A Flow Model for Every Season: Model-enhanced Lidar Measurement Campaigns in Complex Terrain

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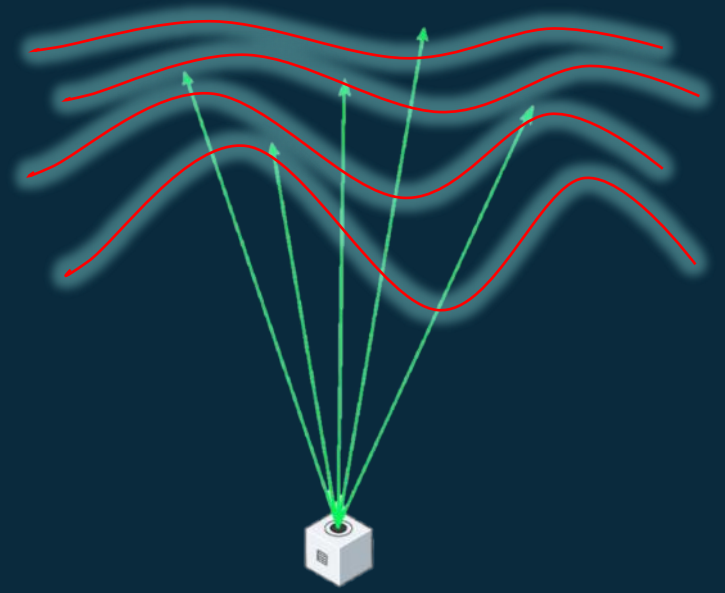
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Lidar campaigns in complex terrain

- Lidar have significant safety, mobility, and simplicity benefits for complex terrain energy yield assessment
- CFD flow model corrections of wind speed are quite mature, and are included in the IEC 61400-15-2 CD
- New TI algorithms have potential to complete the lidar measurement suite in complex terrain
- Simplified flow models can also add value for siting and campaign planning
- Here we examine the whole tool chain at example sites in the United Kingdom



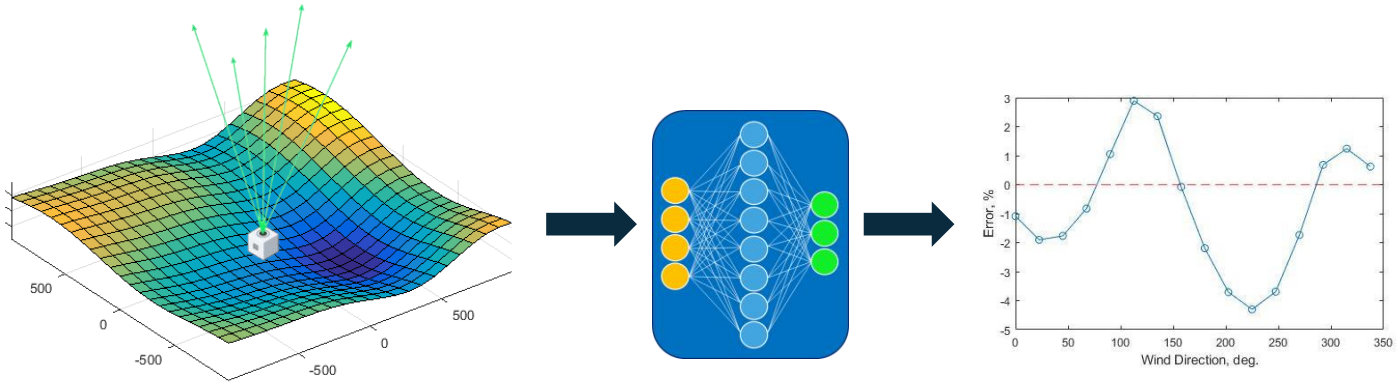


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Three flavors of flow models to help lidars

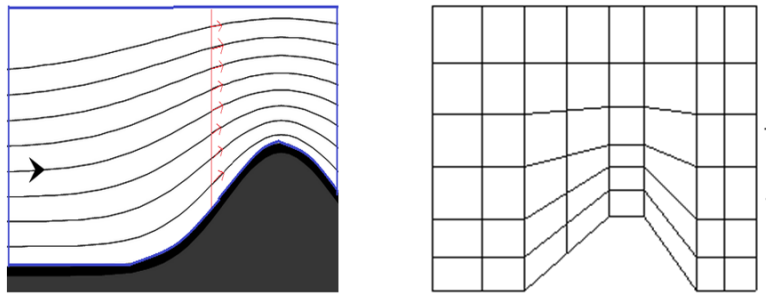
1 CFD surrogate model
Terrain Complexity Estimator

1000s of CFD flow simulations with a virtual lidar to train a neural network to predict the lidar error
Very fast, lightweight, reasonable accuracy



2 Mass conservation CFD
WindCube Flow Complexity Recognition (FCR)

Embedded on WindCube firmware. Model runs every 10-minutes using uncorrected lidar data as model's initial boundary conditions.
Solves 1st Navier Stokes equation only.
Fast enough, lightweight, good accuracy in moderately complex terrain

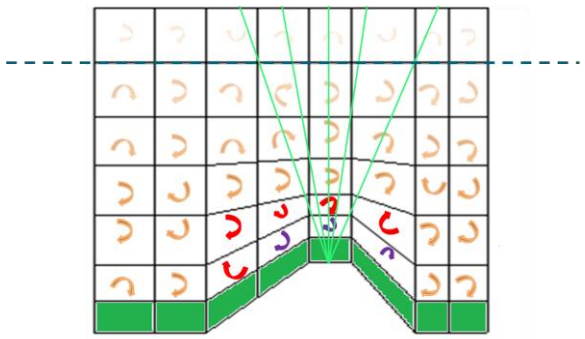


Example of terrain topography

Example of associated grid

3 Mass and momentum conservation CFD
ZephyScience and Deutsche WindGuard Complex Flow Solver

One model run, per wind direction, per site
Solves 2nd Navier-Stokes equation, full RANS CFD
Includes forest canopy parametrization, models complex phenomena
Slower, heavyweight, best accuracy in very complex terrain



Rapid terrain complexity estimation

1

Goal of CFD-surrogate flow model usage

- Identify optimal instrument locations
- Anticipate correction needs.

