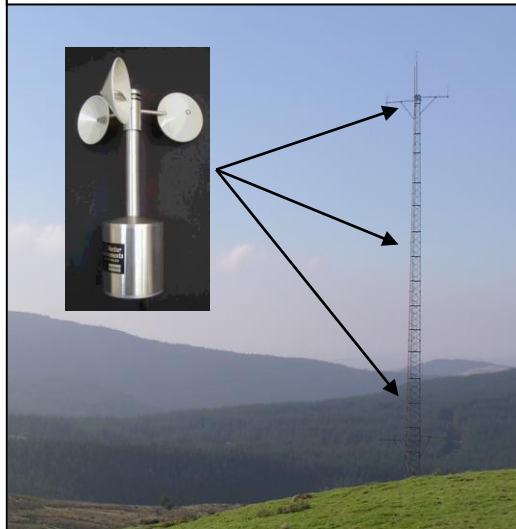


Addressing wind farm performance issues in the Nordics

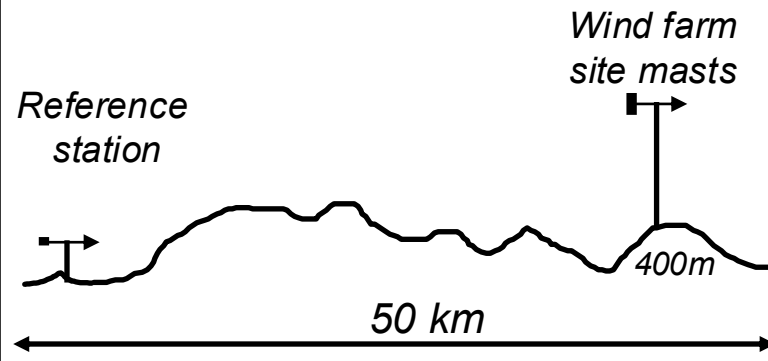
Christiane Montavon, Henning Straume, Jakub Gubanski, Wolfgang Winkler, Ibrahim Serdar Eminoglu

