Atmospheric Stability Affects Wind Turbine Performance and Wake Effect

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Outline

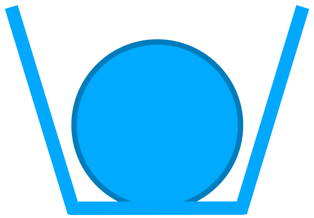
- Introduction to atmospheric stability
- Operational wind farm used in the study
- Turbine performance under different stability conditions
- Wake recovery under different stability conditions
- Discussions

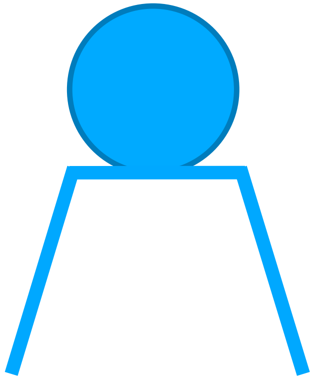
Atmospheric Stability - Definition

➢**In the terminology of IEC 61400-12-1 (Edition 2.0, 2017):**

A measure of tendency of the wind to encourage or suppress vertical mixing:

Stable atmosphere is characterized by a high temperature gradient with altitude, high wind shear, possible wind veer and low turbulence relative to unstable conditions.





Atmospheric Stability – Characterization (Stull, 1988)

- **Lapse rate / vertical temperature difference**

  temperature measurements at two or more heights

- **Richardson number (flux, gradient, bulk)**

  temperature and wind measurements at two or more heights

- **Pasquill-Gifford stability classes (discrete)**

  surface wind speed, cloud cover, ceiling height, solar angle

- **Monin Obukhov length**

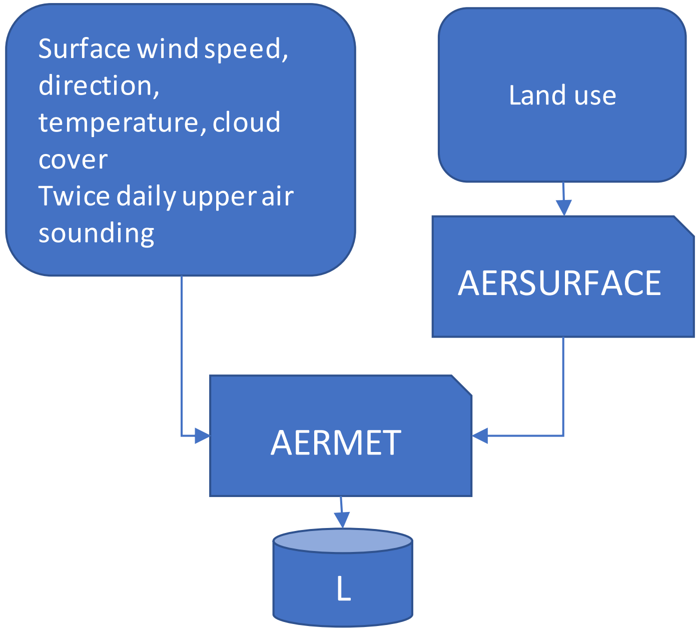
  surface wind, temperature, cloud cover,

  twice daily upper air sounding

  surface characteristics (roughness length, albedo, Bowen ratio)

$$L = -\frac{\rho c_p T_{ref} u_*^3}{kgH}$$

Quantify Monin Obukhov Length (L) with AERMET



L is proportional to the height above surface at which buoyant factors first dominate over mechanical (shear) production of turbulence

