Why does T7 underperform? Individual turbine performance relative to preconstruction estimates.

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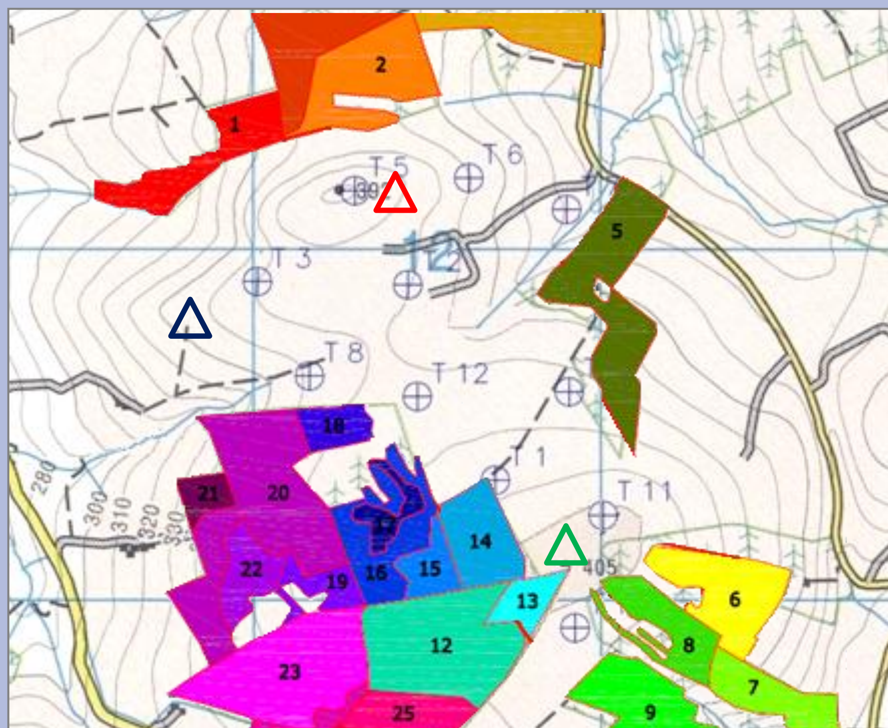
power for good

Example Site Overview

- Moderately complex terrain. 11 multi-megawatt class turbines.
- Inhomogeneous forest cover 5-20m in height.
- Two 40m Masts (turbine hub height is 65m, rotor diameter is 82.4m)

△Mast A
△Mast B
△ Power Performance Mast T3



	CURRENT FORESTRY MEAN HEIGHT (m)	GROWTH RATE
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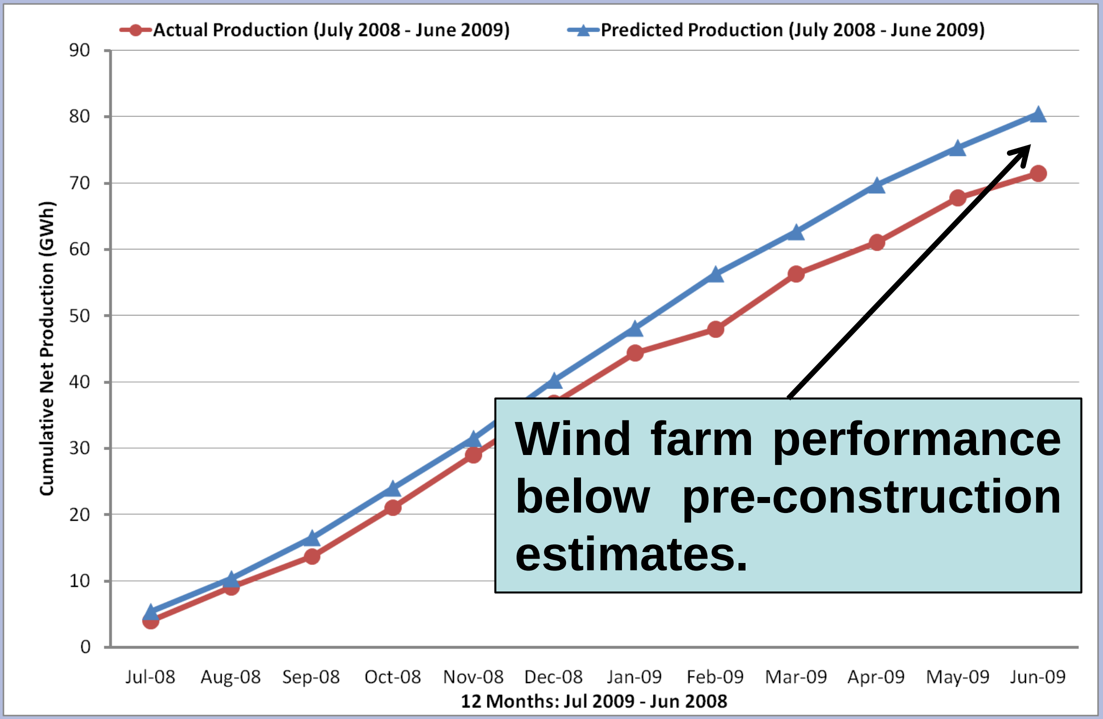
7	16	0.5
8	8	0.4
9	8.5	0.5
10	9	0.5
11	11	0.5
12	12	0.4
13	9.5	0.3
14	7.5	0.3
15	8.5	0.3
16	11	0.3
17	12	0.3
18	10.5	0.3
19	9.5	0.3
20	13	0.3
21	16.5	0.4
22	12	0.4
23	16	0.5
24	17	0.5
25	15	0.5
26	18.5	0.5

Consider one year of operation...



- Data analysis has eliminated windiness and availability as source of underperformance (these issues will not be discussed here further).
- Focus on observed variation in production over wind farm and how this compares with the preconstruction predictions.

A logical framework for Observed Underperformance

$$E = E_0 + \delta E$$

$$\delta E = \delta P + \delta S + \delta W + \delta TI + \delta \alpha + \delta SW + \ldots$$

Energy Yield Error

- E = Post Construction Energy Yield
- E_0 = Pre-construction Energy Yield
- δE = Energy Yield Error

Power Curve Error

- δP = Error due to turbine not performing as expected in standard inflow.