"Simple" terrain (<1%)
No correction needed

Moderately complex terrain
FCR recommended (1-3%)

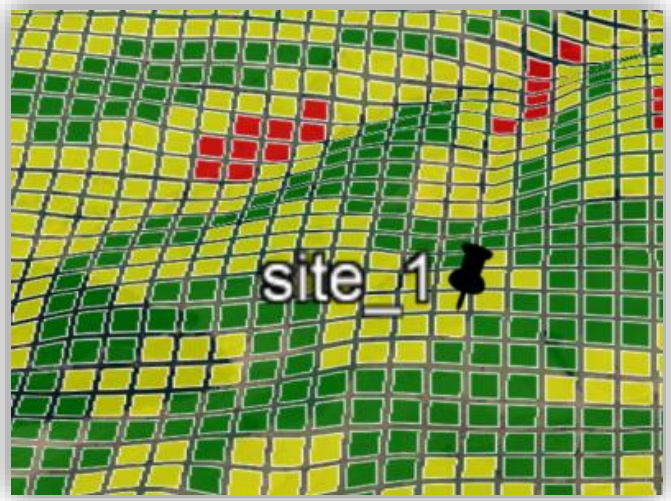
Highly Complex terrain
Data post-processing required with CFD models (>3%)



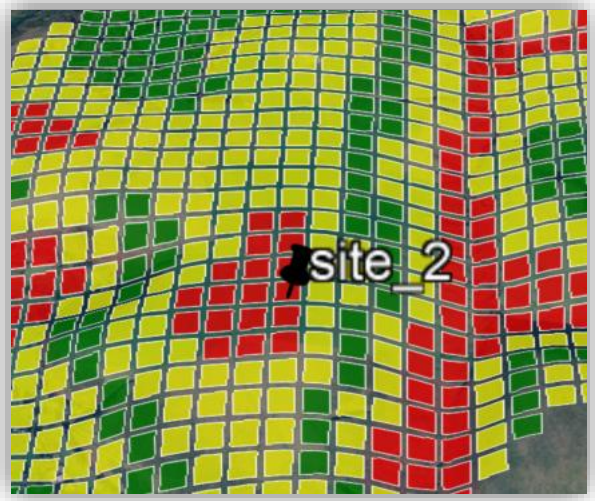
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Rapid terrain complexity estimation

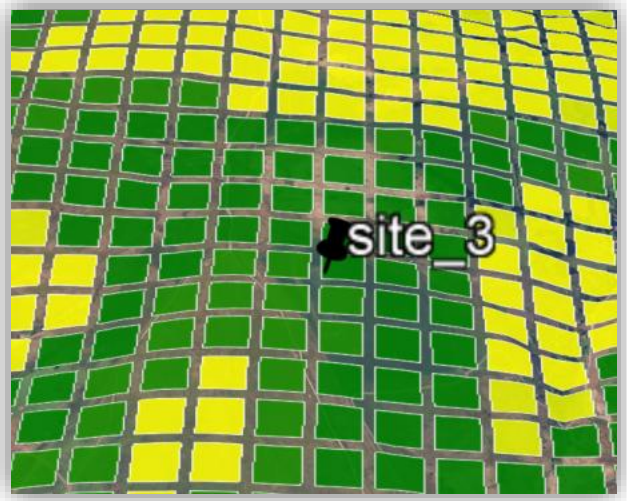
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- Moderately complex.
- Error between 1% and 3%
- FCR should be sufficient
- RIX: 8.58
- 4 months co-located campaign
- 80m mast
- WindCube v2.1