<table>
<tr><th>Stability</th><th>L (m)</th><th>L (m)</th><th>Stability</th></tr>
<tr><td>Neutral</td><td>L<-200</td><td rowspan="3">L<0</td><td rowspan="3">Convective</td></tr>
<tr><td>Convective</td><td>-20>L>-200</td></tr>
<tr><td>Strong Convective</td><td>0>L>-20</td></tr>
<tr><td>Very Stable</td><td>20>L>0</td><td rowspan="3">L>0</td><td rowspan="3">Stable</td></tr>
<tr><td>Stable</td><td>200>L>20</td></tr>
<tr><td>Neutral</td><td>L>200</td></tr>
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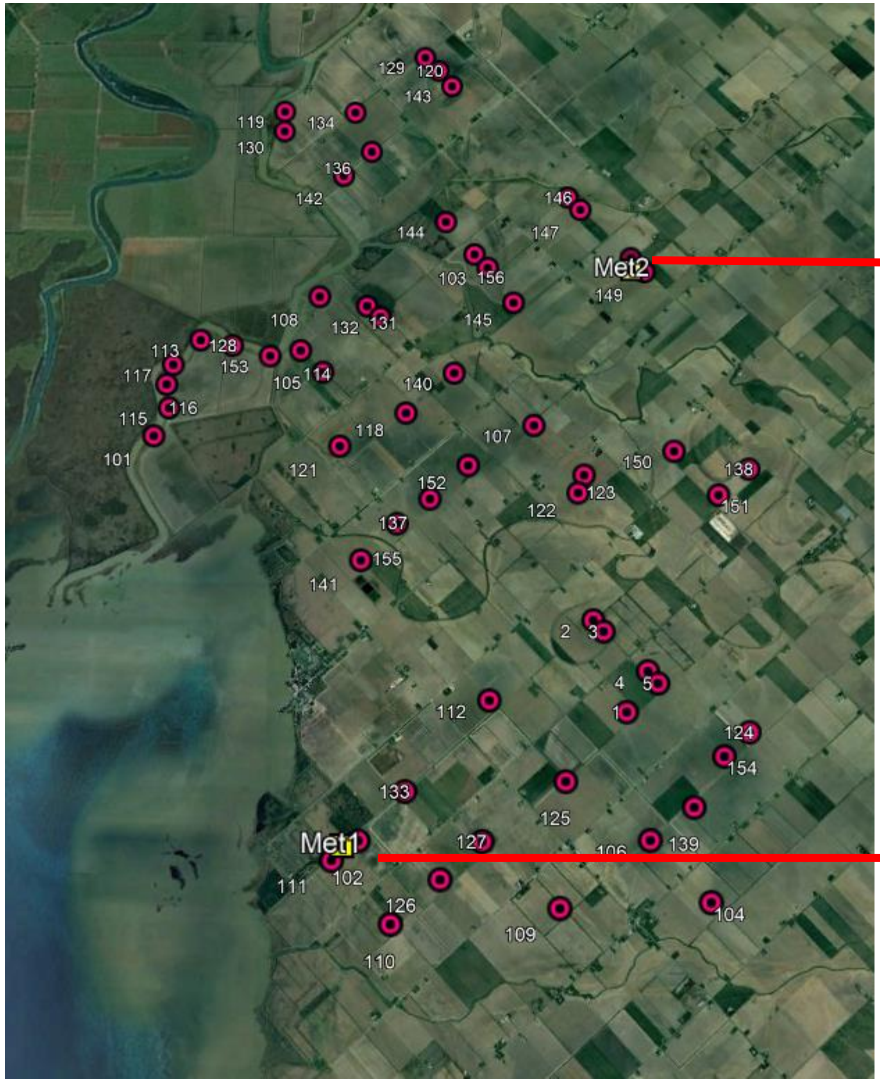
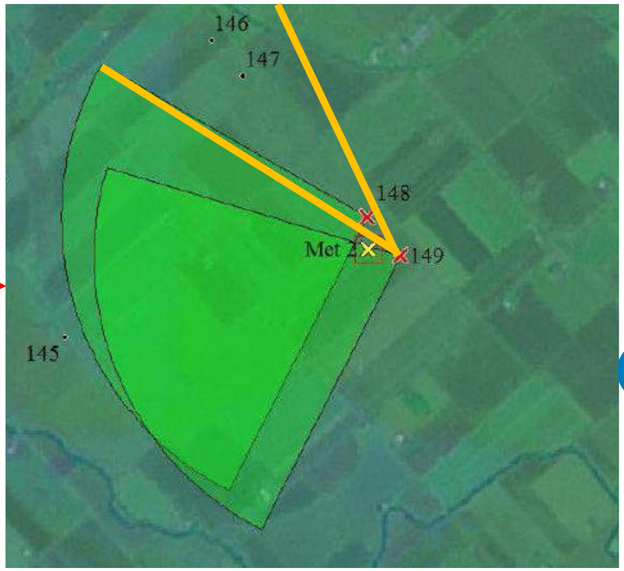
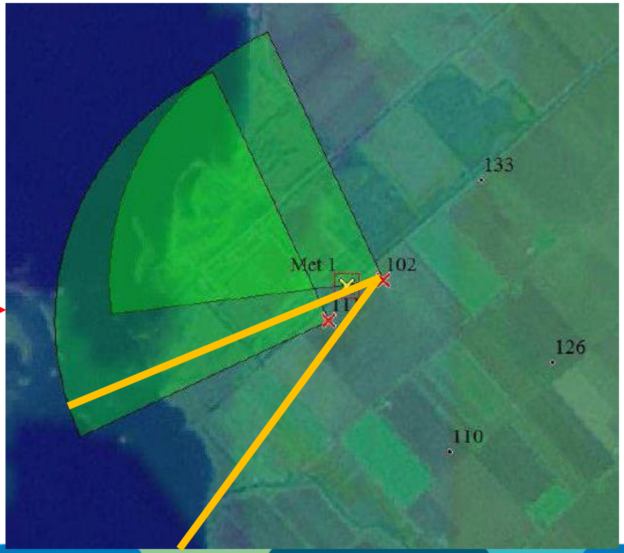
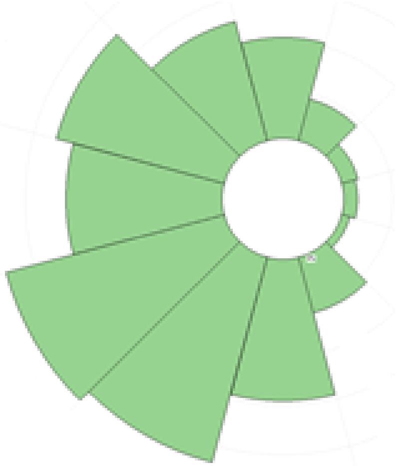
Operational Wind Farm with 2 MET Towers