Wind Flow Errors

- δS = Topo Model (speed up) Error
- δW = Wake Model Error
- δSW = Non-linear topo/wake error

Non Standard Inflow Errors

- δTI = Turbulence Inflow Error
- δα = Shear Inflow Error

A logical framework for Observed Underperformance: Decomposed Errors

$$\delta E = \delta P + \boxed{\delta S} + \delta W + \boxed{\delta TI} + \boxed{\delta \alpha} + \delta SW + \ldots$$

Decompose component errors as follows:

$$\delta S = \delta S_R + \delta S_B$$

δS_R = **Random** error to wind flow model

δS_B = **Bias** error due to wind flow model

$$\delta TI = \delta TI_A + \delta TI_E$$

δTI_A = Change in **available energy** due to TI

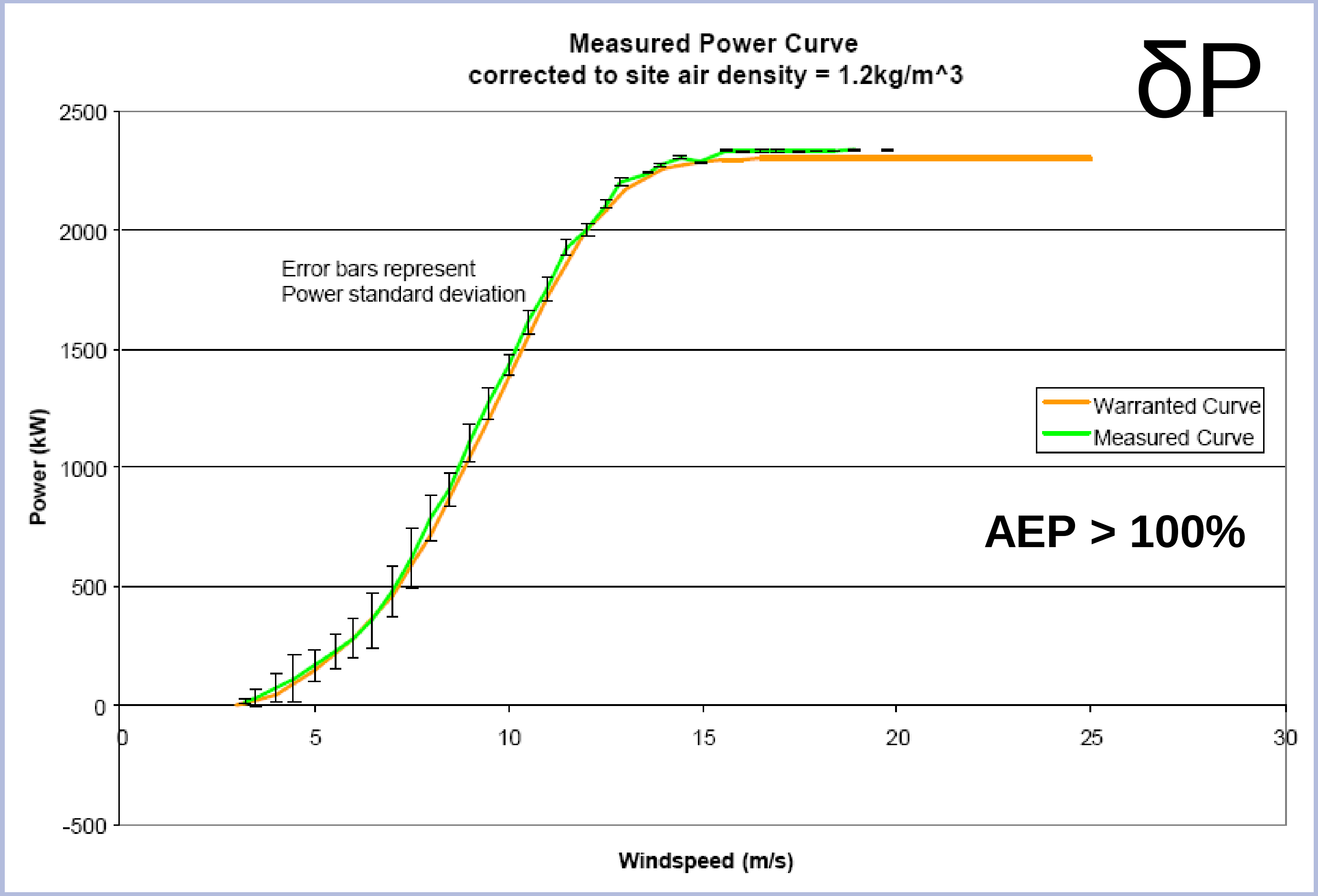
δTI_E = Change in **turbine efficiency** due to TI