Status

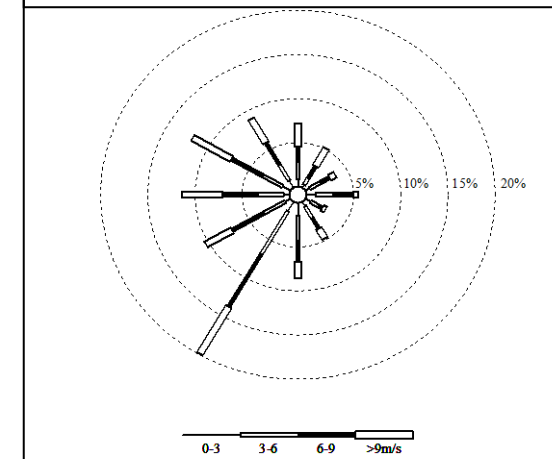
1. Measure wind climate



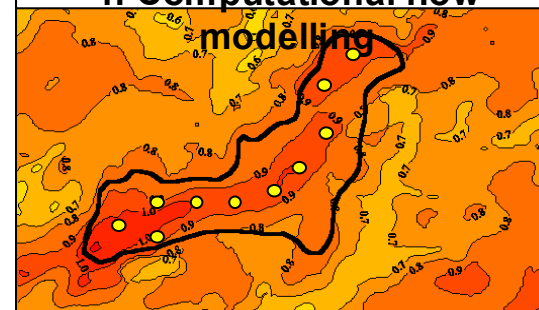
2. Correlate to a long-term reference



3. Calculate the wind rose

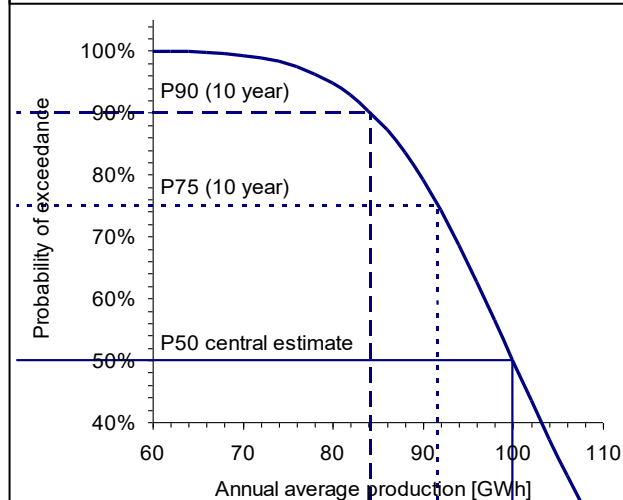


4. Computational flow modelling



long-term wind
forecast steps

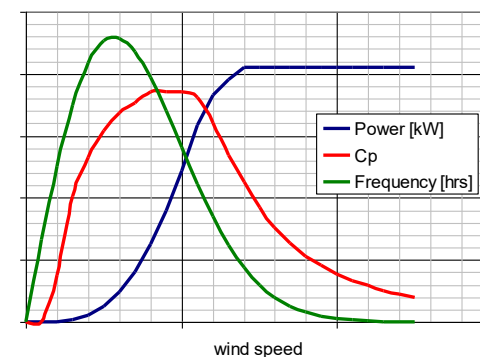
7. Estimate uncertainty



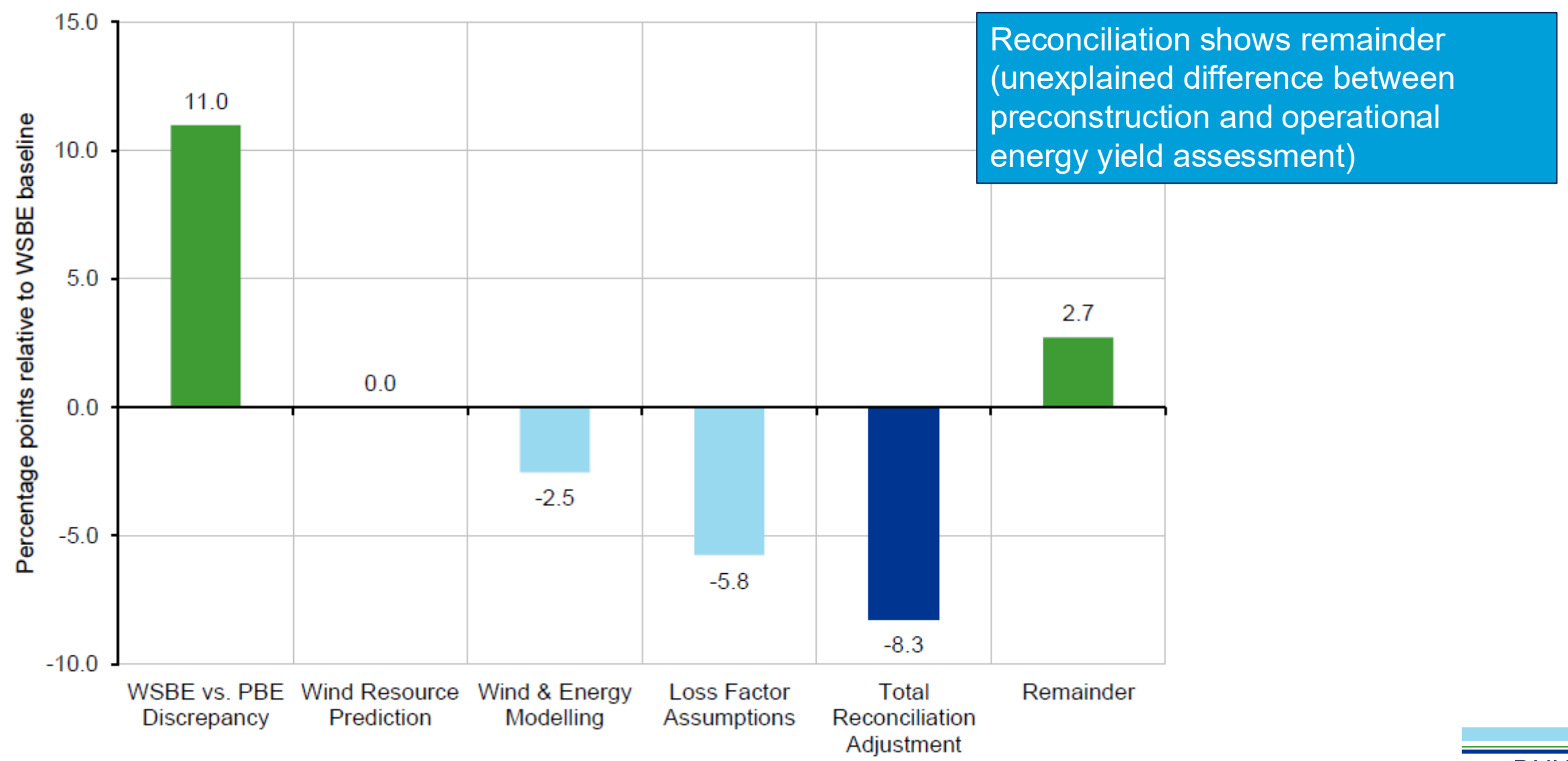
6. Estimate losses

Wake effects
Availability
Electrical efficiency
Turbine performance
Environmental
Curtailments

