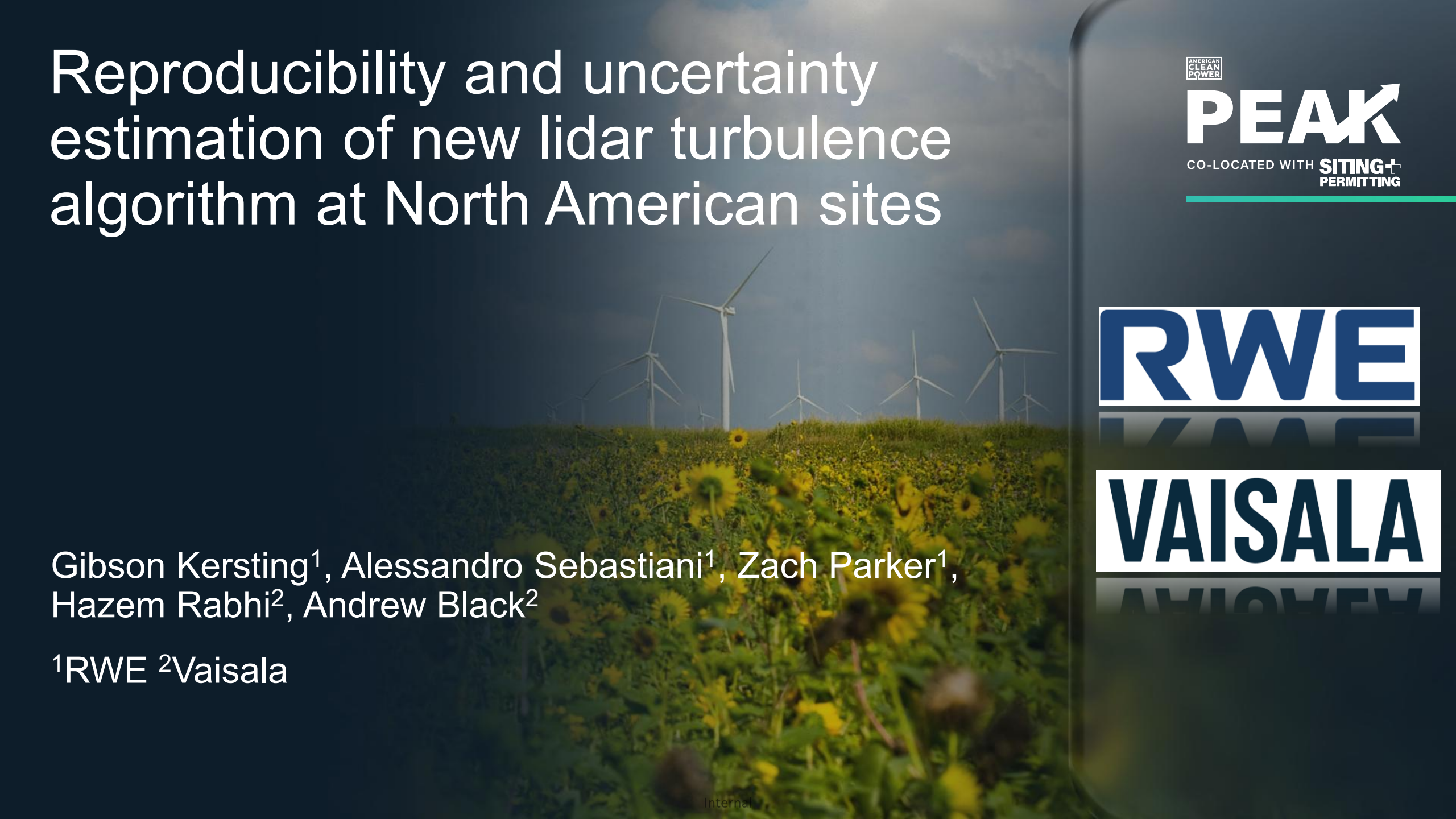
Reproducibility and uncertainty estimation of new lidar turbulence algorithm at North American sites



Gibson Kersting[1], Alessandro Sebastiani[1], Zach Parker[1], Hazem Rabhi[2], Andrew Black[2]

[1]RWE [2]Vaisala

Internal

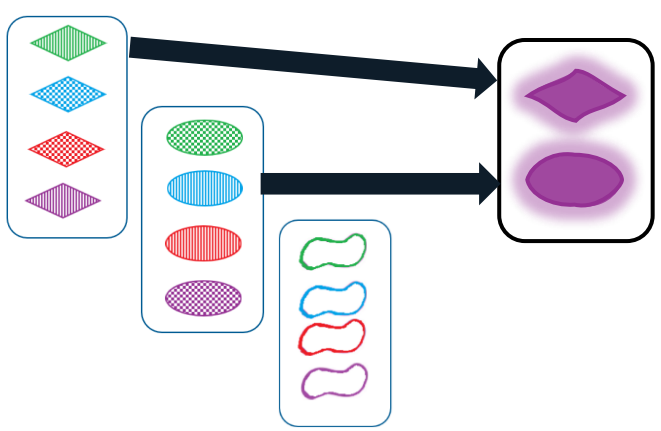
Introduction

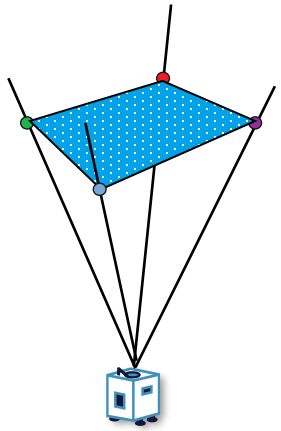
- Today, turbine suitability and loads validation are mostly carried out using cup anemometers
- Lidar systems are already widely accepted for measuring wind speed and wind shear measurements.
- If their ability to measure turbulence can be validated, lidar could carry out all aspects of wind resource assessment.
- Here we examine a new pulsed lidar turbulence algorithm (Pure-TI) against DNV-RP 0661 and IEA Task 52 KPIs