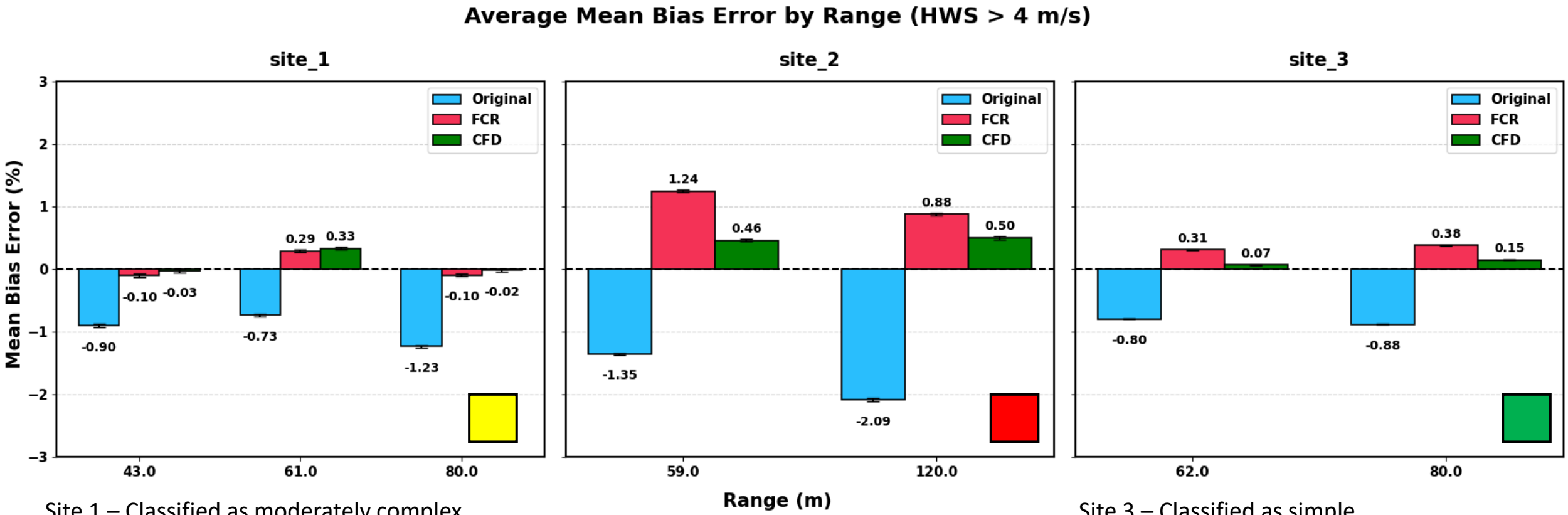


- Site classified as complex.
- Error higher than 3%
- CFD recommended
- RIX: 13.86
- 3.5 months co-located campaign
- 120m mast
- WindCube v2.1



- Site classified as simple.
- Error lower than 1%
- No correction is required
- RIX: 5.29
- 9 months co-located campaign
- 80m mast
- WindCube v2.1

Applying Corrections to Horizontal Wind Speed



Site 1 – Classified as moderately complex
FCR reduces error [-1.2, -0. 9] to [-0.1, 0.29]
FCR is sufficient (full CFD not required)

Site 2 – Classified as complex
FCR over-compensates the error at 59m
CFD here is clearly required, superior to FCR

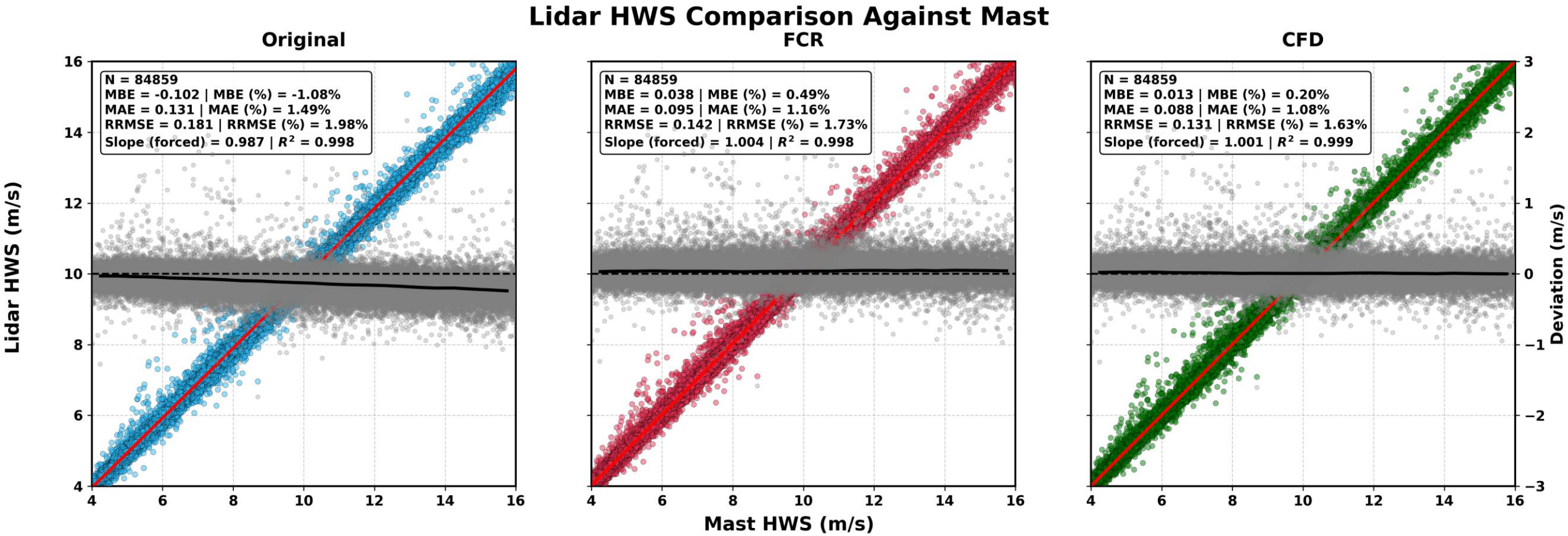
Site 3 – Classified as simple
All altitudes lidar error less than 1%
Both models reduce lidar error
CFD better than FCR, all scenarios <1% error

		Site 1			Site 2		Site 3	
Height		43	61	80	59	120	62	80
$u_{VS,adj}$	FCR	0.40%	0.51%	0.56%	1.29%	1.48%	0.55%	0.63%
	CFD	0.43%	0.53%	0.60%	0.90%	1.29%	0.43%	0.51%

IEC 61400-15-2
Flow correction uncertainties

$$u_{VS,adj} = 0.5 * u_{VS,flow}$$

Applying Corrections to Horizontal Wind Speed



For original reconstruction, clear deviation with wind speed values.