Shaded areas between two black lines are PPM / Non-waked sectors
Areas between two orange lines are waked sectors



Turbine Performance Indicators

➢ **Determination of the measured power curves under different stability conditions:**

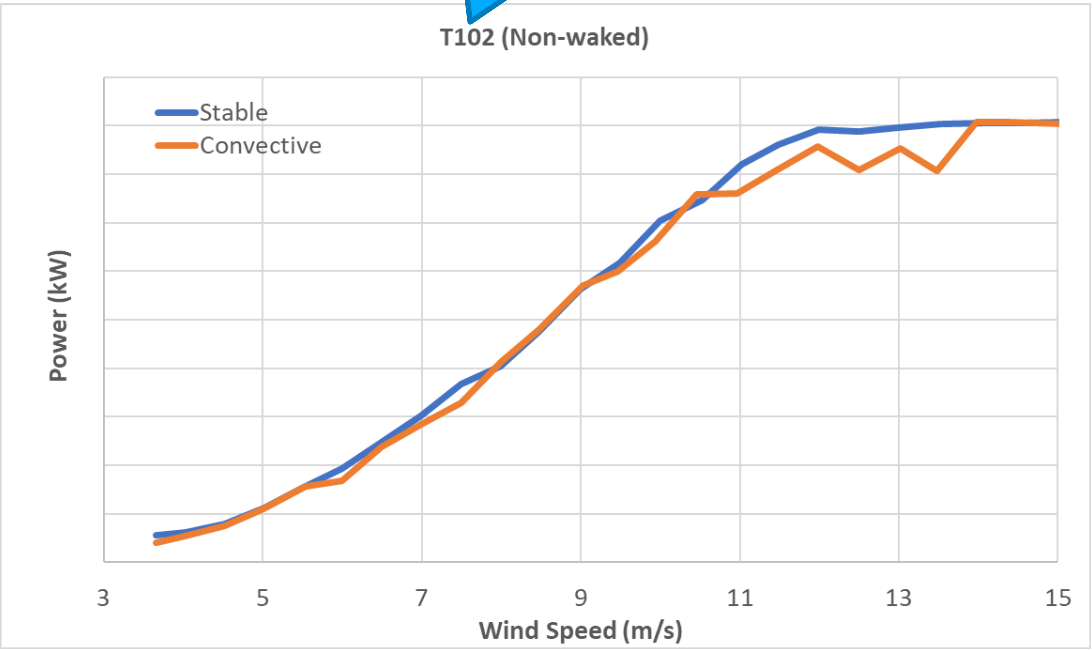
- Data screening / rejection
- Air density normalization
- Determination of measured power curves under convective ($L<0$) and stable conditions ($L>0$)