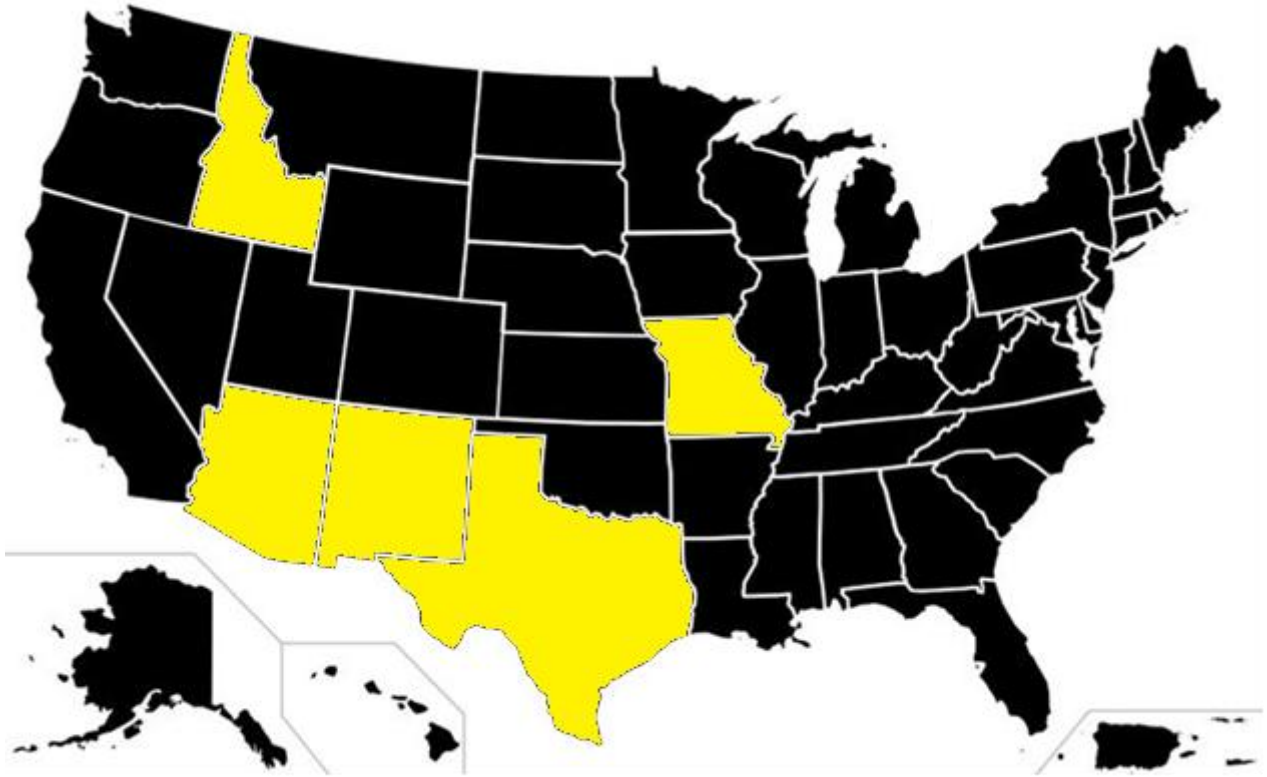
Internal

Pure-TI: Physically-Unified Reconstruction of Turbulence Intensity

- Algorithm presented at Peak 2025
- Physics-based reconstruction method for WindCube lidar
- Results shown here are from blind tests at 14 sites in the United States
- 500k datapoints ~9.5 years of data







Key Performance Indicators – DNV-RP 0661

These KPIs were developed by the DNV-JIP and published in DNV-RP 0661 :

Wind speed-binned average TI : $TI(V_{hub}) = \frac{\sigma_{Vhub}}{V_{hub}}$

$TI(V_{hub})$ Relative Mean Bias Error (RMBE) should meet passbands:

- Energy Yield Assessment: ±10%
- Site Suitability: -6% to +10% (WS < 7m/s) -3% to +10% (WS > 7m/s)
- Loads Validation: ±5%

$TI(V_{hub})$ Relative Root Mean Square Error (RRMSE)

- Site Suitability: ≤ 30% (WS < 7m/s) ≤ 15% (WS > 7m/s)
- Loads Validation: ≤ 15%

Key Performance Indicators – IEA Task 52

These KPIs are **in development** by IEA Wind Task 52's Turbulence sub-group:

Damage Index of a timeseries (m ∈ [4, 9, 14]) (not binned by V_{hub}): $DI = \left[\frac{1}{N}\sum_{i=1}^{N}\sigma_i^m\right]^{\left(\frac{1}{m}\right)}$

Effective TI (m ∈ [4, 9, 14]) (binned by V_{hub})

$$\sigma_{eff}(V_{hub}) = \left[\frac{1}{N}\sum_{i=1}^{N}\sigma_i^m\right]^{\left(\frac{1}{m}\right)} \text{ therefore: } I_{eff}(V_{hub}) = \frac{\sigma_{eff}(V_{hub})}{V_{hub}}$$

90% Quantile TI (Representative TI, I90) (1 m/s bins):

$$\sigma_{90,V_{hub}} = \overline{\sigma_{V_{hub}}} + 1.28 \cdot std\left(\sigma_{V_{hub}}\right) \text{ therefore: } I_{90}\left(V_{hub}\right) = \frac{\sigma_{90,Vhub}}{V_{hub}}$$

Interquartile range ("IQR", 25th-75th) must fall within a passband. For Damage Index, the bias IQR must lie with ±3% of the cup reference. Effective TI is ±3% and I90 is ±5%, for each wind speed bin

Internal

Key Performance Indicators – CFARS

These KPIs were developed by DNV and Fugro, based on CFARS Site Suitability Initiative:

Wind speed-binned average TI : $TI(V_{hub}) = \frac{\sigma_{Vhub}}{V_{hub}}$

Same metric as DNV-RP 0661
Passbands not normalized

$TI(V_{hub})$ Relative Mean Bias Error (RMBE) should meet passbands:

- Best practice: ±1%
- Minimum practice ±2%

Representative TI MBE: $\sigma_{90,V_{hub}} = \overline{\sigma_{V_{hub}}} + 1.28 \cdot std(\sigma_{V_{hub}})$

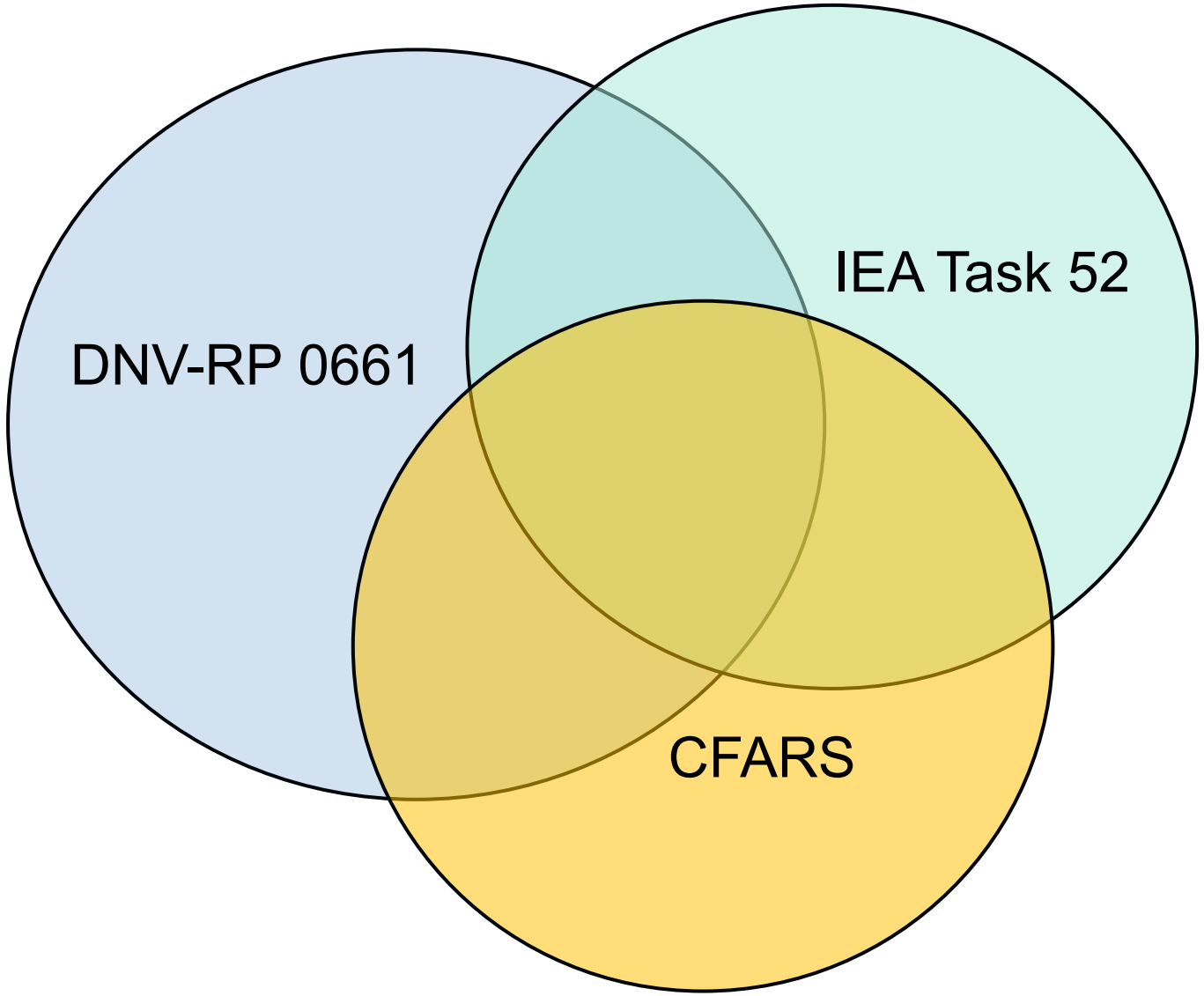
Same metric as CFARS
Passbands not normalized

