%
Mar	0.1%
Apr	0.4%
May	0.2%
Jun	0.0%
Jul	0.0%
Aug	0.0%
Sep	0.0%
Oct	0.5%
Nov	2.1%
Dec	4.7%



Conclusions/Benefits of Havsnäs R&D Project

- With the benefit of a site which:
  - Is typical of most in northern Sweden – cold climate, forested.
  - Has multiple dispersed met mast locations typical of RES sites in Sweden
  - Has comprehensive extra instrumentation and data sets
  - Has access to wind farm operational data
- We can conclude that:
  - Existing methods used by RES/NV for wind measurement, shear extrapolation, wind flow modelling and yield prediction are fundamentally right.
  - Evaluation of stability via gradient measurement methods may be the most practical method to employ on these harsh, challenging sites.
  - Remote sensing measurements and their detailed evaluation (e.g. Profile validation, rotor equivalent wind speeds, wind veer, power performance) should become a standard part of the measurement campaign for this environment.
  - Further work (more test cases) required to assess benefit of coupled mesoscale/CFD models to energy yield prediction process.
  - Pilot Project has been valuable and has improved knowledge of cold climate issues considerably.

Acknowledgments

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  - Nicola Atkinson, Iain Campbell, Alex Clerc, Jennifer Cronin, Alice Ely, Simon Feeney, Gail Hutton, Marine Lannic, Malcolm MacDonald, Alastair Oram, Magnus Andersson, Jeremy Bass , Paul Berrie, Garyth Blair, Richie Cotton, Cody Cox, Victor Donnet, Alan Duckworth, Euan George, Magnus Hopstadius, Loïs Legendre, Lenton McLendon , Stephen Peters, Peter Stuart, Colin Walker, Min Zhu
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- The final report will be published on the Energimyndigheten web site in the coming months.

Energimyndigheten

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