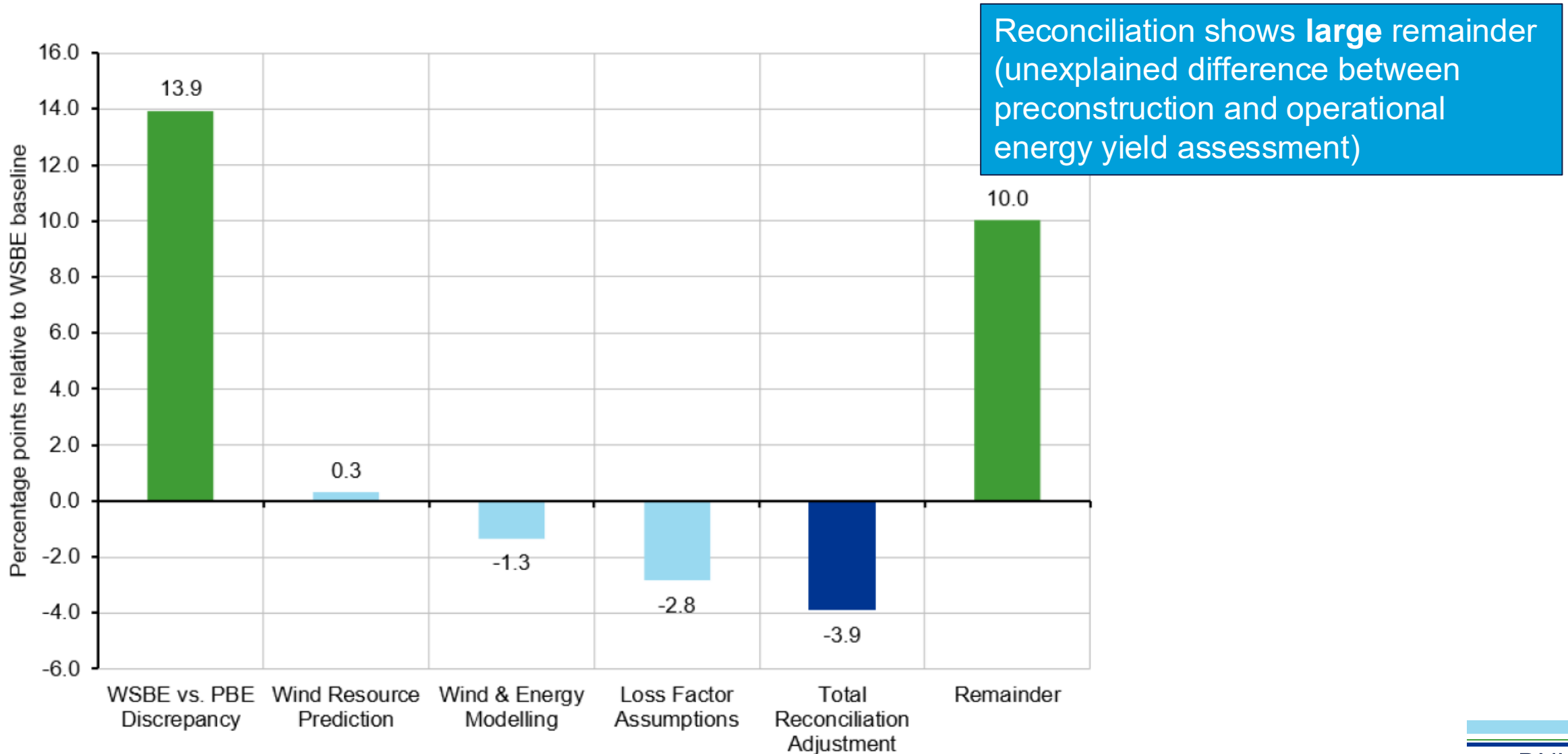
5. Apply turbine characteristics



Frequent occurrence for wind farm in the Nordics

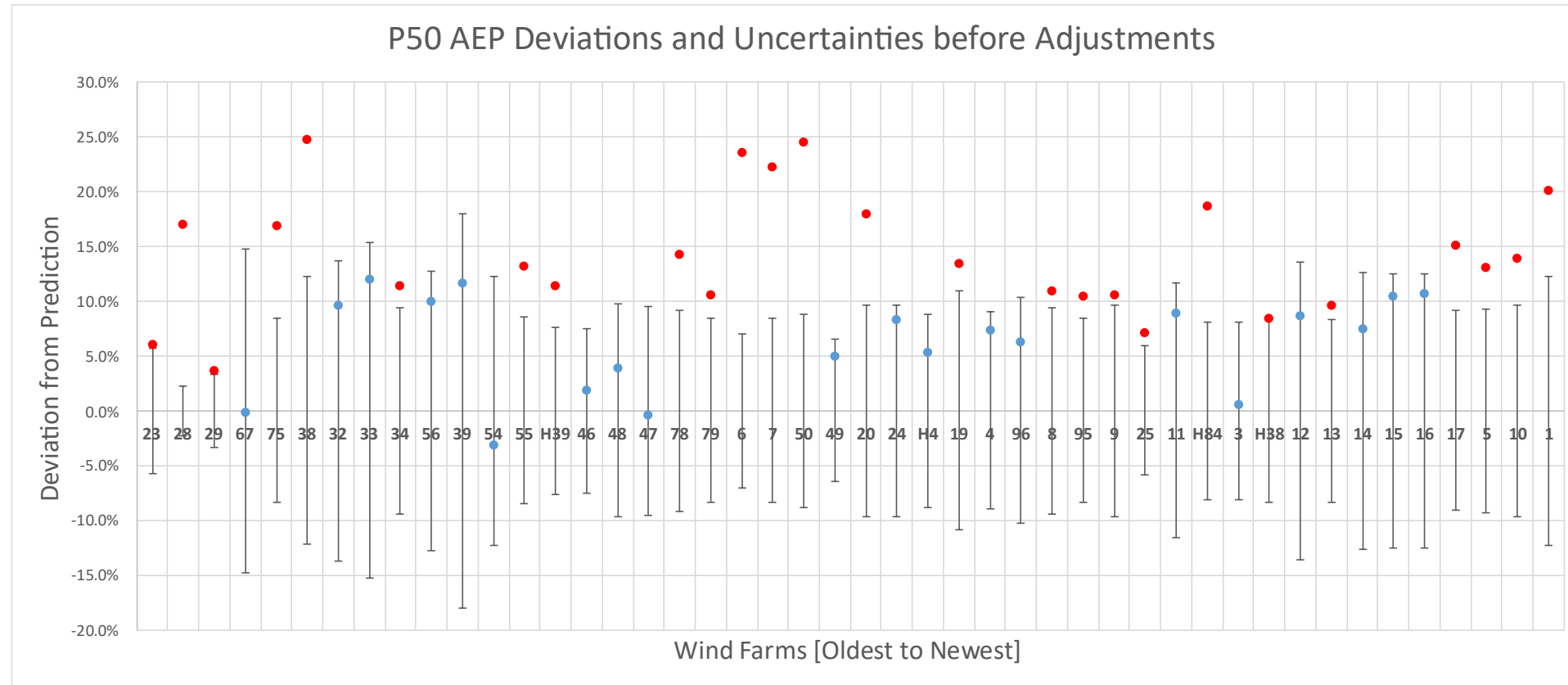


Frequent occurrence for wind farm in the Nordics



Reconciliation

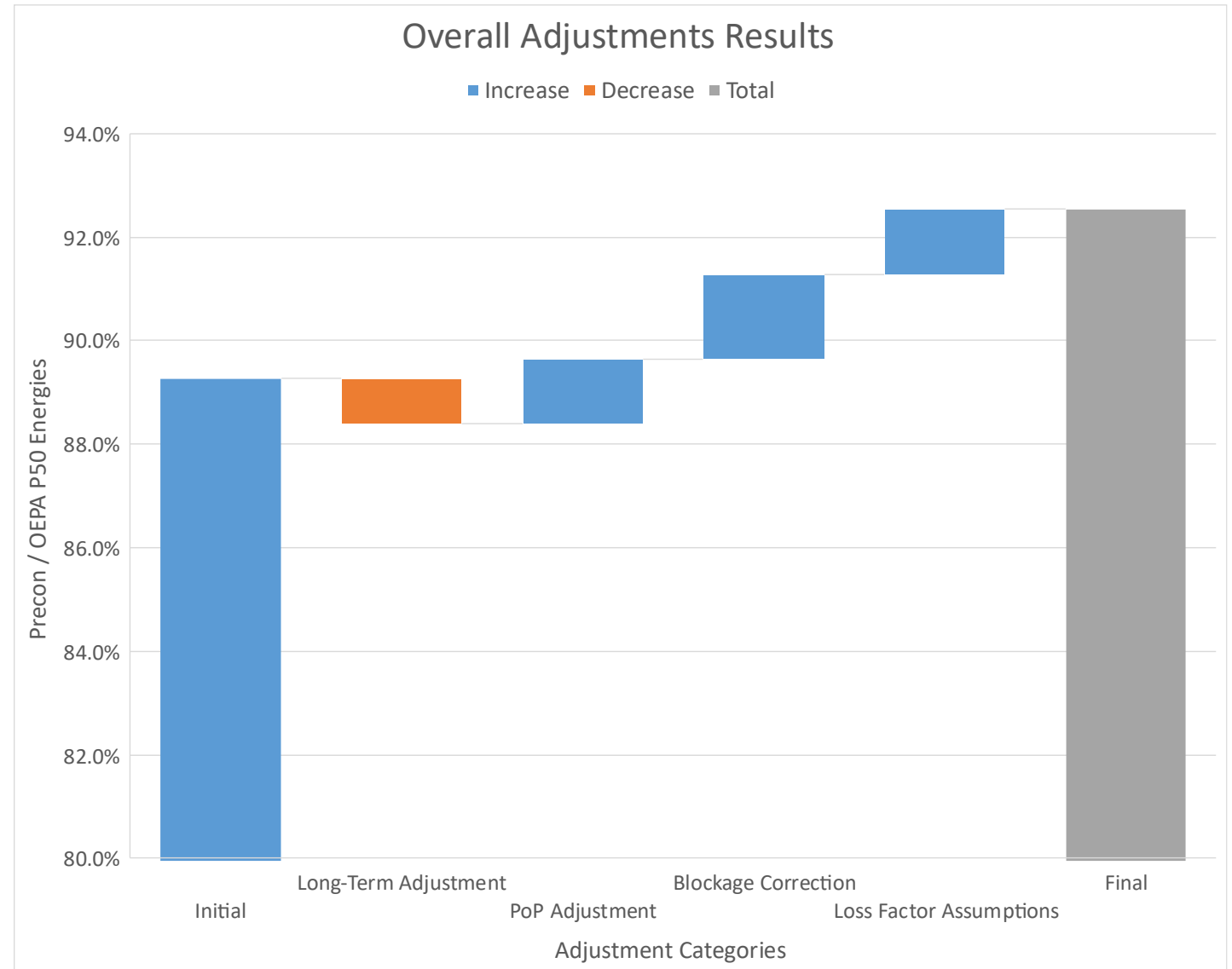
- **Initial Deviations:**
 - 26 projects with initial deviations greater than uncertainty limits.



Reconciliation