$\sigma_{90,V_{hub}}$ MBE should meet passbands

- Best practice: ±1.5%
- Minimum practice ±3.0%

Internal

Key Performance Indicators

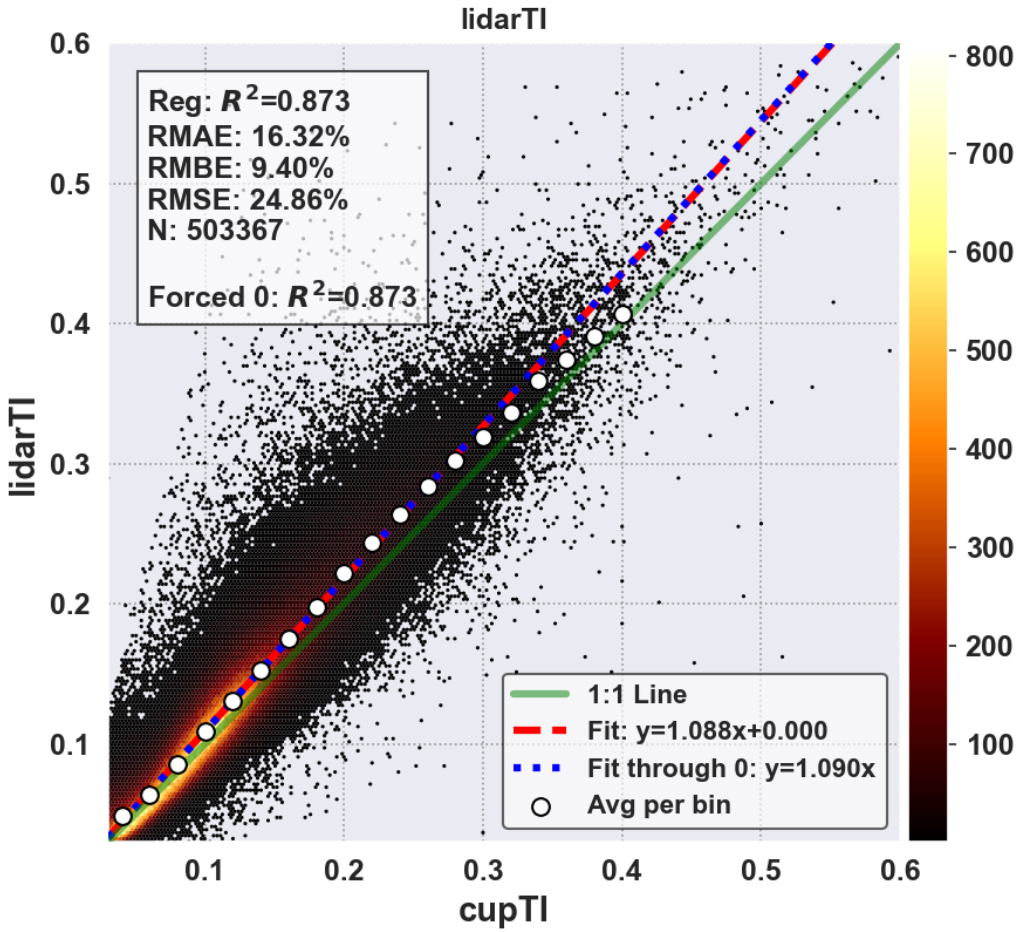


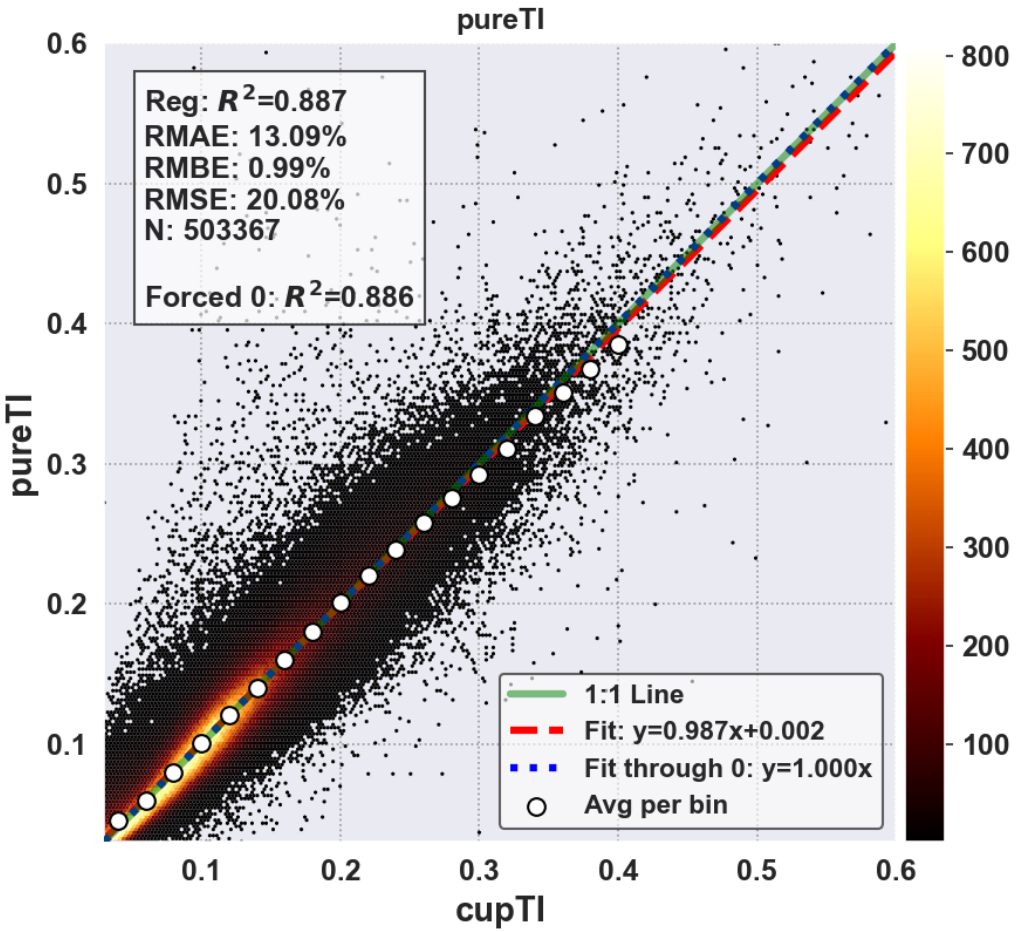
Some overlap
- By wind speed-bin
- Rep. TI and Mean TI
- Application-specific