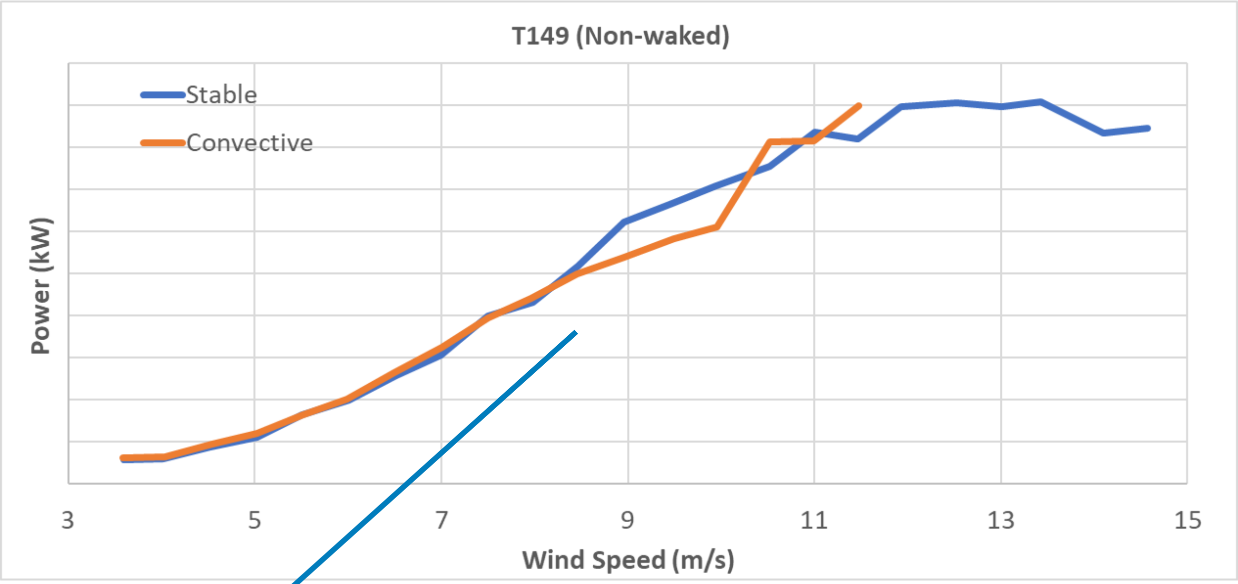
➢ **Annual energy production (AEP)**

- AEP-extrapolated under convective and stable conditions
- % difference in AEP-extrapolated between convective and stable conditions