- **Reconciliation Results:**

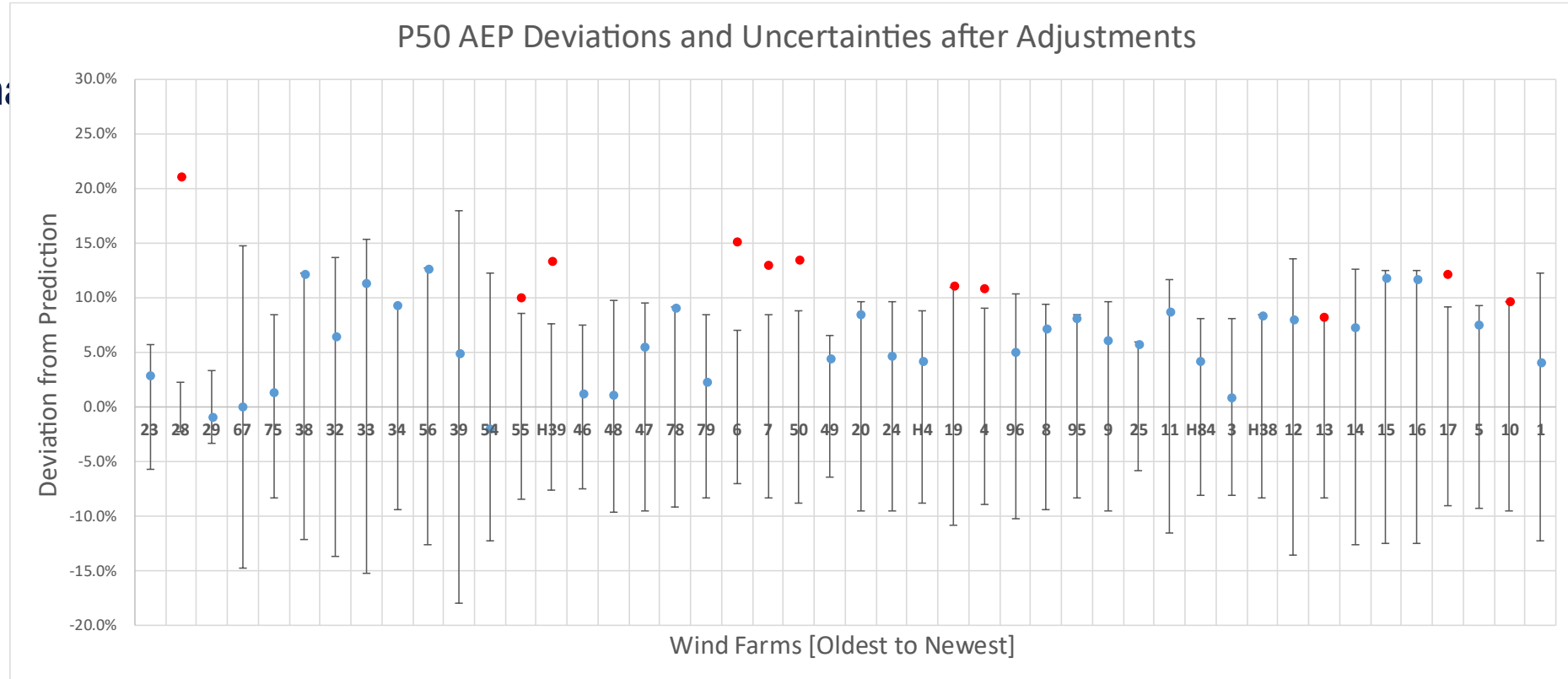
- Average initial P50 ratio 89.3% (10.7% deviation).
- State-of-the-art reanalysis datasets increase the gap.
- Other adjustments bridge the gap.
- Adjusted P50 ratio 92.6% (7.44% discrepancy).



Reconciliation

- **Final Discrepancies:**

- 11 projects with discrepancies greater than the uncertainty limits.
- Overestimation bias continues.