Some disagreement
- Relative vs. absolute error
- IQR vs. site-by-site
- RRMSE or not
- A/symmetric passbands

Let’s have a look!

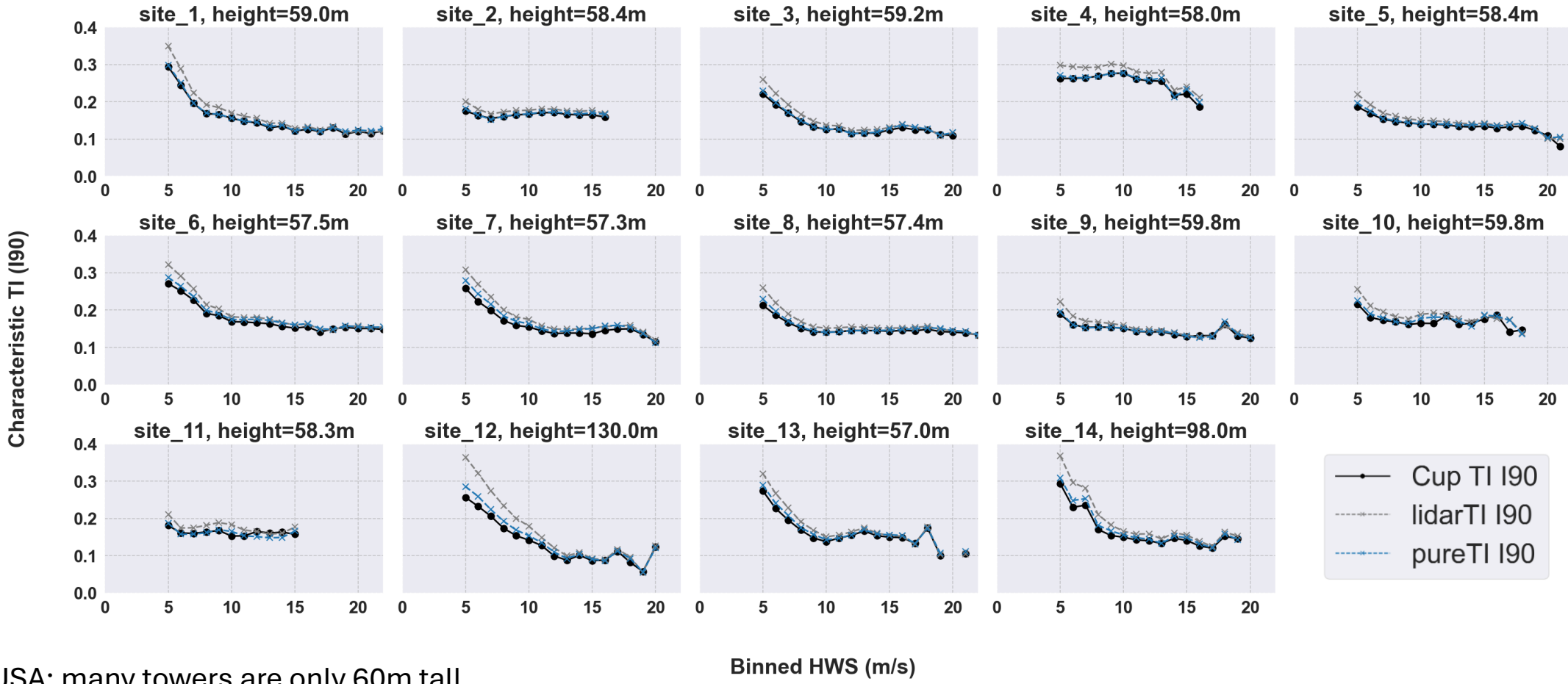
Overall Results – US Sites Only





Internal

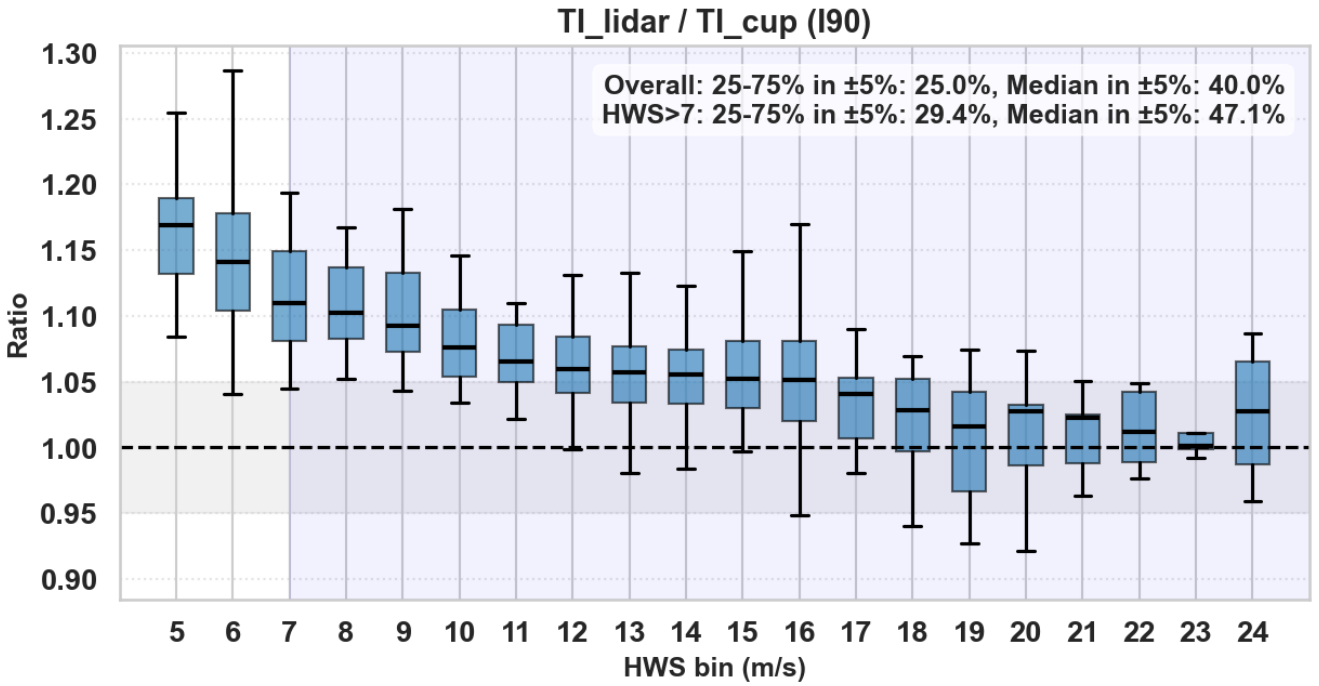