Turbine Performance for Non-Waked Turbines

4% higher under stable conditions with AEP-extrapolated



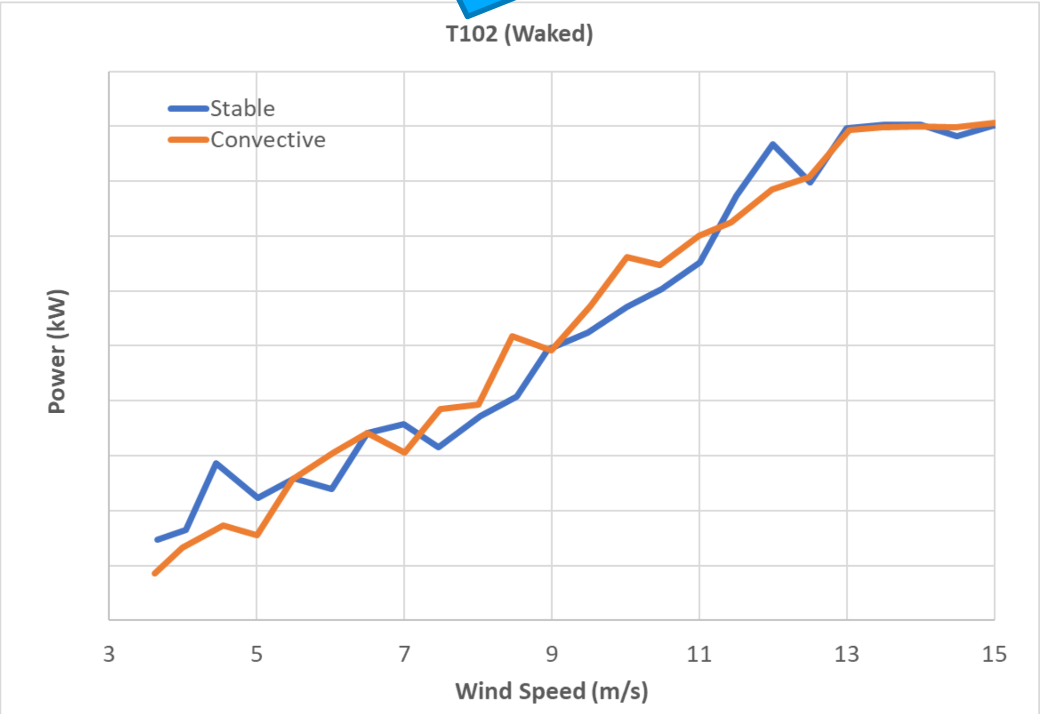


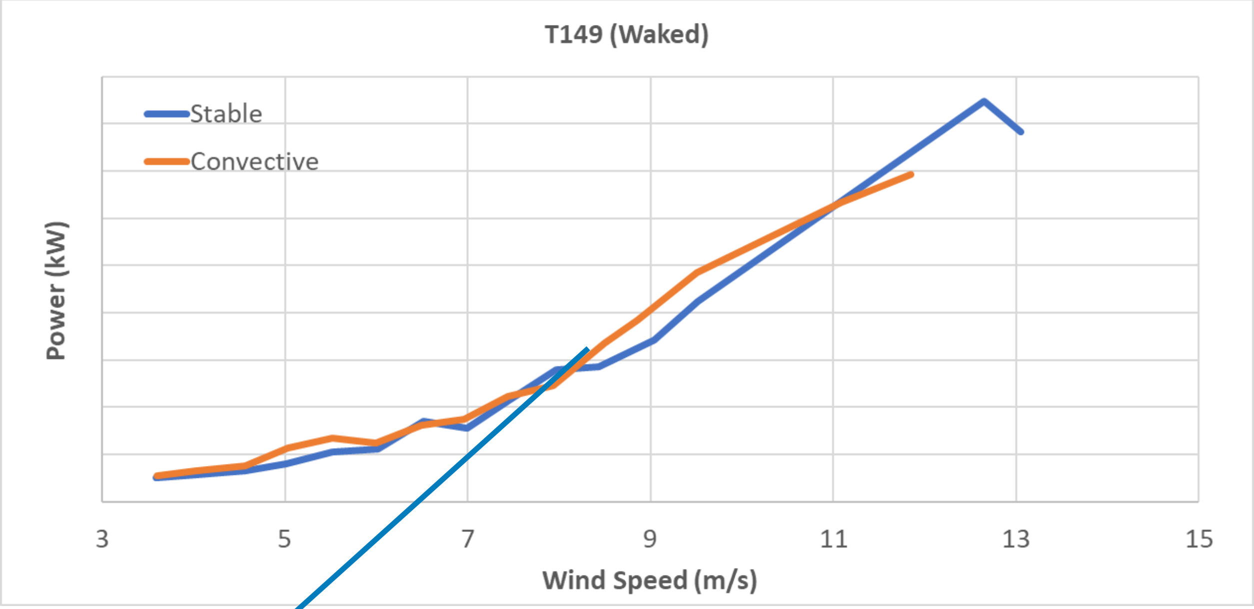
2% higher under stable conditions with AEP-extrapolated