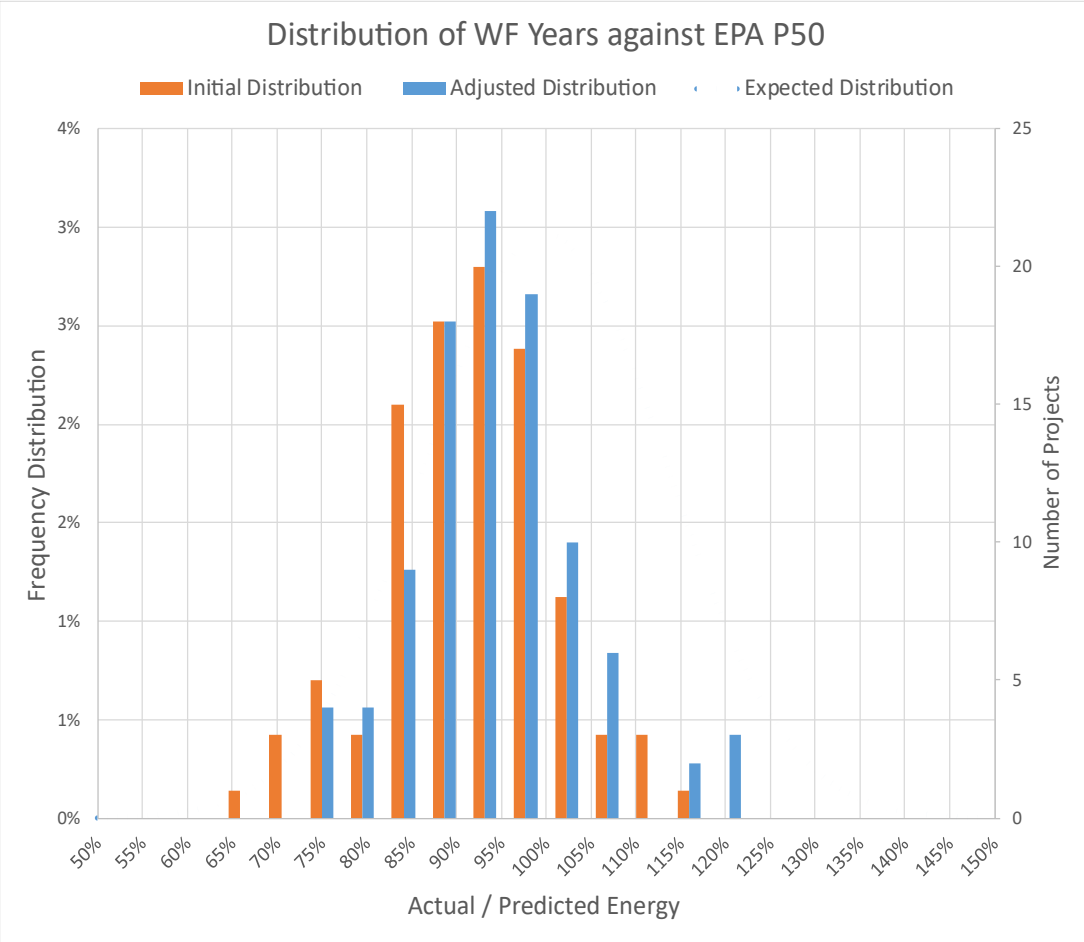


Nordics

Preliminary results from 4GW of wind in the Nordics:

- Operational energy yield assessments were performed by DNV
- Wind resource assessments to meet DNV Standards:
 - Acceptable input data
 - State of the art methodology

Country	No. of WFs	DNV	Other	Avg. Deviation P50 AEP
Sweden	27	14	13	11.2%
Norway	12	1	11	8.8%
Finland	7	4	3	12.3%
Total	46	19	27	10.7%