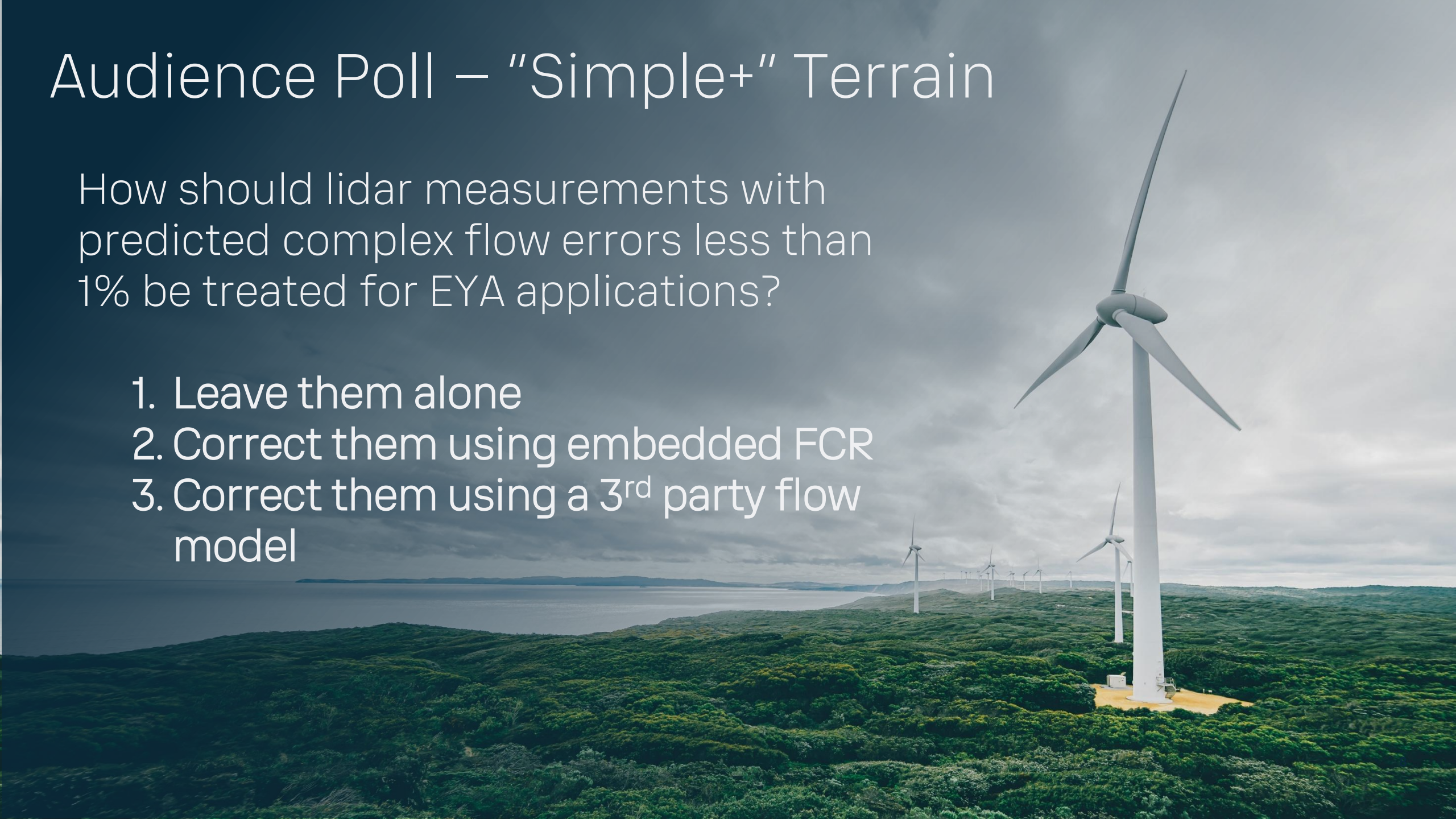
FCR correction accounts for this deviation