Representative TI Curves

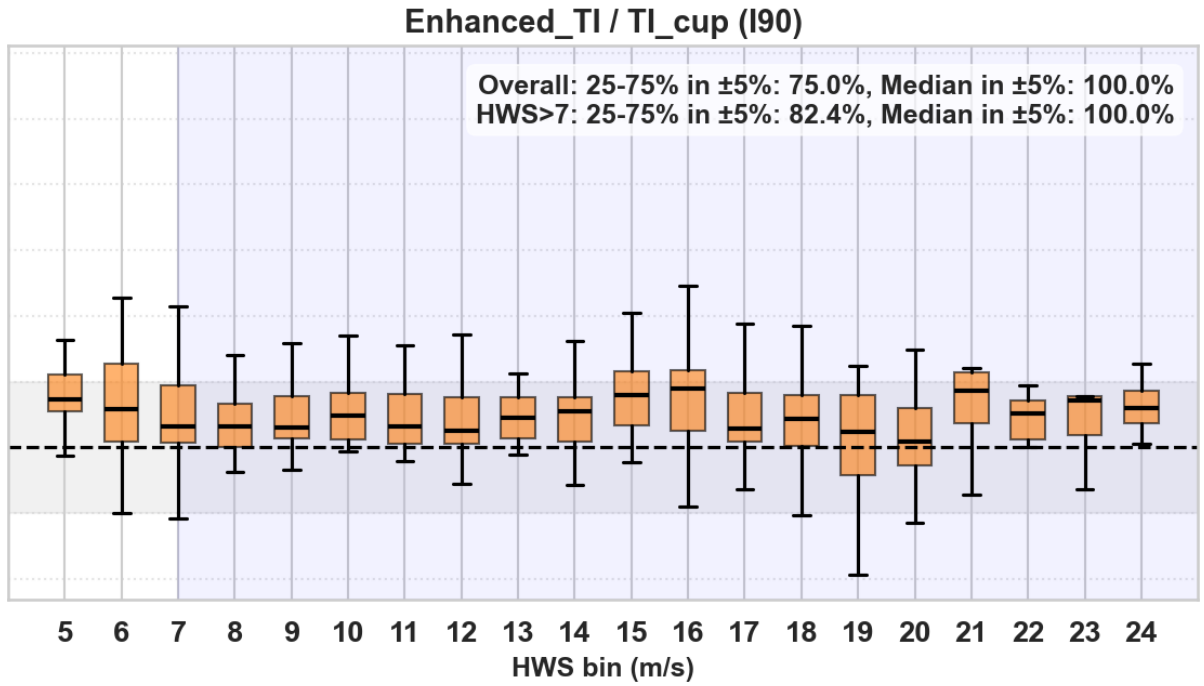


USA: many towers are only 60m tall

Common to use σ_{60m} to estimate σ_{hub}

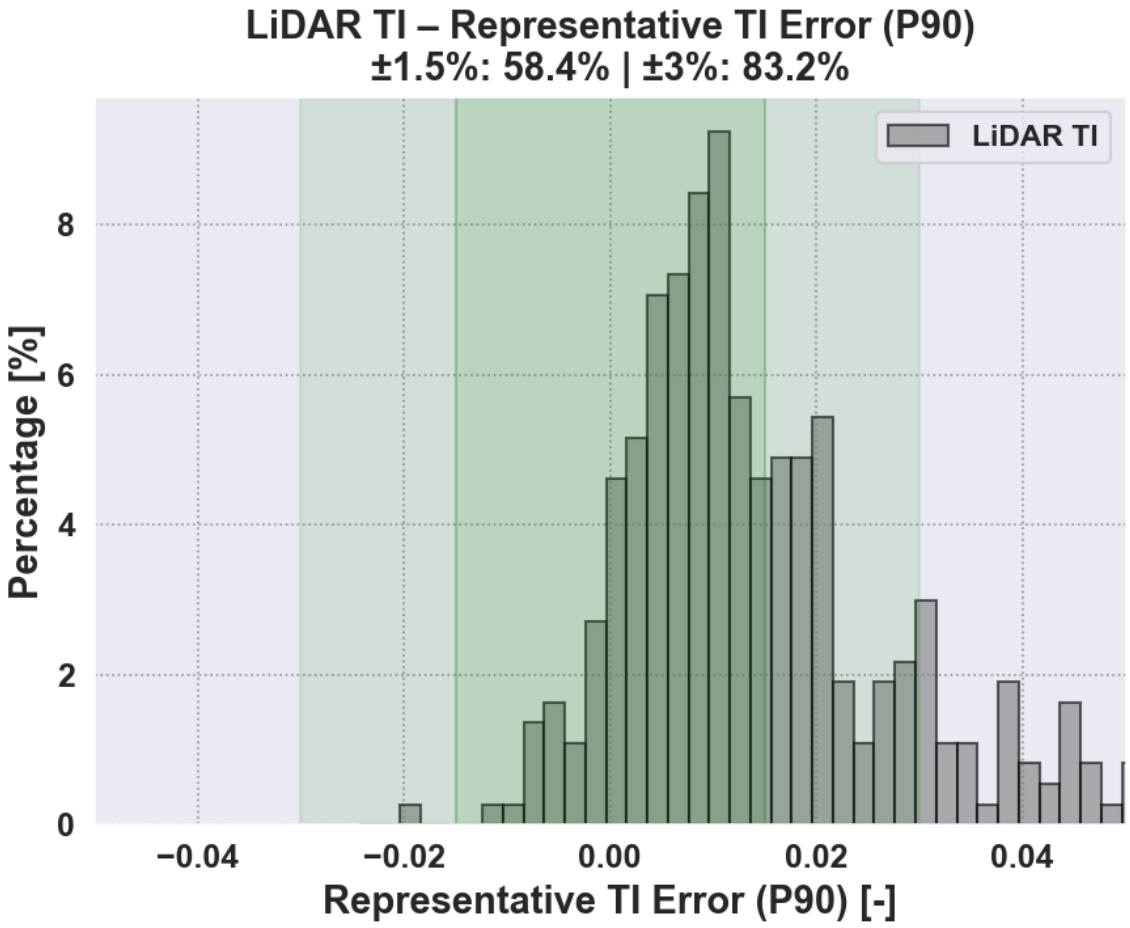
Representative TI RMBE (IEA Task 52)