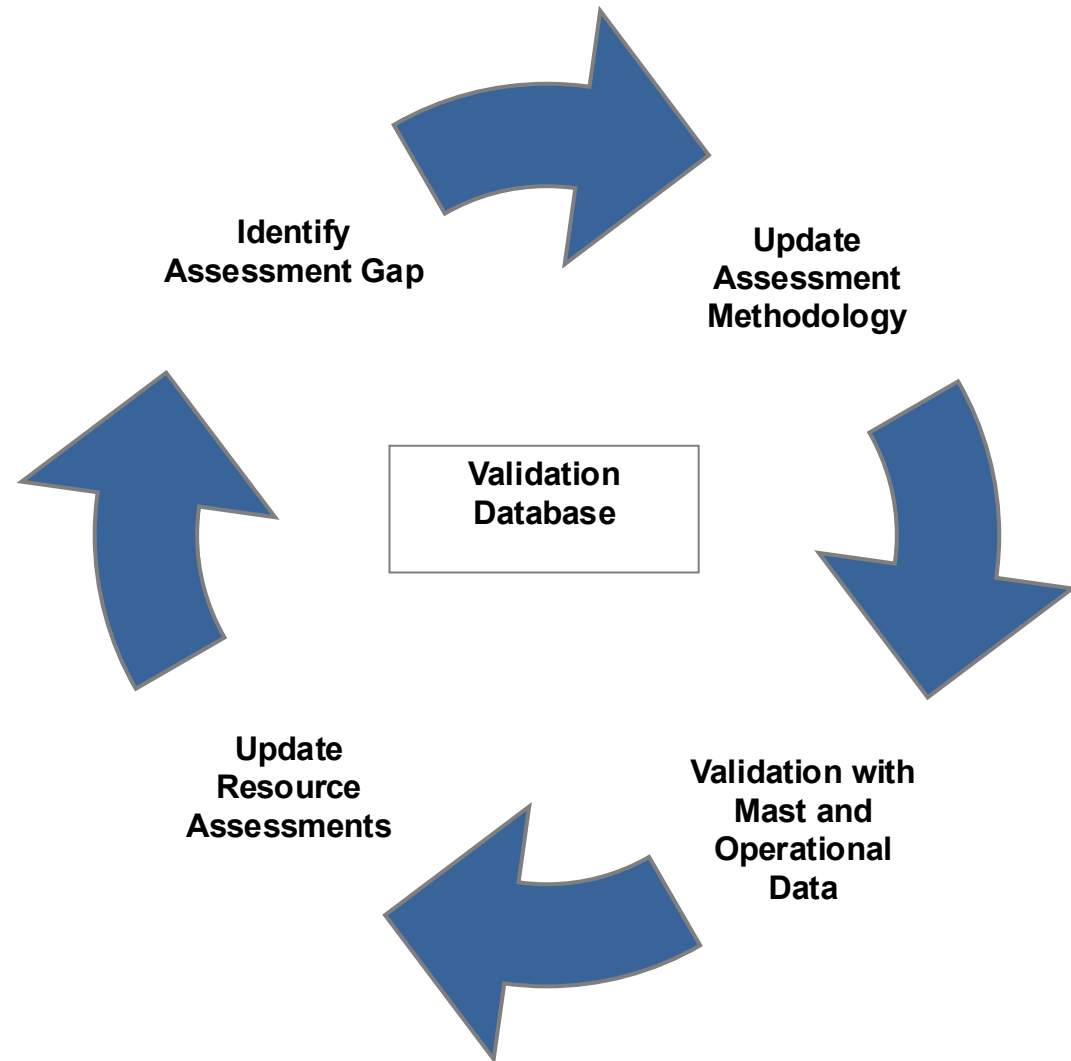
97 Wind Farm Years

Using Feedback to Improve Methods

Y Perform Detailed Forensics on SCADA Data from Operating Projects

- Availability and loss analysis
- Power performance assessment
- Wake and flow model validation

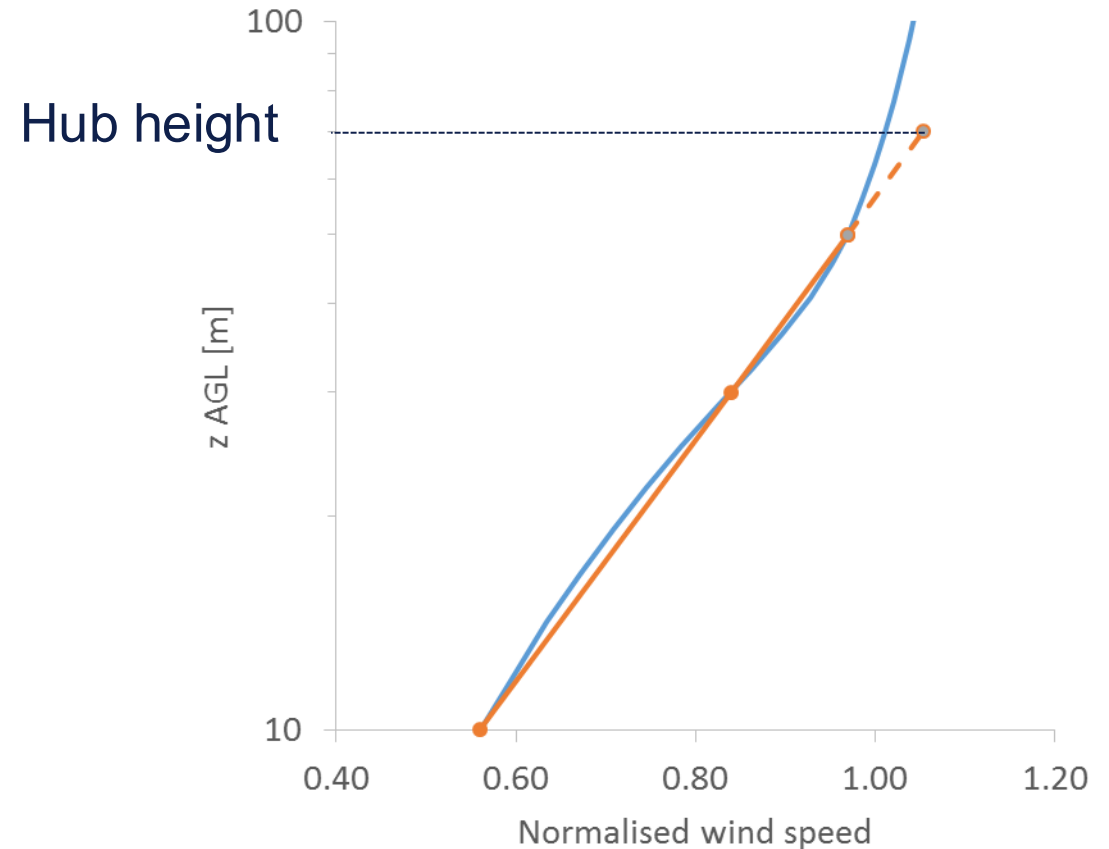
Y DNV Conducted Analyses of Wind Farm SCADA Data This Feedback is Used to Validate and Refine Methods