$$\delta \alpha = \delta \alpha_A + \delta \alpha_E$$

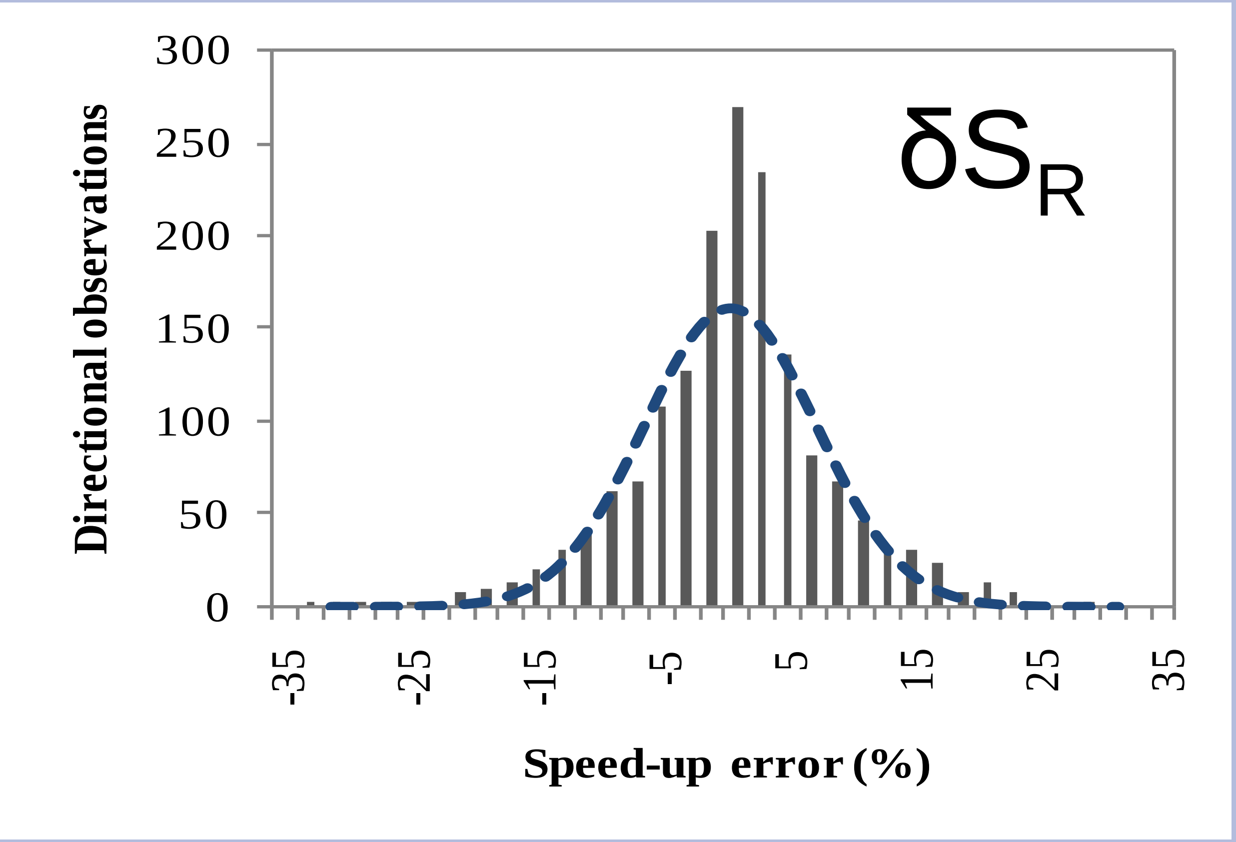
$\delta \alpha_A$ = Change in **available energy** due to α

$\delta \alpha_E$ = Change in **turbine efficiency** due to α

Performance in standard inflow covered by IEC Power Performance Test



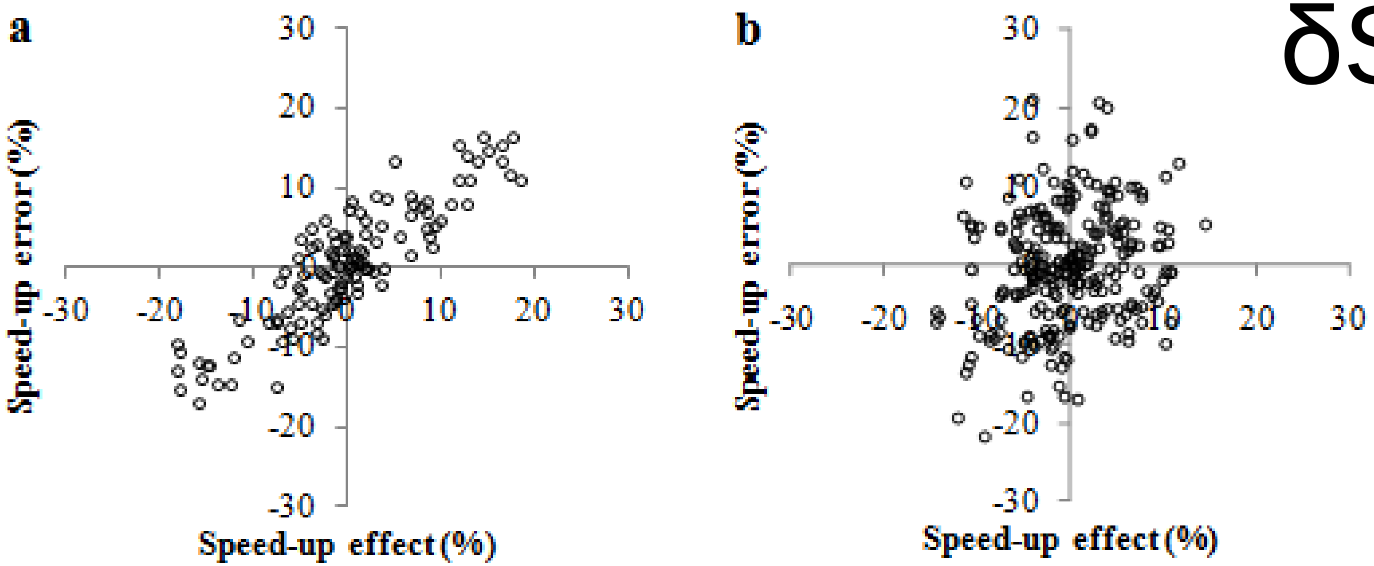
Example Speed Up Random Error from Met Mast Data



- Random error is a source of uncertainty, but on average, across many turbines (and wind farms), it should average to zero.
- Will manifest as 'noise' in per turbine error analysis.

Example Speed Up Bias Error from Met Mast Data

δS_B



Bias **No Bias**

Fig. 4: ε_S vs. η_S for (a) a site in France with 8 masts and (b) a site in Sweden with 10 masts.

- **Bias error can average out over wind farm if met mast is 'half-way up hill'**
- **However even if wind farm error is zero, errors will still be visible per turbine.**
- **Unclear why bias is seen on some sites and not others?**

Non-standard inflow errors

$$\delta TI = \delta TI_A + \delta TI_E \qquad \delta\alpha = \delta\alpha_A + \delta\alpha_E$$

- Turbine power curves are typically measured in 'standard inflow' conditions e.g. TI = 10-12% and α = 0.15 – 0.2.

- **What happens if TI = 18% and α = 0.45?**

- The above terms will manifest as a change in the turbine power curve, for two possible reasons?

  - δTI_A and $\delta\alpha_A$ describe change in **available/apparent energy** e.g. Albers method for effect of 10minute averaging of non-linear power curve.

  - δTI_E and $\delta\alpha_E$ describe possible change in **efficiency** (aerodynamic, mechanical or electrical) in non-standard inflow.

TI_A Power Curve Correction: Numerical Study

Non-standard TI correction: impact on yield for different mean wind speeds and turbulence intensities...