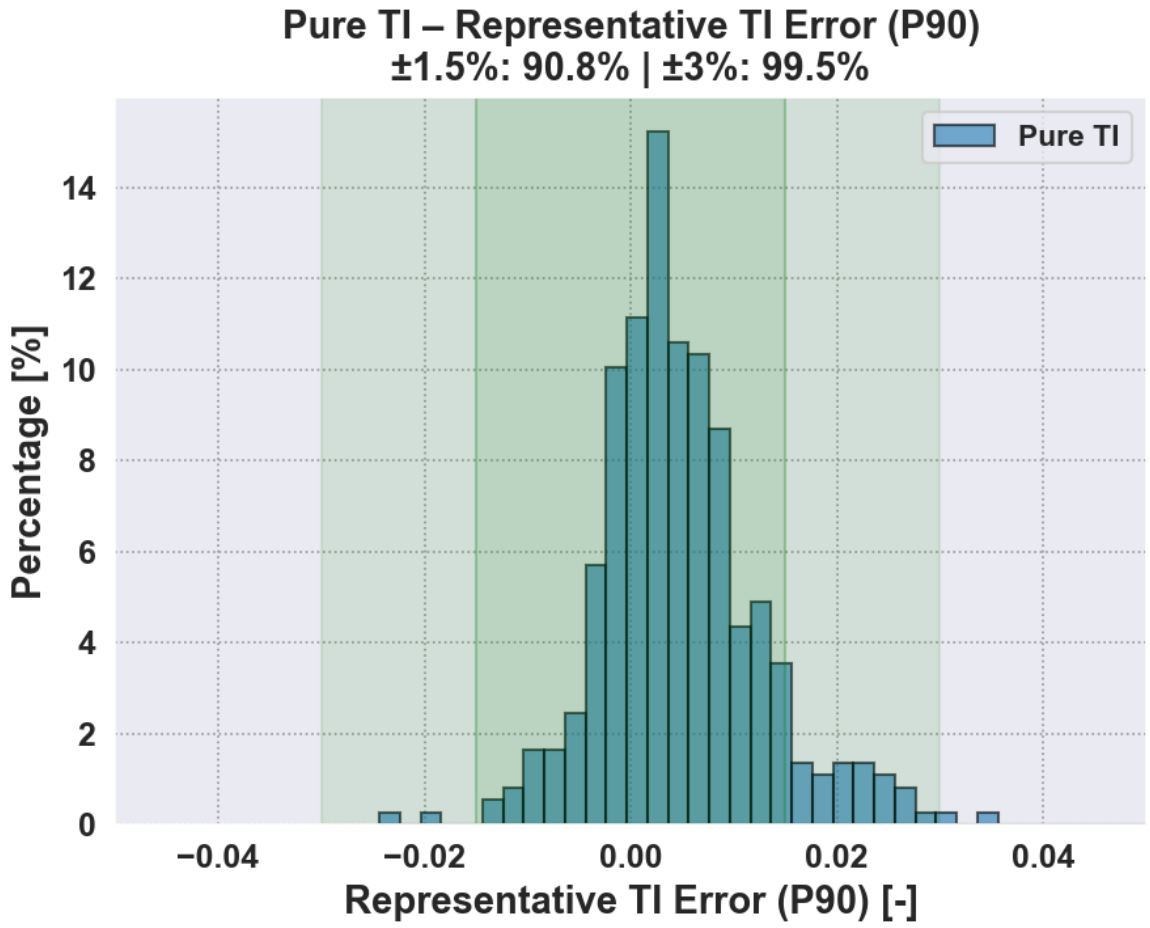




Internal

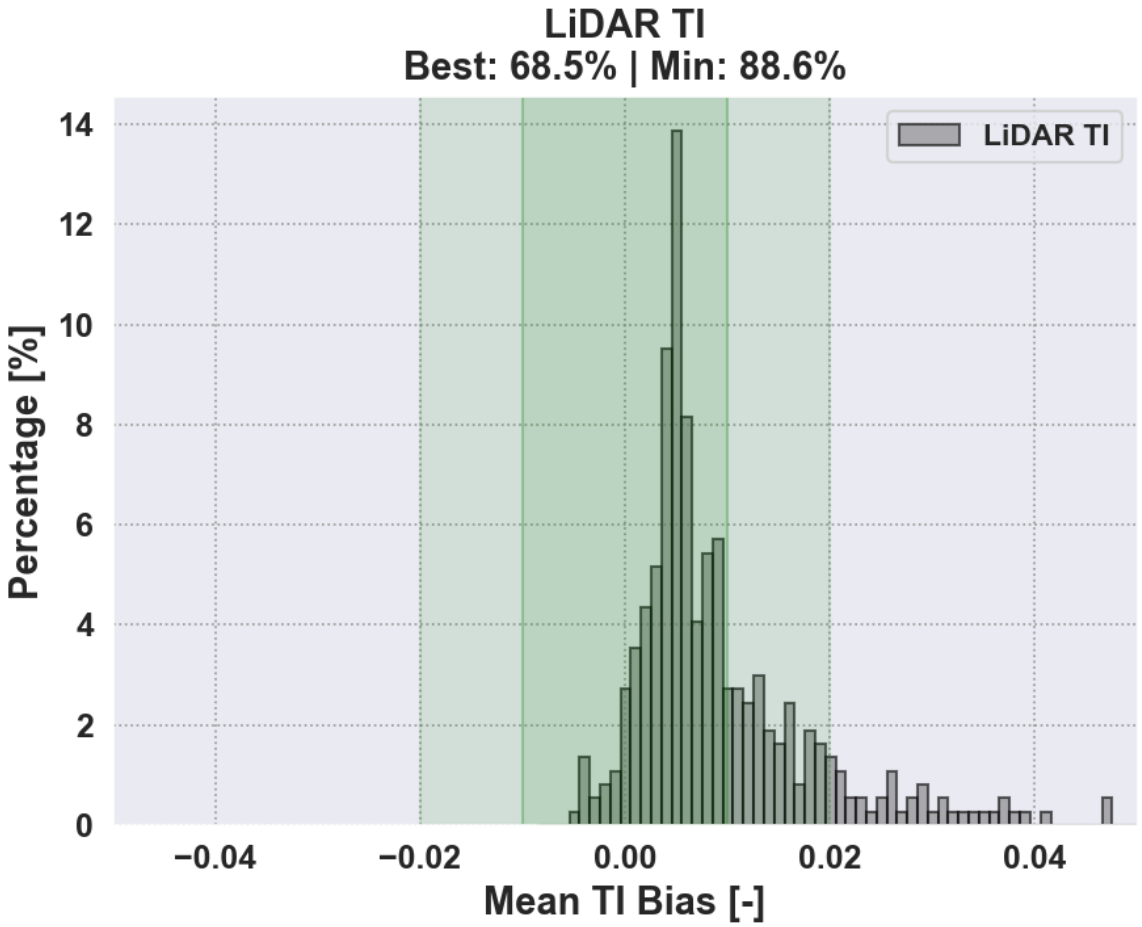
Representative TI MBE (CFARS)