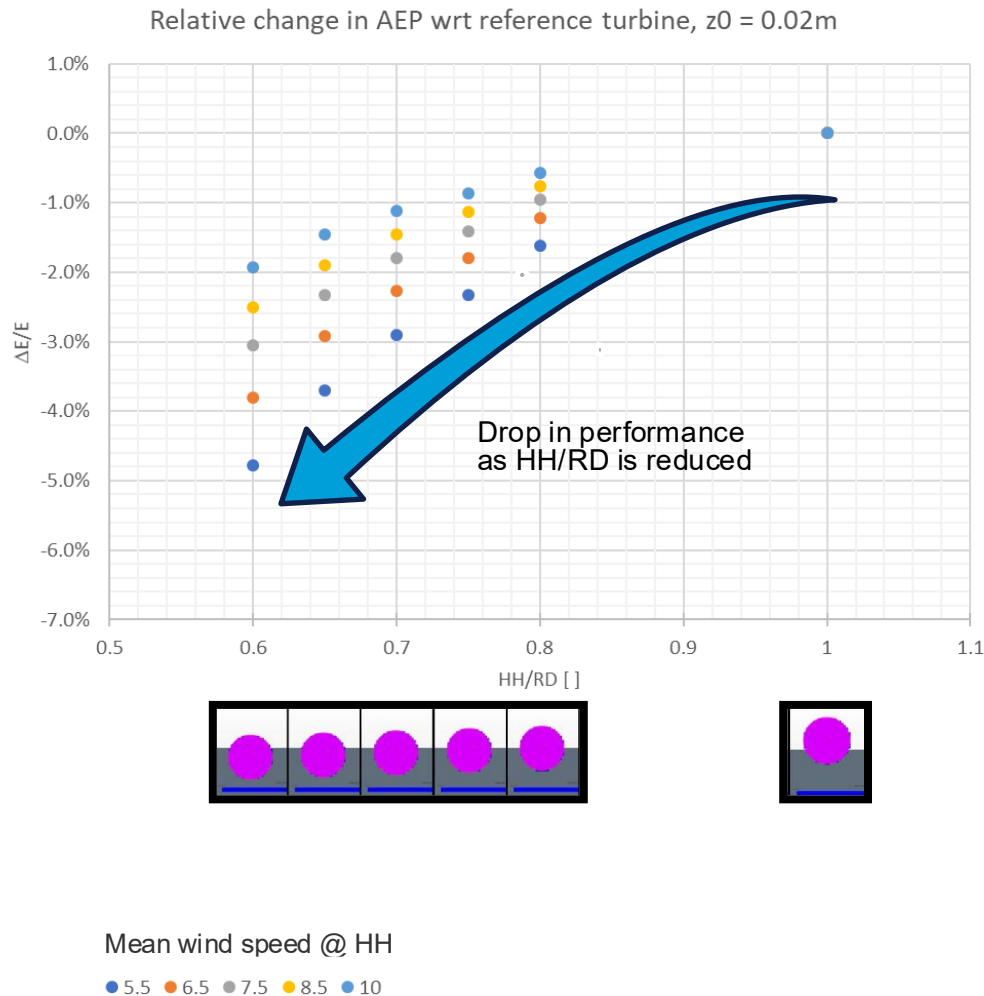
Potential root causes

Vertical extrapolation – non-simple profiles

- Measurements below hub height
- Extrapolating to hub height with constant shear assumption leads to wind speed over-estimation compared to actual wind speed profile
- High risk of this happening
 - Downstream of coastal transition
 - Low-level jets
 - Low boundary layer heights (and tall turbines with large rotors, since these operate closer to the top of the boundary layer)

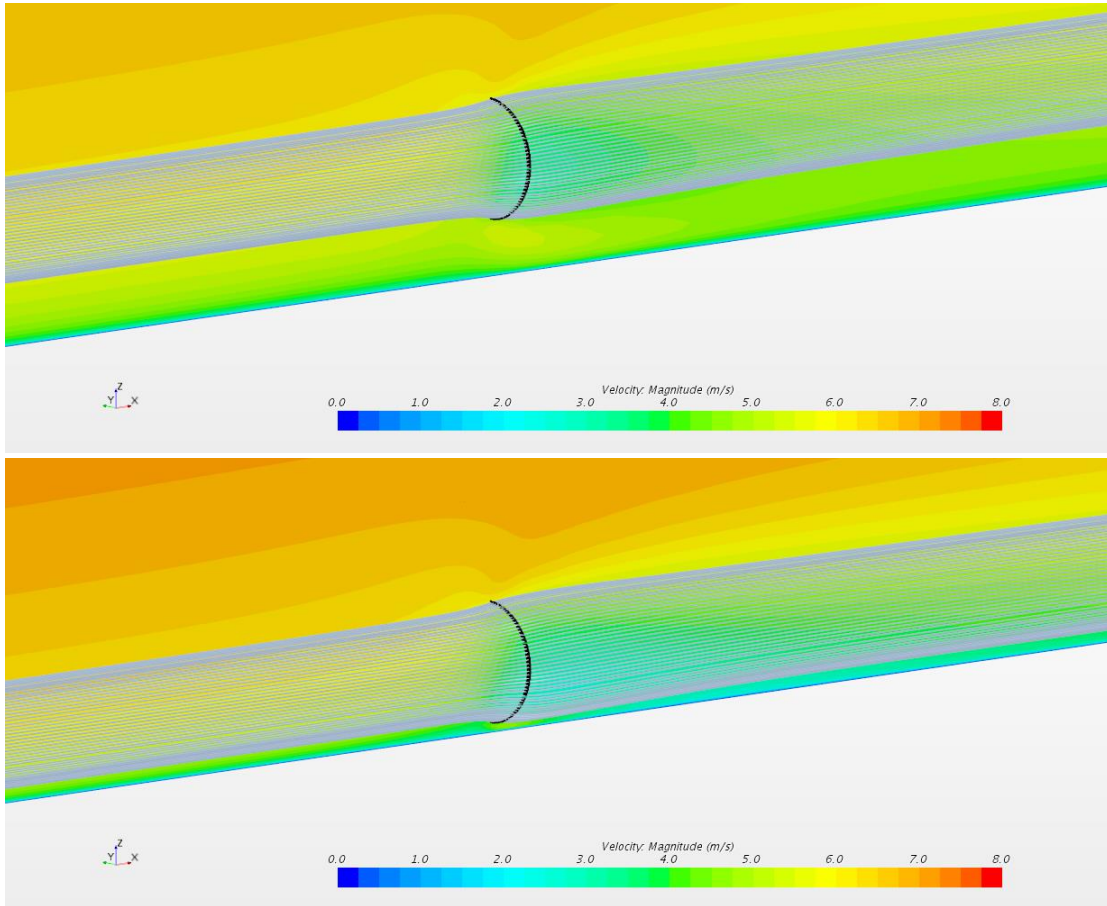


Turbine performance – stubby turbines



- Plot shows magnitude of change in AEP (wrt to $HH/RD = 1$) for a single turbine operating in neutral conditions, for a roughness of 0.02m . All HH/RD assume same frequency distribution @ HH.
- Performance hit is largest :
 - when roughness is increased.
 - for low wind speed sites
 - when atmospheric conditions are stable compared to neutral.→ Forested sites strongly affected (high roughness, low wind speed)
- CFD analysis only so far, no validation against field data
- Wake recovery reduced as well