Turbulence Intensity

Mean Wind Speed

WS\TI	0.05	0.06	0.07	0.08	0.09	0.10	0.11	0.12	0.13	0.14	0.15	0.16	0.17	0.18	0.19	0.20
5.0	3%	2%	2%	2%	2%	1%	1%	1%	0%	0%	-1%	-1%	-1%	-2%	-2%	-3%
5.5	2%	2%	2%	2%	1%	1%	1%	1%	0%	0%	0%	0%	-1%	-1%	-1%	-2%
6.0	1%	1%	1%	1%	1%	1%	1%	1%	1%	0%	0%	0%	0%	0%	-1%	-1%
6.5	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	0%	0%	0%	0%	0%	0%
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8.0	0%	0%	0%	0%	0%	0%	0%	0%	1%	1%	1%	1%	1%	1%	2%	2%
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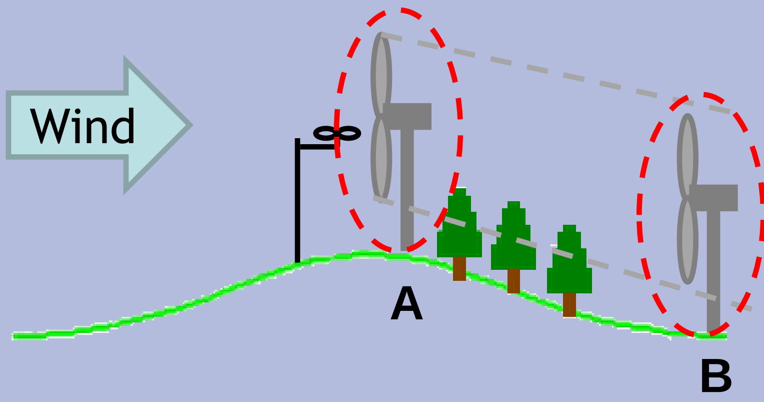
9.5	-1%	-1%	0%	0%	0%	0%	0%	0%	1%	1%	1%	1%	2%	2%	2%	2%
10.0	-1%	-1%	0%	0%	0%	0%	0%	0%	1%	1%	1%	1%	2%	2%	2%	2%
10.5	-1%	-1%	0%	0%	0%	0%	0%	0%	1%	1%	1%	1%	2%	2%	2%	2%
11.0	-1%	-1%	0%	0%	0%	0%	0%	0%	1%	1%	1%	1%	2%	2%	2%	2%

1-2% predicted underperformance at high TI and high mean wind speed.

Correlation of Error Terms

• **Hypothesis:** non-standard inflow is associated with regions of large topo and wake model errors.

• **Consequence:** non-standard wind flow errors correlate with topo and wake errors.



Turbine A: low topo error, low wake error and standard inflow.

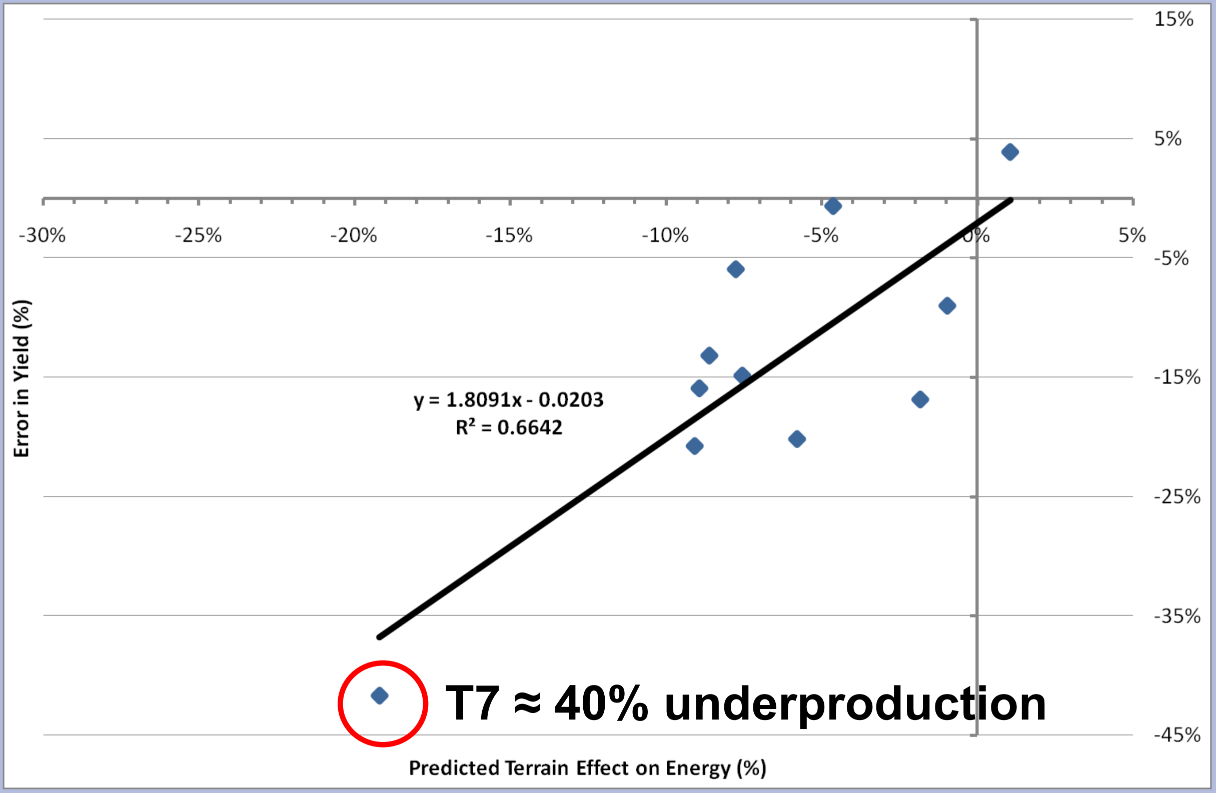
Turbine B: larger topo error, larger wake error and larger non-standard inflow error.

• **Real world situations allow errors to add coherently i.e. ‘bad’ turbines can be ‘really bad’ turbines.**

Example Site Individual Turbine Performance - Speed Up Bias Error?