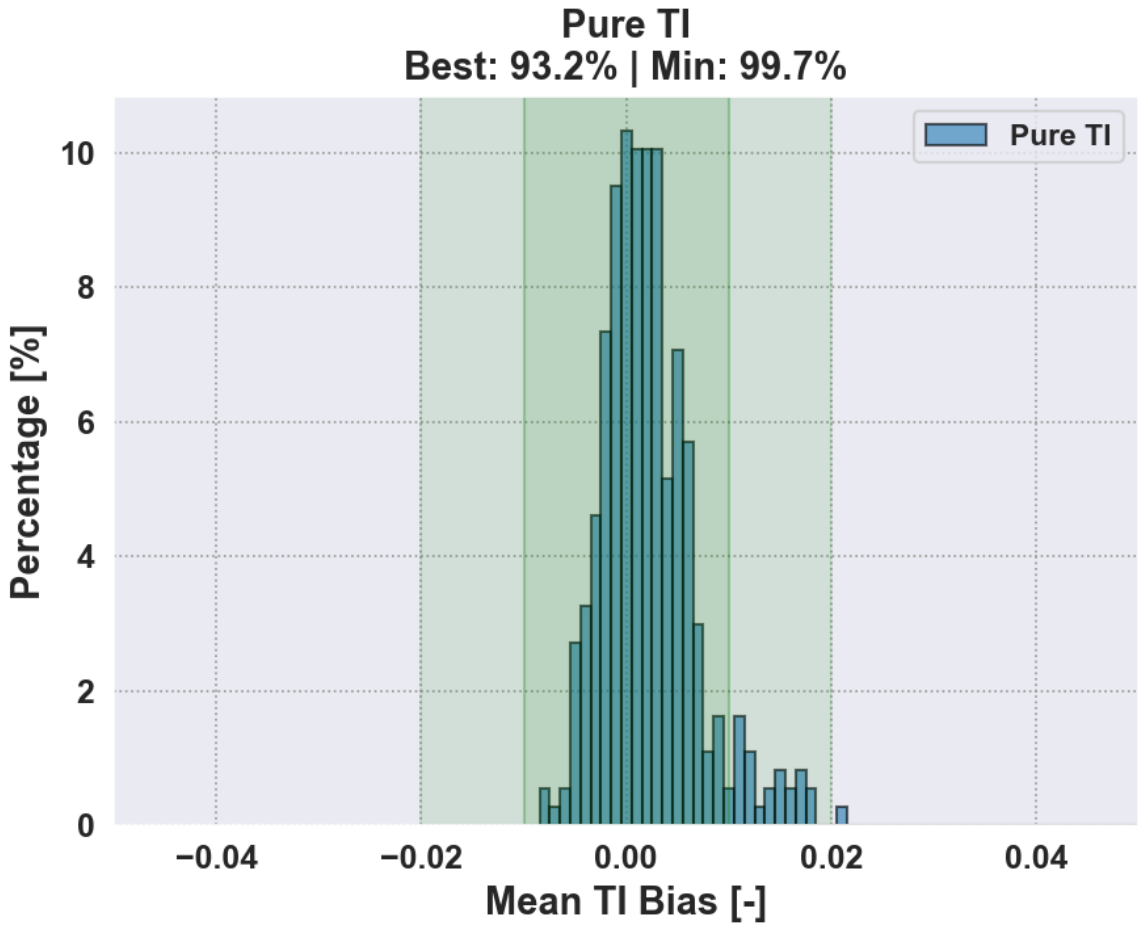




Internal

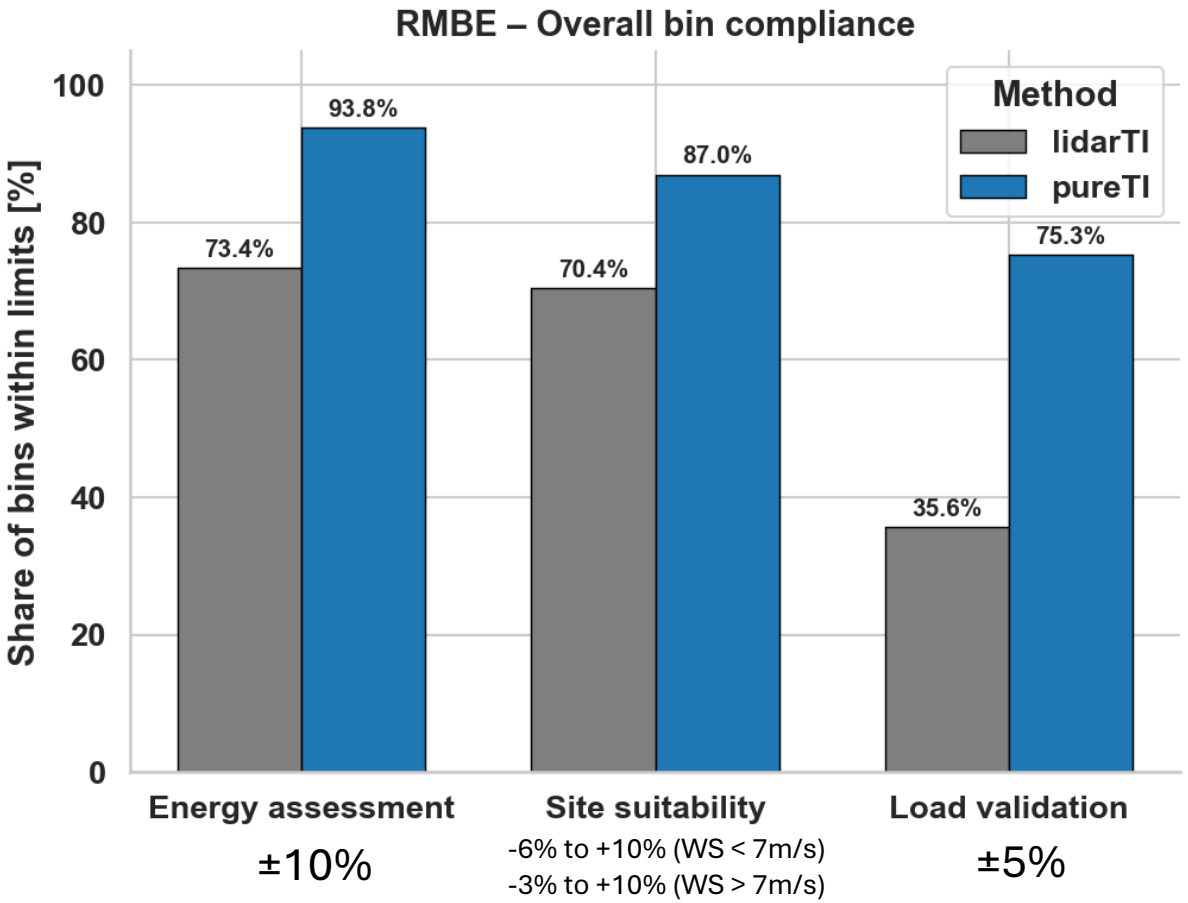
Mean TI MBE (CFARS)