Note – T149 is located downwind edge of the wind farm

Turbine Performance for Waked Turbines

0.5% higher under convective conditions with AEP-extrapolated

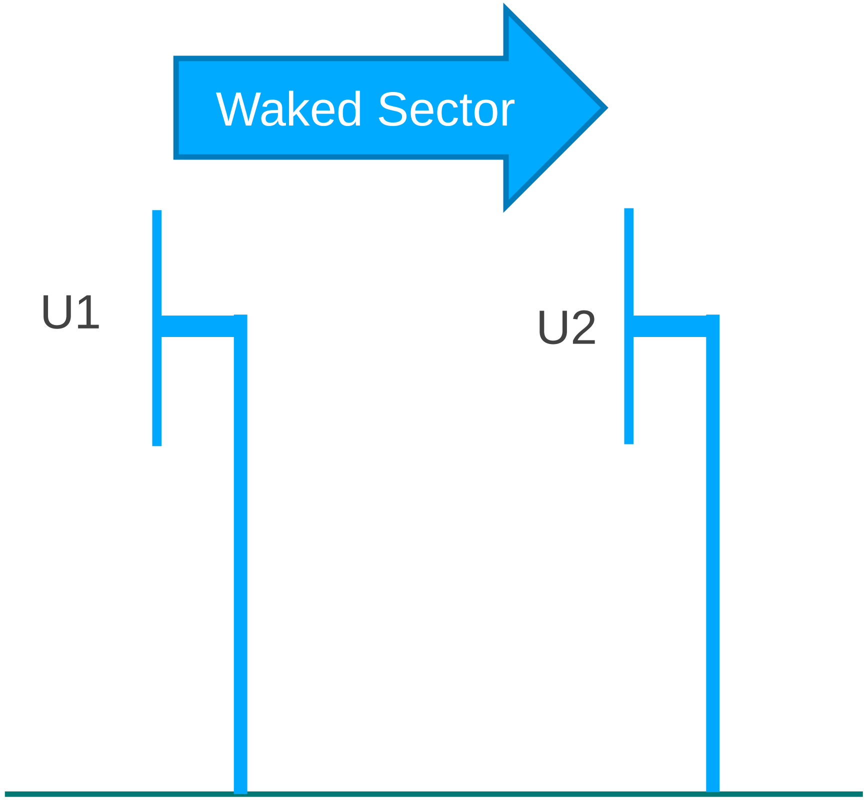




2% higher under convective conditions with AEP-extrapolated

Note – T149 is located downwind edge of the wind farm

Wind Speed Deficits for Waked Turbines under Different Stabilities

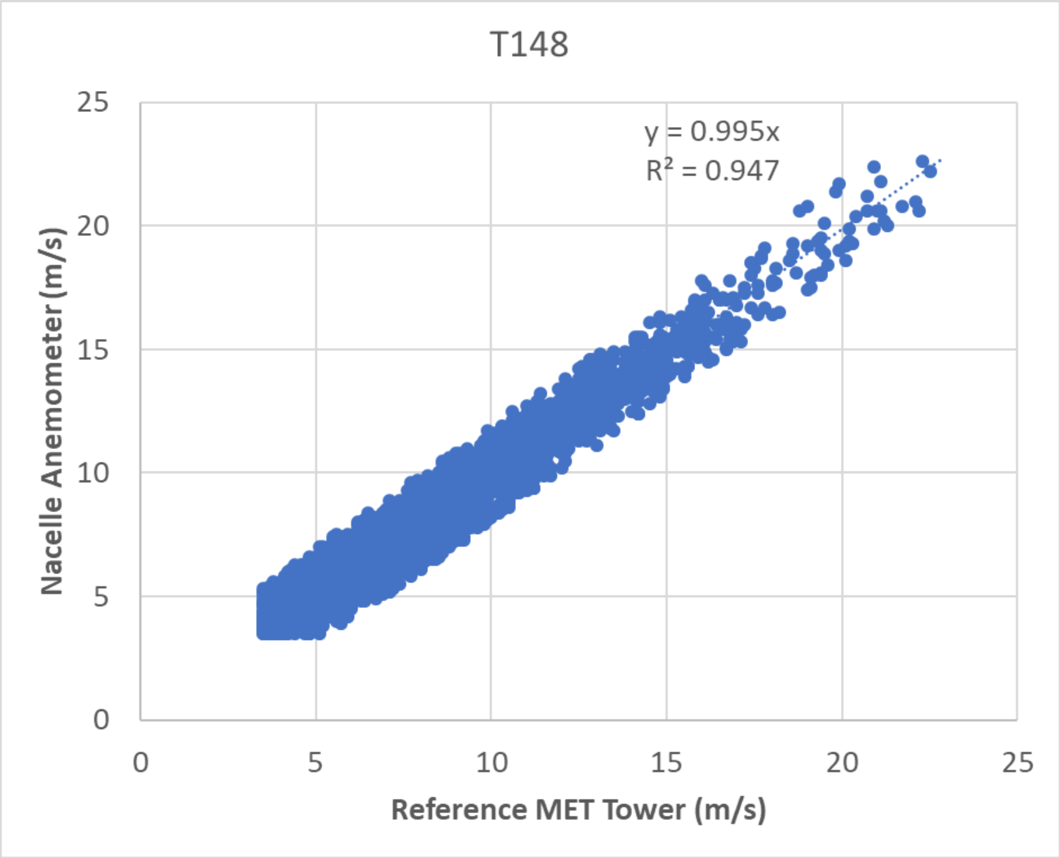


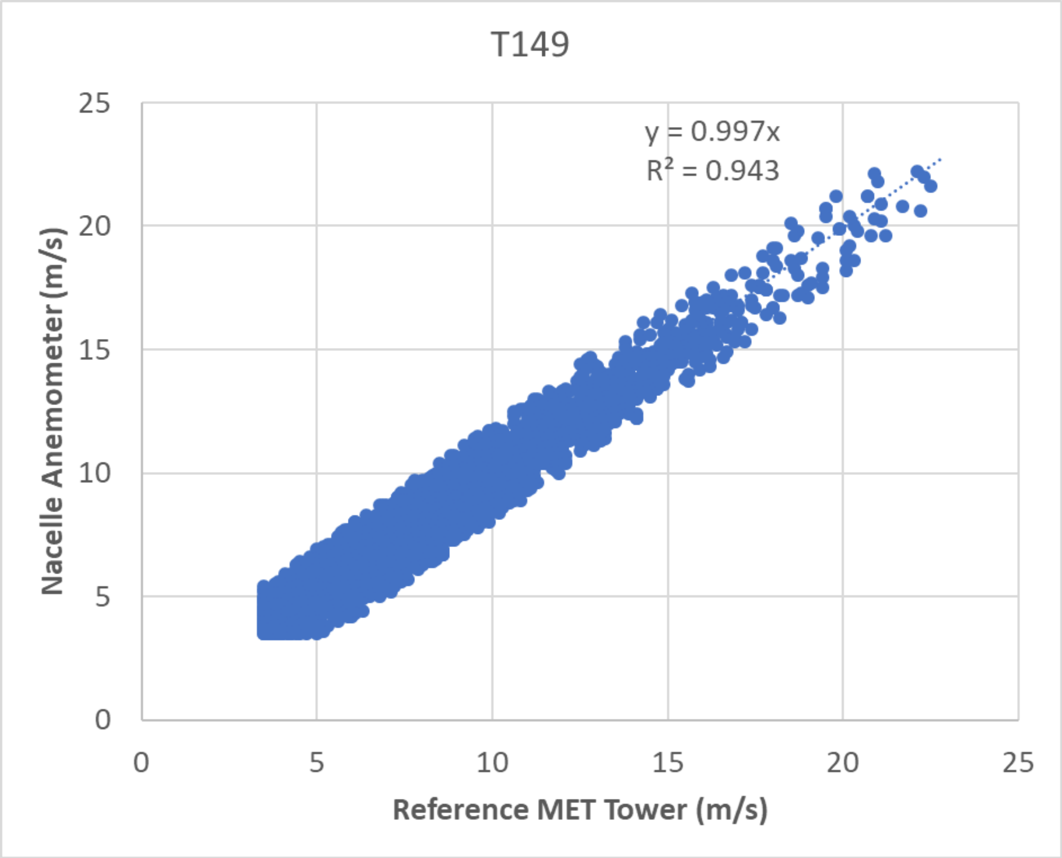
$$\Delta U = \frac{U1 - U2}{U1} \text{ x } 100\%$$