CFD correction works slightly better than FCR, on average

Audience Poll – "Simple+" Terrain

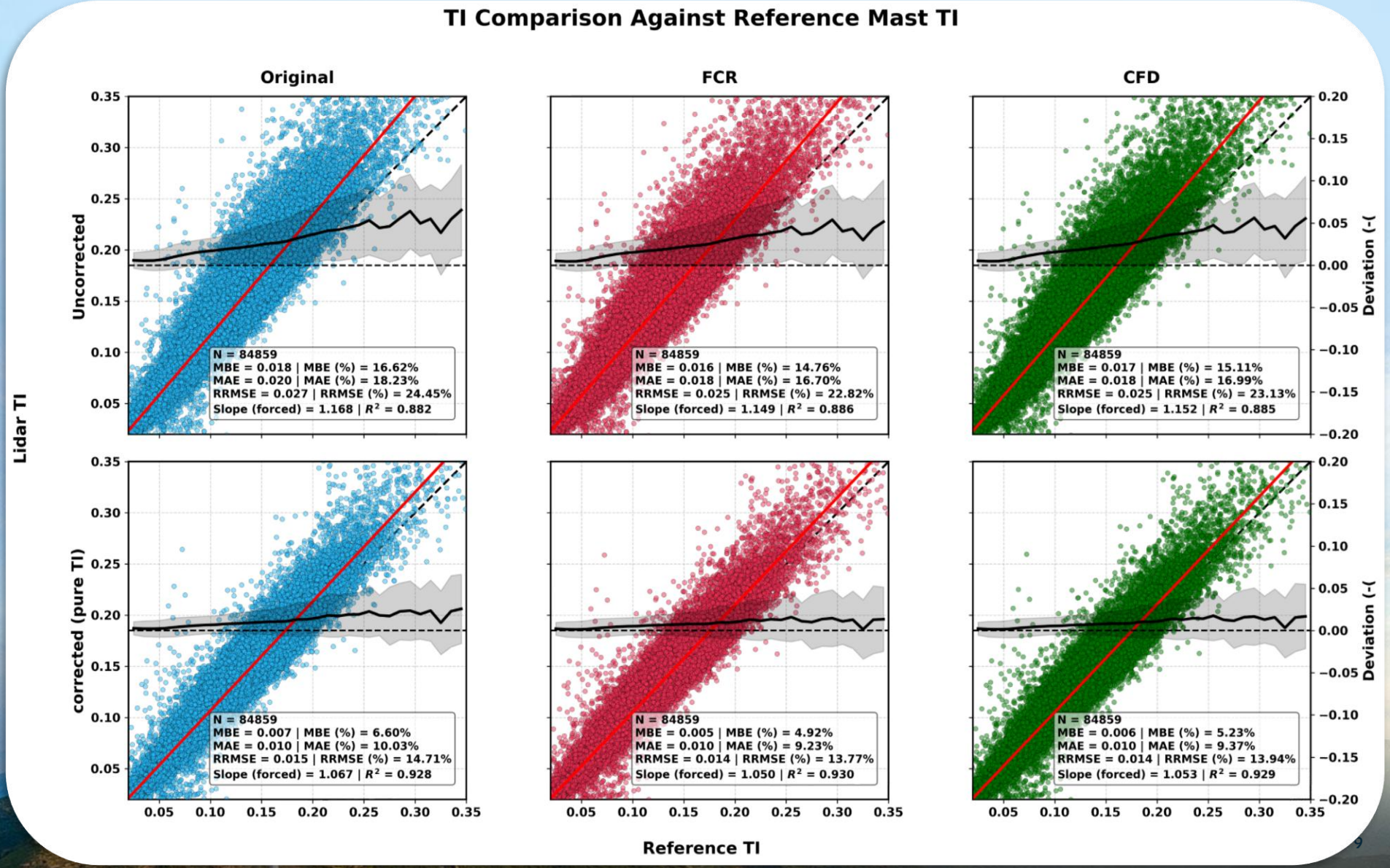
How should lidar measurements with predicted complex flow errors less than 1% be treated for EYA applications?