- Plot error in yield vs. predicted terrain effect

δS_B?

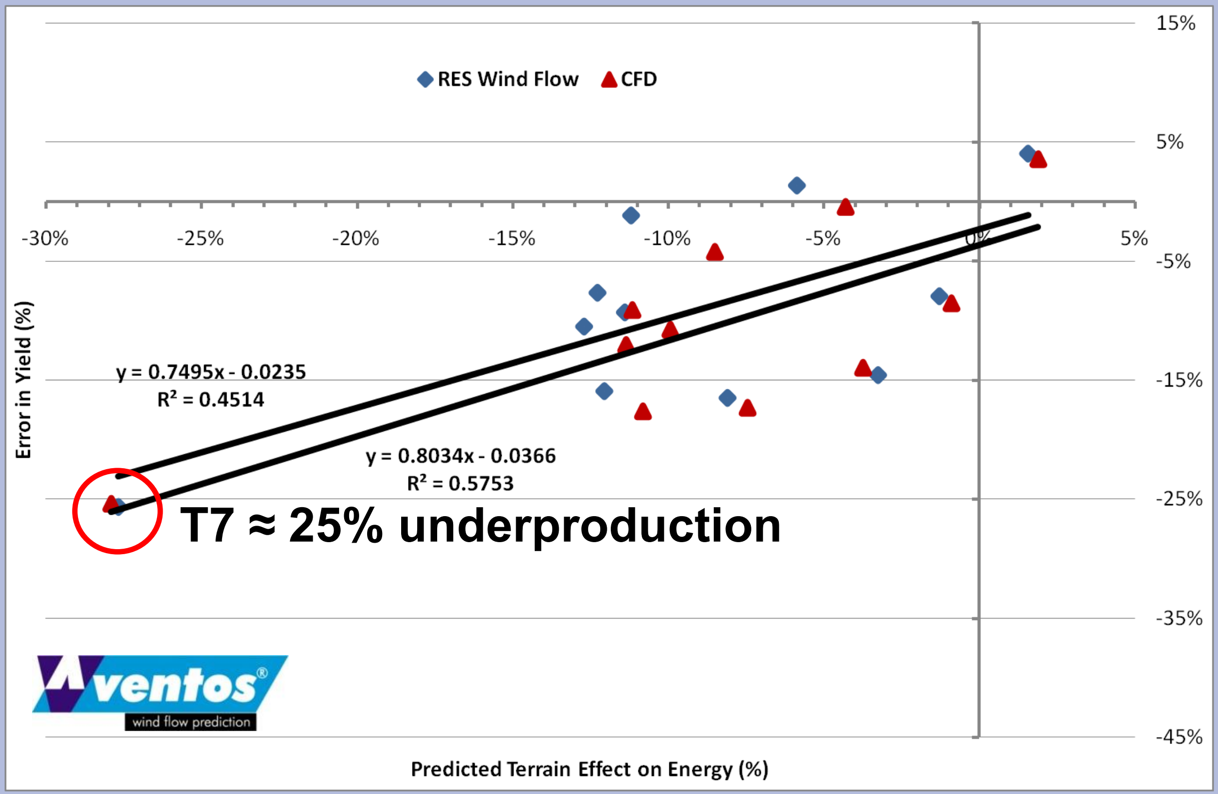


- Correlation between predicted terrain effect and error in energy yield.

Example Site Individual Turbine Performance - Increase roughness & CFD?

δS_B?

- Site also modelled using CFD, including canopy model. Increasing roughness improves agreement.



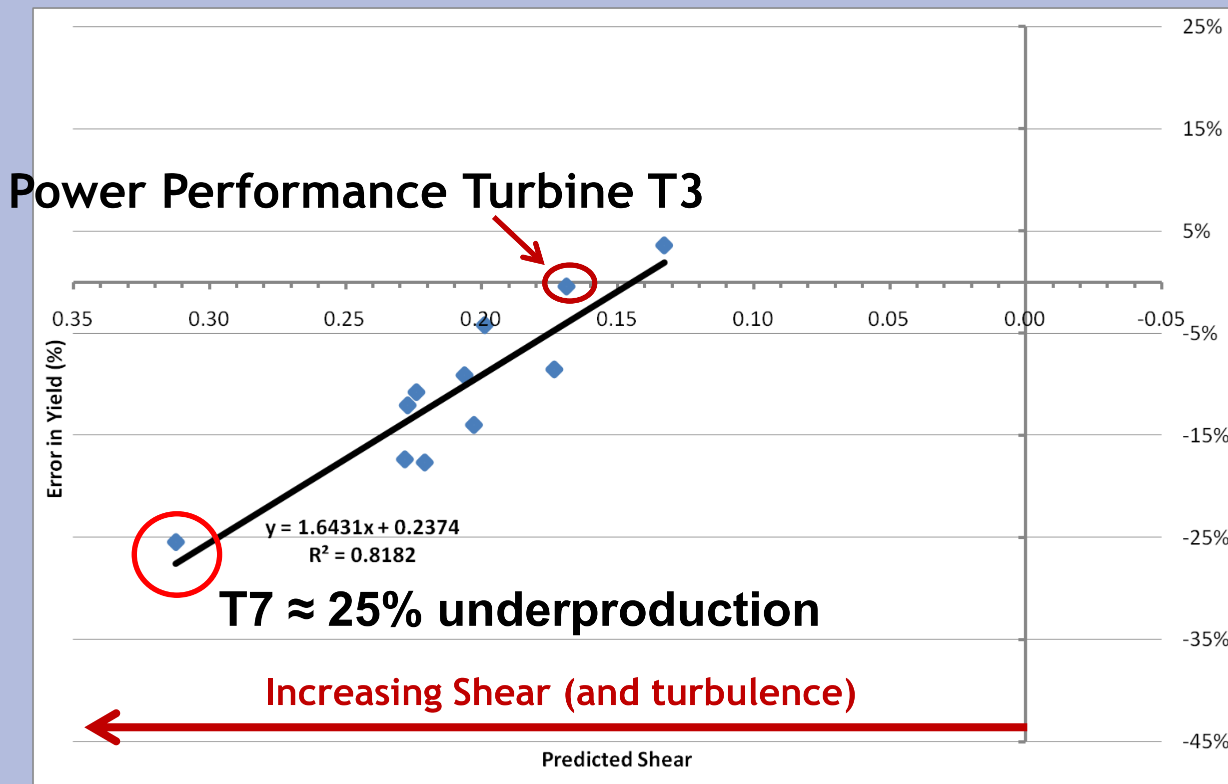
- CFD and increased roughness in very close agreement. Roughness increased from default 0.04m to 2m, potentially more representative of the site (tree height up to 20m).