- Use wind speeds recorded by nacelle anemometers
- Benchmark wind speed deficits (ΔU) between 2 WTGs within common non-waked sector
- Estimate wind speed deficits (ΔU) between 2 WTGs within waked sector

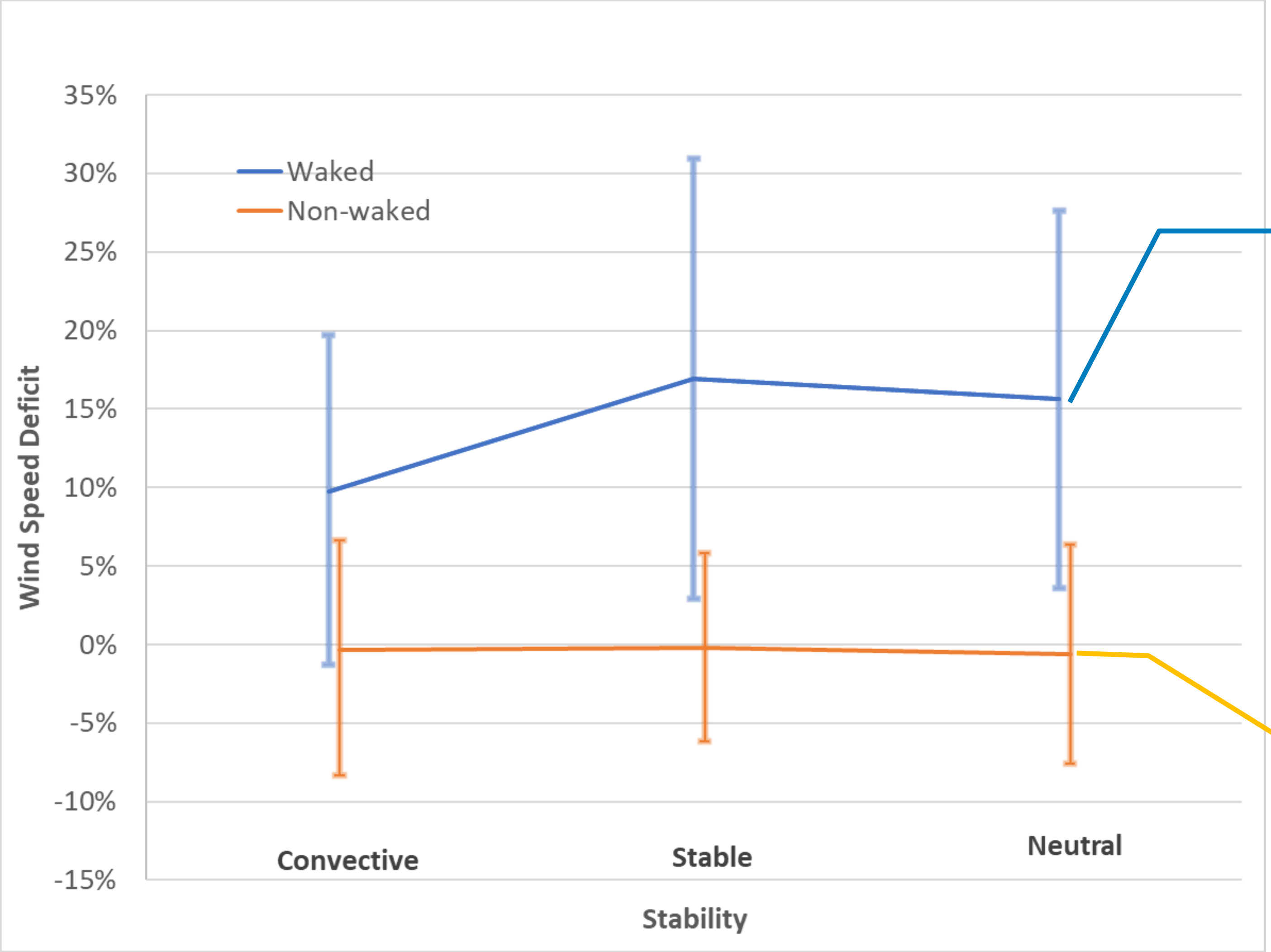
Stability	L (m)
Stable	200>L>0
Convective	0>L>-200
Neutral	L<-200 or L>200