1. Leave them alone
2. Correct them using embedded FCR
3. Correct them using a 3rd party flow model



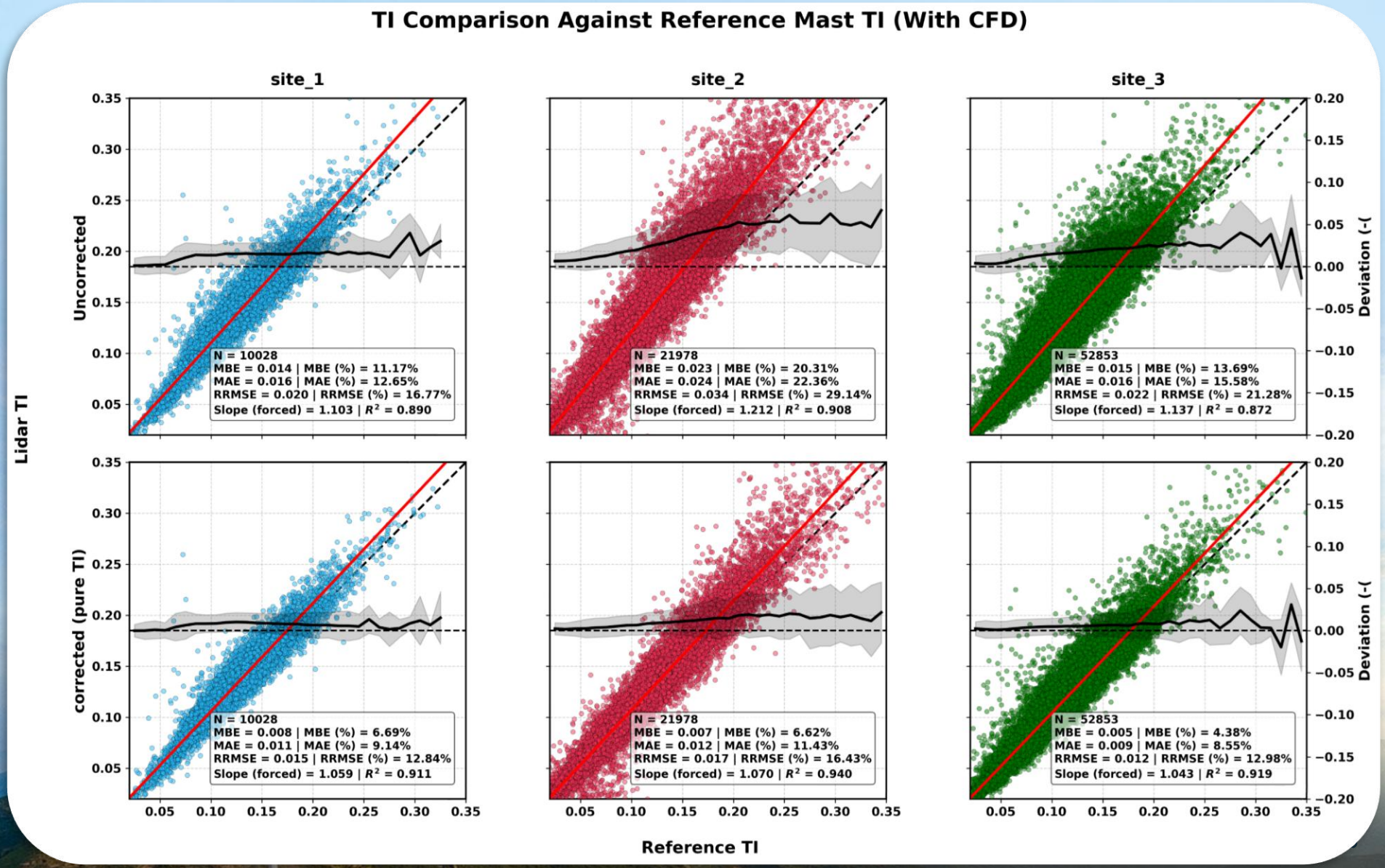
Turbulence Intensity Measurements

- Uncorrected lidar TI show a systematic positive bias in TI using the traditional computation of σ_{HWS}
- Vaisala's new Pure TI algorithm significantly reduces bias and scatter
- Pure TI computes σ_{HWS} only
- Pure TI does not treat complex terrain differently than simple terrain
- FCR and CFD further improve agreement with the cups through correction of the wind speed in the denominator of TI



Turbulence Intensity Measurements

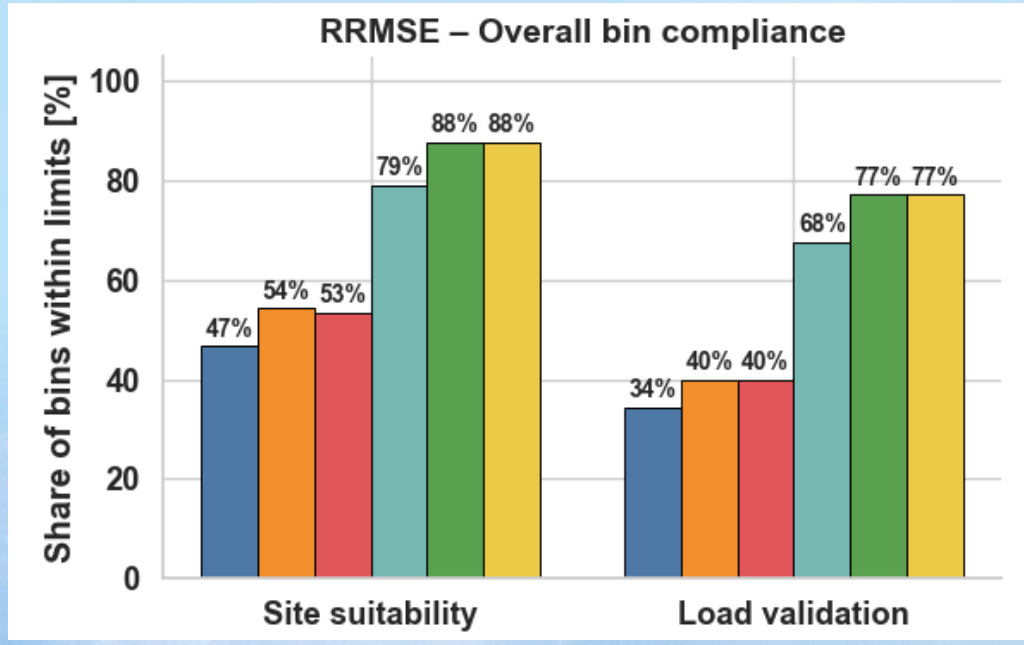
- TI overestimation reduced from 10-20% to 4%-7%
- Pure TI with CFD applied to wind speeds exhibits slightly higher errors than at simple sites
- Pure TI with CFD skill roughly follows terrain complexity