Effect of non-standard inflow?

- Still an error in the predictions; other causes – high shear?

δα?

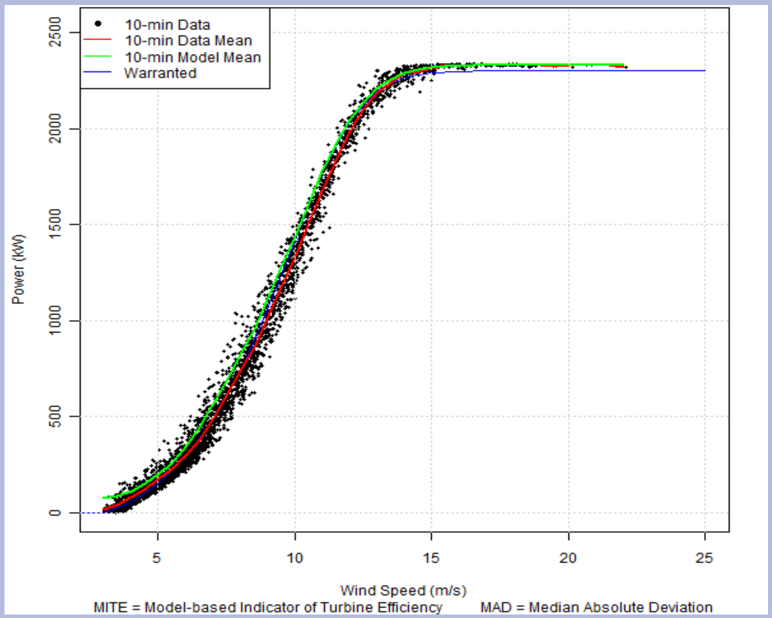
δTI?



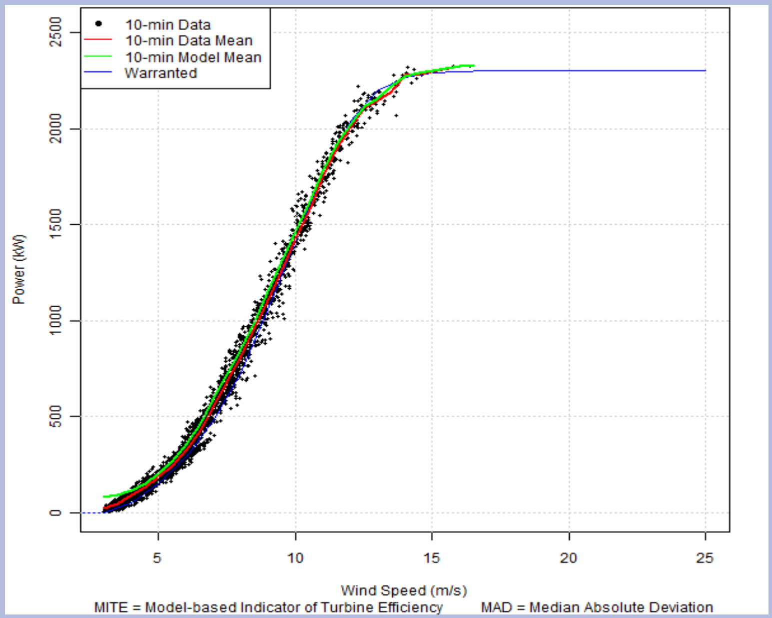
- Strong correlation between high α/TI and error in energy yield predictions?

Effect of non-standard inflow? (It seems not!)

- If power performance error due to non-standard inflow is cause of under performance then observed power curved should appear distorted...



T3 ≈ 0% underproduction



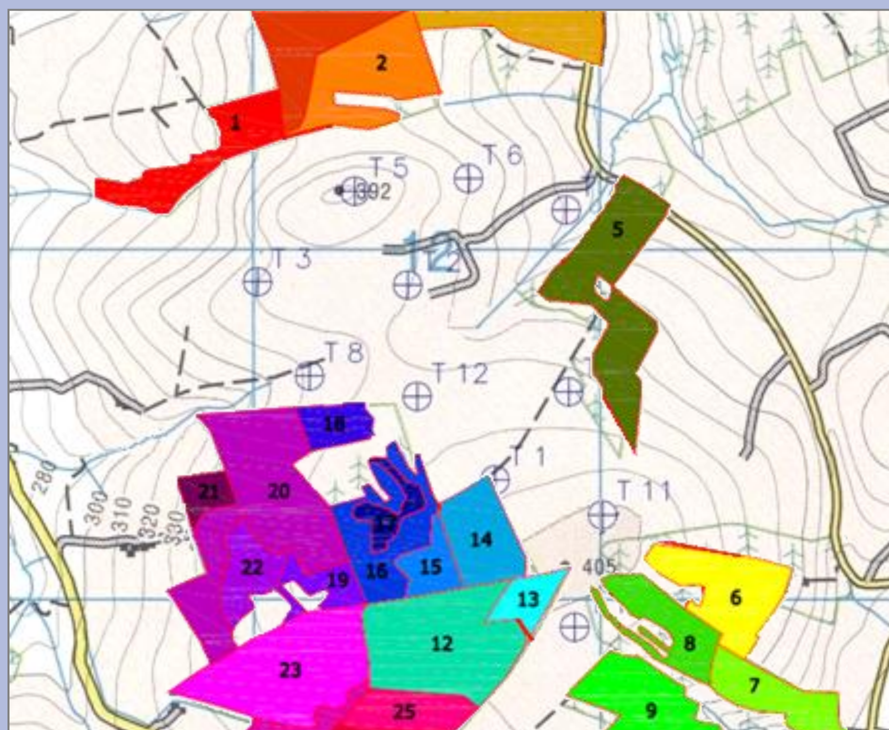
T7 ≈ 25% underproduction

- **Nacelle power curve indicates non-standard inflow errors are relatively small (on this project) i.e. δα ≈ 0% and δTI ≈ 0%**

Why does T7 underperform?