Wind Speeds Collected by Nacelle Anemometers





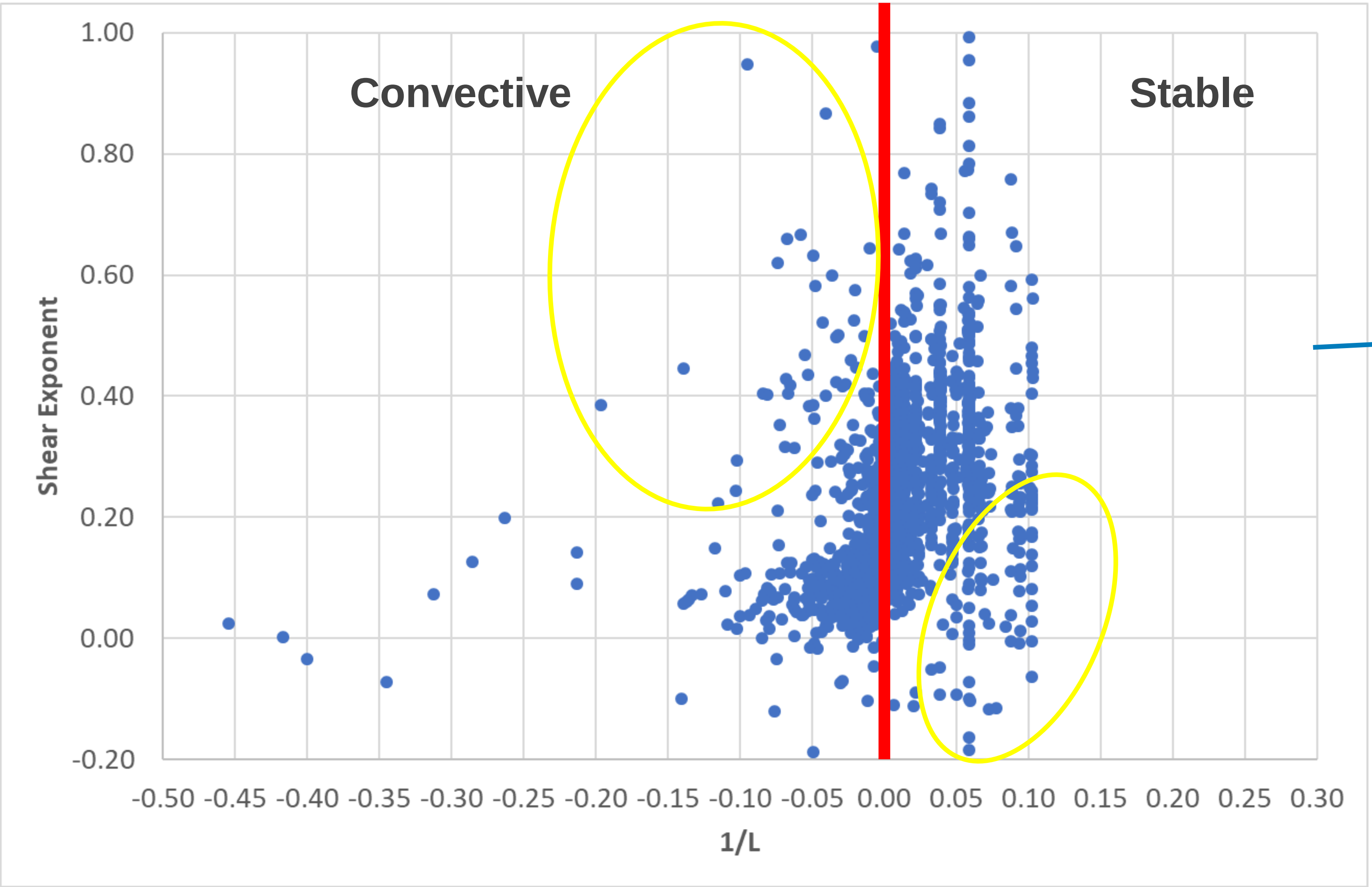
Wind Speed Deficits for Waked Turbines under Different Stabilities



Wind speed deficits are much lower under convective conditions than those of other stability conditions, which might suggest that the wake effects could be reduced due to an enhanced vertical mixing under convective conditions.

Wind speed deficits do not vary for non-waked sector between two turbines (T148 and T149) under different stability conditions.

Limitations of Monin Obukhov Length (L)



Inconsistency between L and wind shear exponent exists.

L is a local stability parameter for surface layer (~100 m).

With turbine tip heights well above the surface layer, decoupling between the surface layer and the layer above might not be captured / reflected by L.

Discussions

- Wind turbines without the influence of wake, tend to perform better under stable conditions due to lower turbulence productions.
- Wind turbines with the influence of wake, tend to perform better under convective conditions due to enhanced wake recovery.
- Wake effect could be reduced due to enhanced vertical mixing under strong convective conditions.
- Atmospheric stability does affect wind turbine performance and wake effect and should be considered in energy yield assessment.
- Monin Obukhov is a good stability indicator with current industry practice / data availability, but some limitations should be recognized.

Thank You!

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