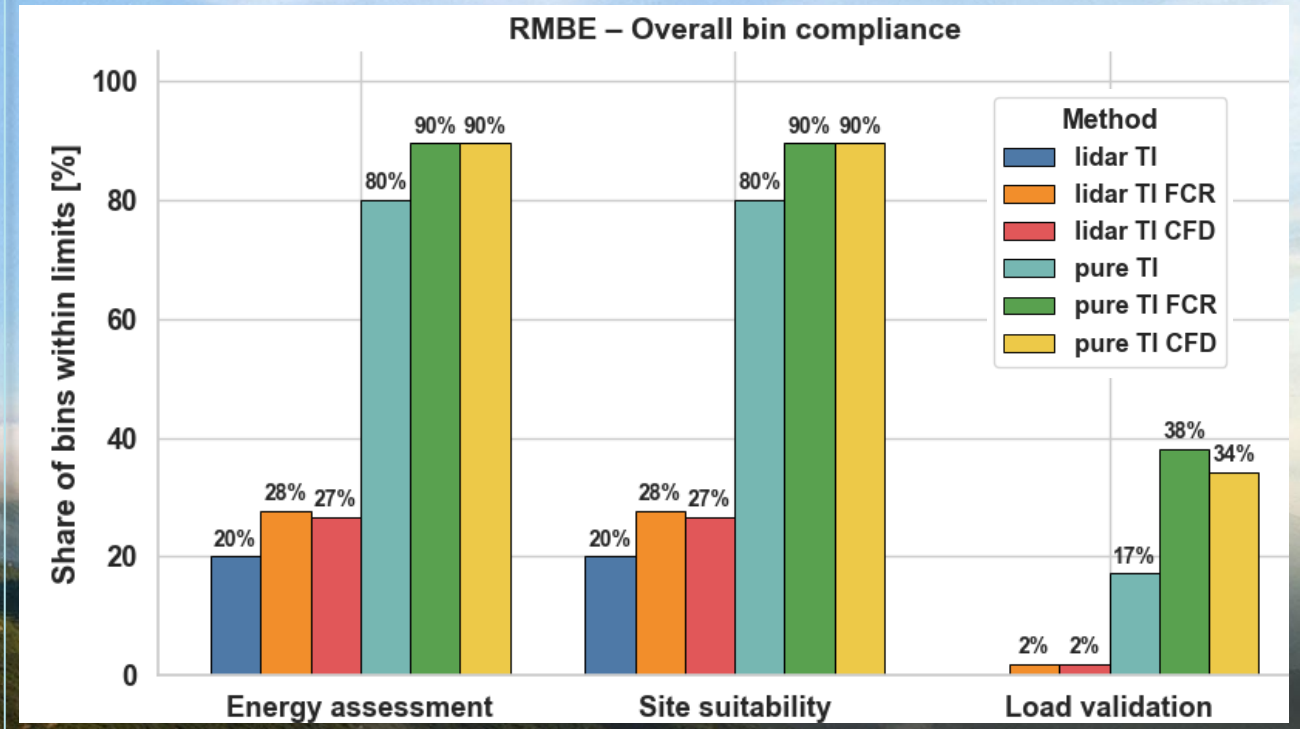


DNV-RP 0661 KPIS
Pure TI + CFD

Error Metric	Application	Passband (cup as reference)
RMBE	Energy Yield Assessment	±10%
	Site Suitability	-6%→+10% (WS<7 m/s) -3%→+10% (WS>7 m/s)
	Loads Validation	±5%
RRMSE	Site Suitability	≤30% (WS<7 m/s) ≤15% (WS>7 m/s)
	Loads Validation	≤15%







Conclusions

- Different types of flow models can be used at different phases of lidar-based complex terrain project development to methodically reduce uncertainty
- Lightweight CFD-surrogate models accurately predict performance of more detailed flow models used to adjust data across large projects areas
- FCR and CFD can both correct WindCube lidar wind speeds to low uncertainty for standalone complex terrain measurement campaigns
- IEC 61400-15-2 method for flow correction uncertainty well describes the errors
- Pure TI in combination with FCR or CFD gives conservative, nearly cup-equivalent TI in complex terrain

Thank you for your attention!

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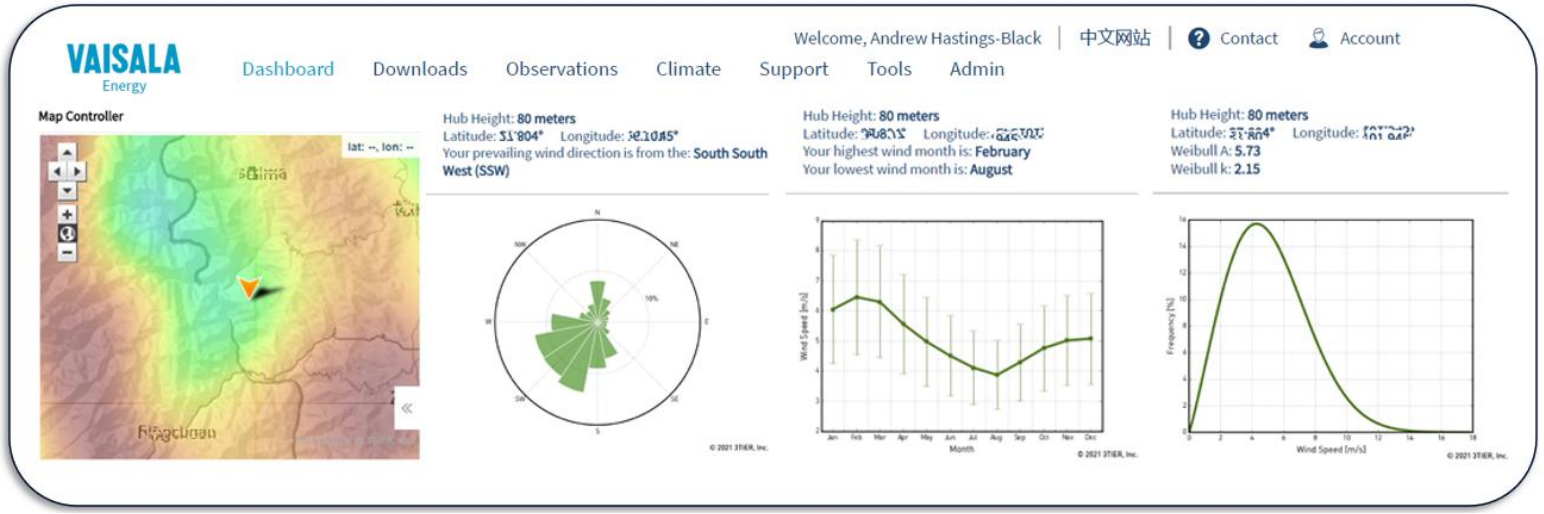
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Appendix