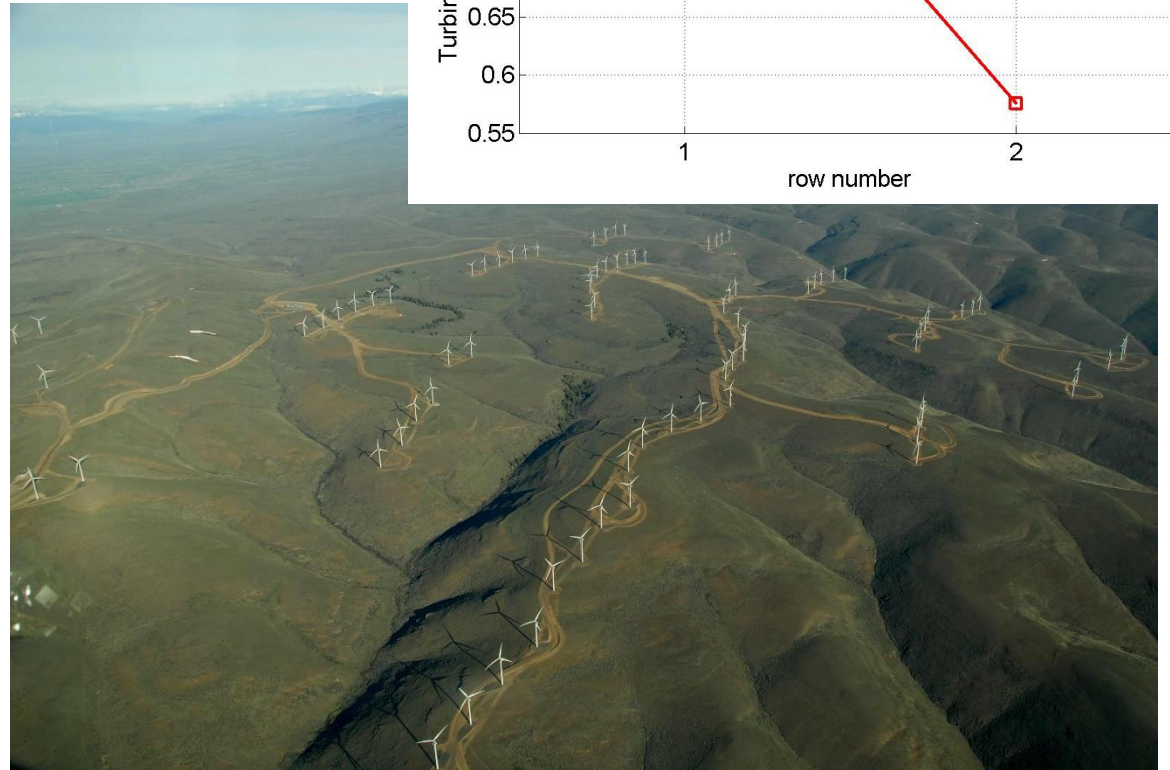
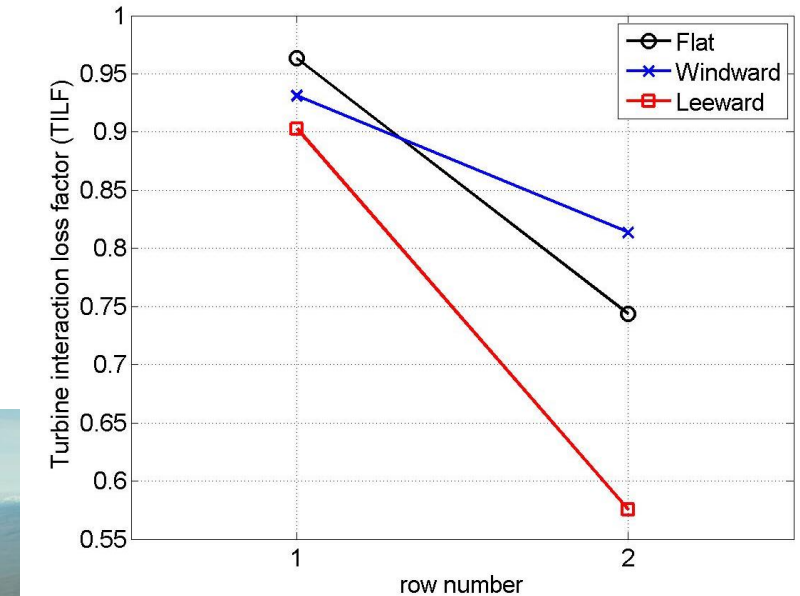
Reduced HH/RD also affects wake recovery



- Reduced entrainment below the turbine
- Slower wake recovery
 - Double whammy! Not only the single turbine performance is affected, but the wake losses are amplified too.
- Both effects have the potential to reduce wind farm yield in a non-negligible way. This is very noticeable in the CFD, but as yet unvalidated (difficult to get data with low enough uncertainty to validate)

Turbine interaction losses

- Wakes and blockage are highly sensitive to atmospheric stability/boundary layer height
 - Strong losses in stable conditions
 - Weaker losses in neutral and unstable conditions
 - Asymmetry between magnitude of losses across stability conditions not well represented by modelling neutral only losses
 - Sensitivity not accounted for in engineering models
- All engineering models neglect sensitivity of turbine interaction losses with terrain (and most of them ignore the feedback from the wind farm to the atmosphere)
- Sensitivities can be accounted for by high-fidelity models



Several potential root causes

VERTICAL EXTRAPOLATION

- Relevant when
 - Measurements below hub heights
 - Low boundary layer heights / velocity profile does not follow simple law
- Conditions likely making it worse
 - Frequent stable conditions
 - Downstream of coastal transition
 - Low-level jets

TURBINE PERFORMANCE

- Relevant when
 - Stubby turbines (small hub height to rotor diameter ratio)
 - Velocity profile departs from assumed profile when deriving power curve
- Stubby turbine performance issue amplified when
 - Stable conditions
 - High roughness

TURBINE INTERACTION LOSSES

- Turbine interaction losses (wakes and blockage) typically larger when:
 - Conditions are stable
 - Low boundary layer height
 - Low hub heights (stubby towers have an impact on the wake recovery as well as individual turbine performance)
- Engineering models not accounting for:
 - Terrain effects
 - Low boundary layer height/Stability effect in the inversion layer & above the boundary layer

Commonality across all three: stable conditions and low boundary layer heights

→ All tend to impact wind farm performance negatively

Could these explain tendency for underperformance in the Nordics?

Thank you!

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