- Conclusions so far for this example site (other sites may be different):

$$\delta E = \delta P + \delta S + \delta W + \delta TI + \delta \alpha + \delta SW + \ldots$$



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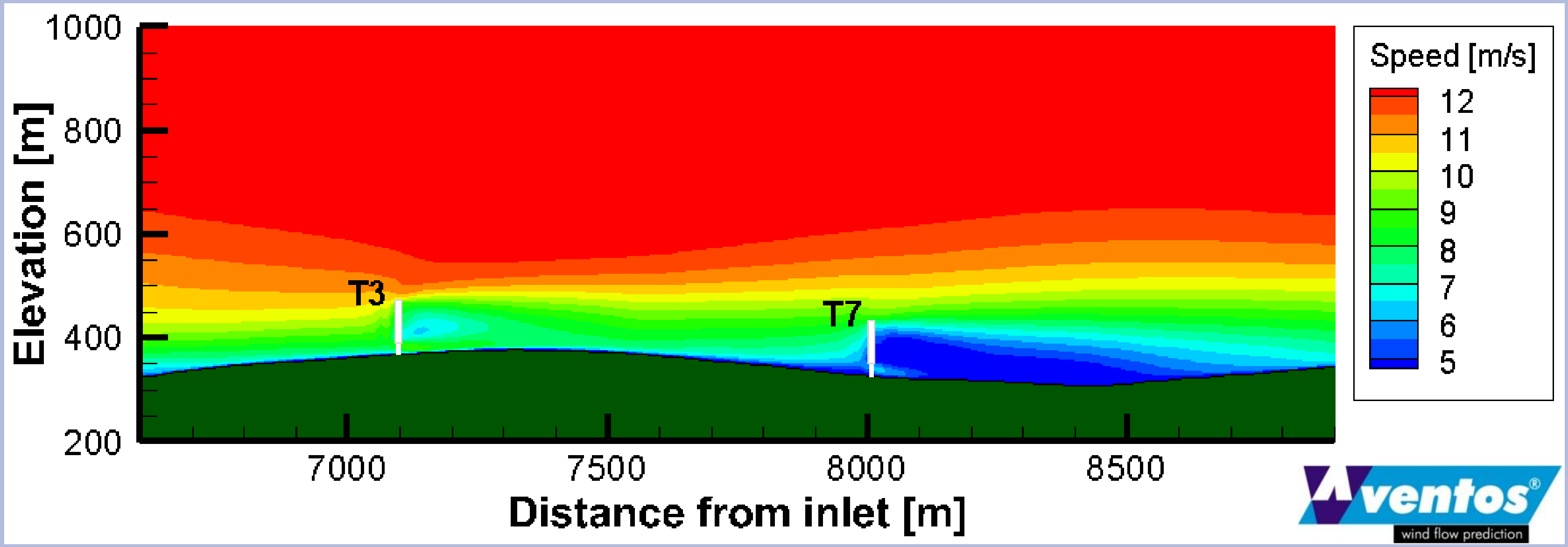
Wakes

T7 has ≈25% underproduction, could this be explained by wakes?

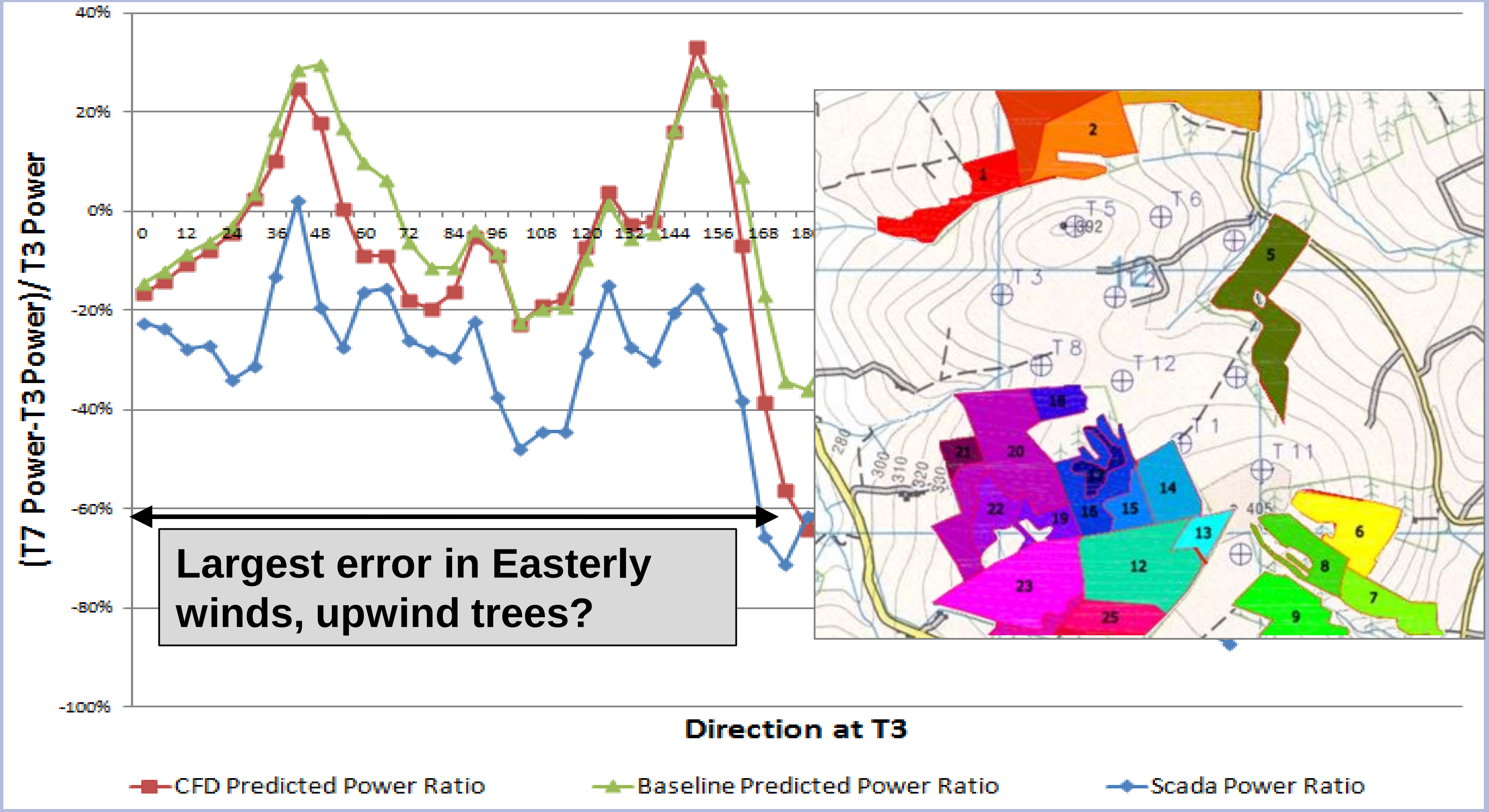
δW — **The predicted wake loss is ≈ 10%, could the wake model error really explain 25% underperformance?**