CFD Surrogate model 1
Terrain Complexity Estimator (TCE)

- The simulations used for training the neural network were generated with **ARIA MERCURE**,
- Average annual wind rose is retrieved from Vaisala Energy API



- Estimates generated on Compass platform are available at all altitudes up to 200m

Mass conservation CFD

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- Flow Complexity Recognition minimizes the functional:

$$J(V,\lambda) = \int_{\Omega} (u-u_0)^2 + (v-v_0)^2 + \frac{1}{\alpha}(w-w_0)^2 d\Omega + \int_{\Omega} \lambda \left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} \right) d\Omega$$

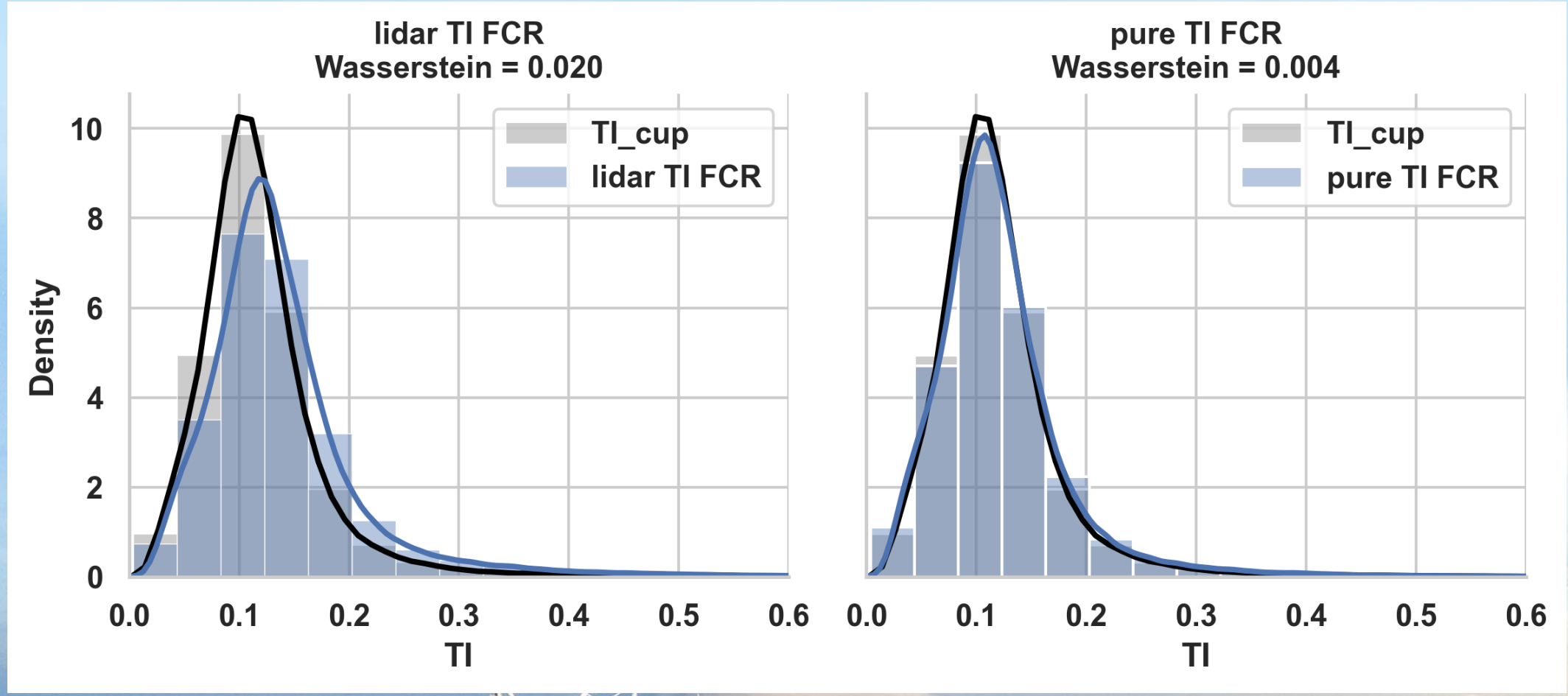
- Ω is the internal volume of the computation domain
- *J* is minimized when the values of its derivatives w.r.t *V* and λ are simultaneously zero
- $\vec{V_o} = \begin{pmatrix} u_0 \\ v_0 \\ w_0 \end{pmatrix}$ represents the original measurements and $\vec{V} = \begin{pmatrix} u \\ v \\ w \end{pmatrix}$ the final field with $div\, \vec{V} = 0$
- The resulting wind field at the location of the Windcube is consistent with the initial Windcube measurement but also considers the surrounding topography and especially the wind flow curves within the measurement volume.

RANS CFD

3

- The CFD lidar correction used is the ZephyLIDAR Complex Flow Solver developed by Deutsche WindGuard and ZephyScience
- 36 flow directions have been evaluated, for each 10° wind direction.
- Turbulence model: **Re-normalisation Group k-epsilon.**
- Land cover data : **ESA-WorldCover-V2-2021**
- Digital Elevation Model: **FABDEM V1-2**

TI distribution



The **Wasserstein distance** measures how much "work" is needed to transform one probability distribution into another.

Characteristic TI Curves

- Used to select turbine based on upper distribution of bin-wise TI Defined in IEC 61400-1
- $y = \mu_{TI,i} + 1.28 * \sigma_{TI,i}$ in each wind speed bin, *i*