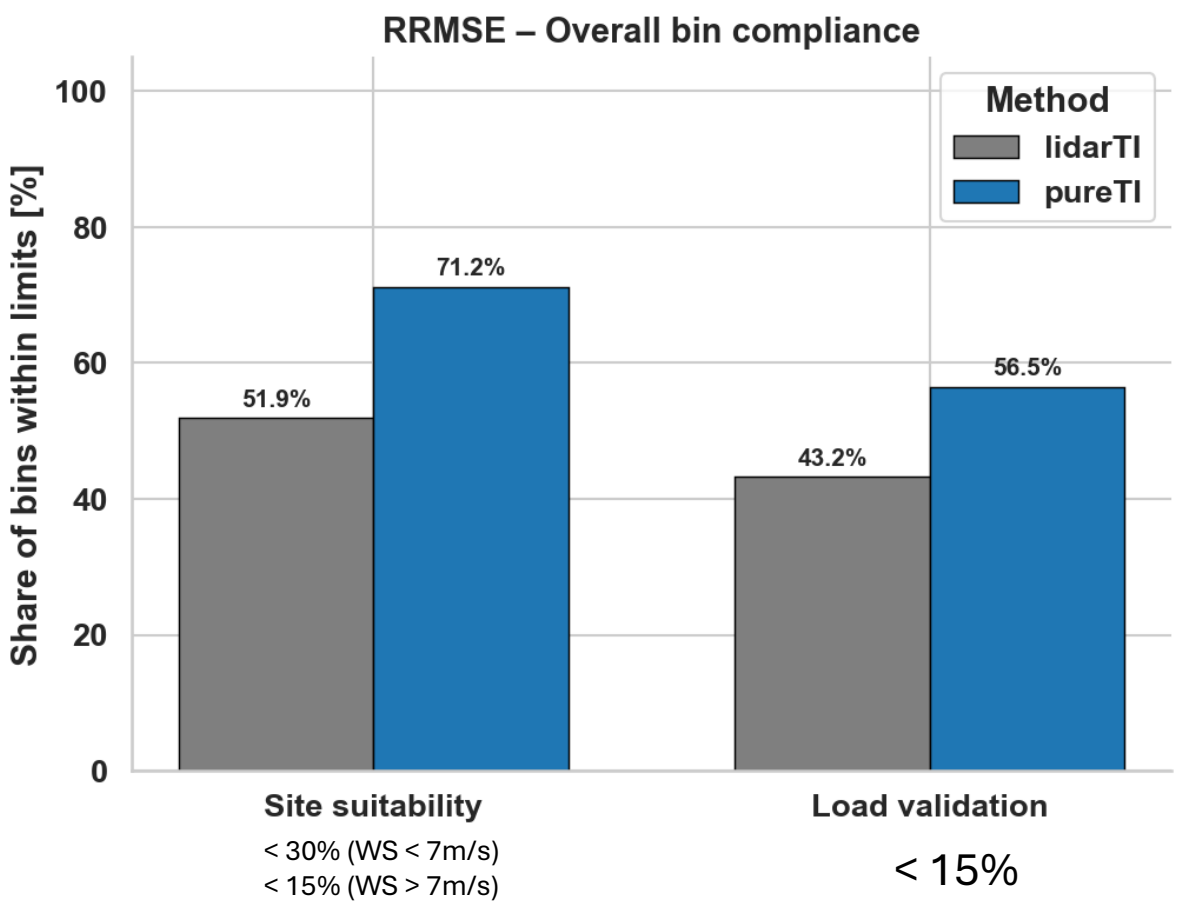




Internal

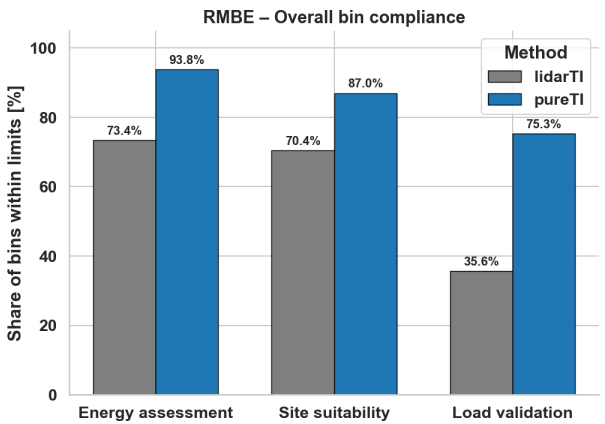
TI RMBE and RRMSE (DNV-RP 0661)





Internal

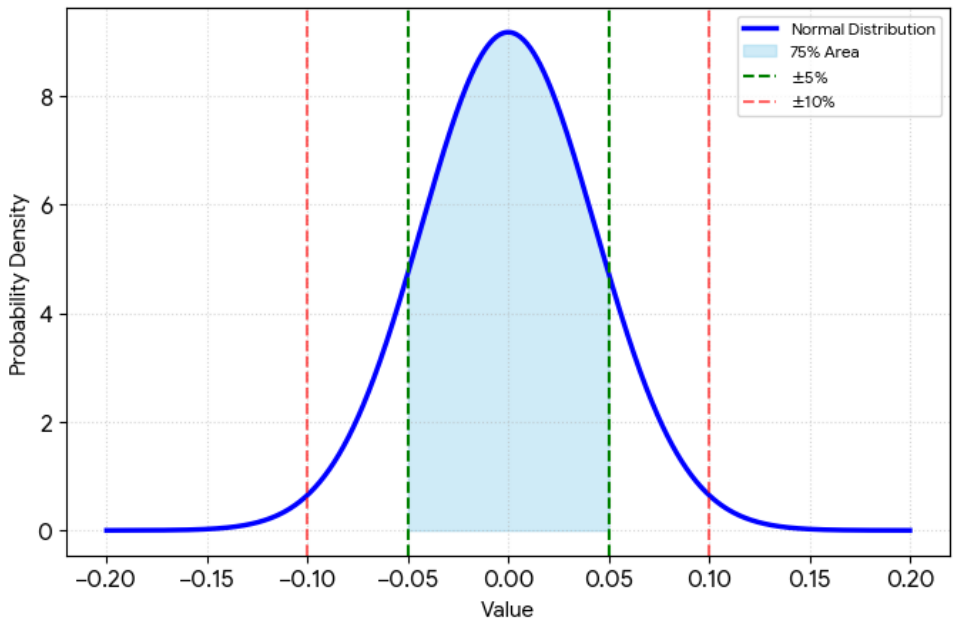
TI RMBE and RRMSE (DNV-RP 0661)



±10% ±5%

Residual errors form a distribution with:

- 75.3% of values within ±5%
- 93.8% of values within ±10%



Residual errors can be modeled by a Normal distribution with:

- $\sigma = 0.0435$, $\mu = 0$ (or 0.0099)

This can be interpreted that the Pure-TI algorithm has 4.35% *relative* uncertainty for wind speed-binned average TI

Ex: for TI = 15%, this would yield an *absolute* error of 0.6%

Internal

Conclusions & Next Steps

- Pure-TI is meeting industry KPIs at US sites:
  - CFARS: 93% Mean TI Best Practice, 90% Rep. TI Best practice
  - IEA Task 52: 82% Bin IQR within 5% for Rep. TI, 100% median values w/i 5%
  - DNV-RP: 87% Bin Mean TI RMBE within Site Suitability passbands, 75% for Loads
- Pure-TI exhibits low uncertainties from residual errors:
  - ~20% uncertainty for 10-minute TI
  - ~4.35% uncertainty for wind speed-binned mean TI
- Validating RRMSE KPI may not add value for the SS/LV/EYA applications
- Worldwide validation, including complex terrain, to be presented at WindEurope

Appendix – Distribution Comparison