δSW — **Is there a non-linear interaction of the wake and terrain that could be captured by a CFD model?**



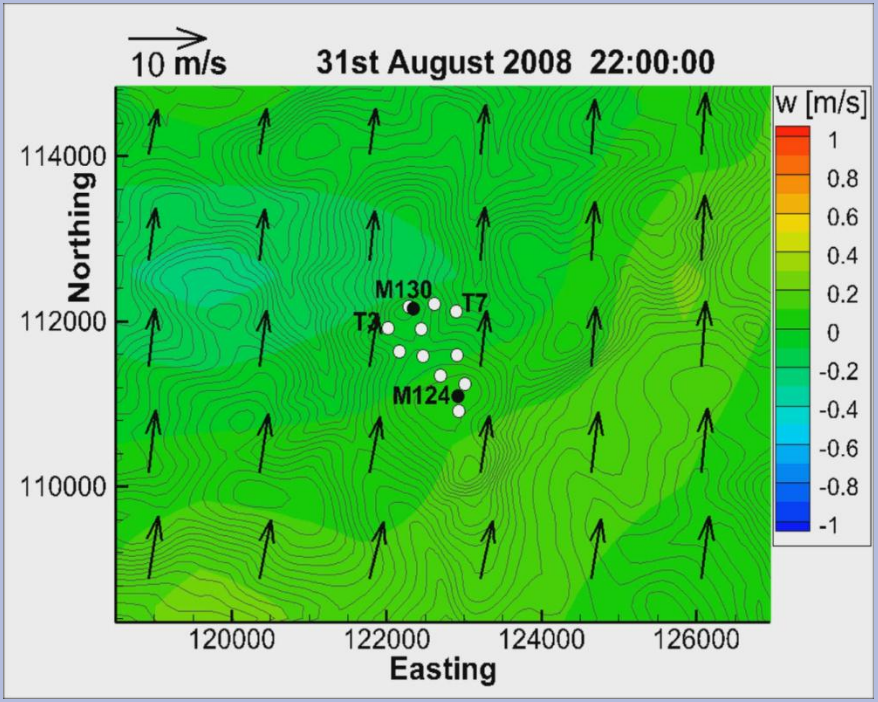
More work needed!

Directional Power Ratio: T7 vs. T3

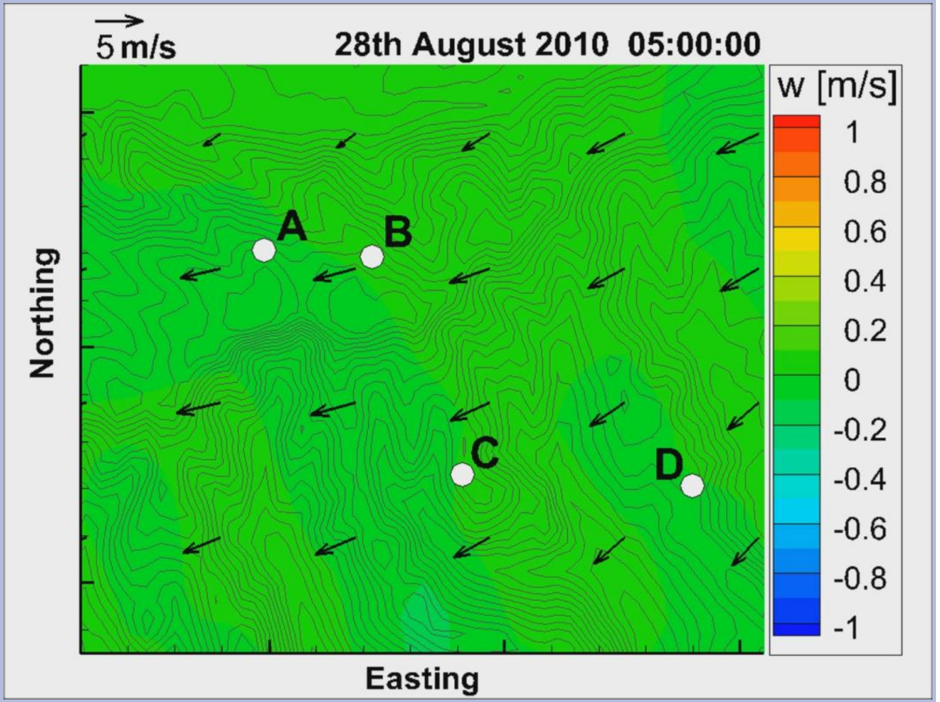


Power Ratio when T3 is between 9.5-10.5 m/s when all turbines are operational.

Coupled Mesoscale-CFD models help understand impact of stability effects.



Example Site (Ireland)



Comparison Site (Turkey)

Conclusions: So Why Does T7 Underperform?

$$\delta E = \delta P + \delta S + \delta W + \delta TI + \delta\alpha + \delta SW + \ldots$$

<u>For this particular site</u>:

- Power performance errors (δP, δTI and δα) don't appear significant.
- Speed Up error important, but probably doesn't explain everything.
- Wake model errors need further investigation.
- Possibly other sources of error not identified.
- Relatively low lower tip hub height (24m) may make this site more sensitive to model errors.

<u>Other sites with different atmospheric conditions and turbine types are likely to be different</u>! Care must be taken to how 'lessons learnt' are applied to pre-construction estimates.

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