When models needs to be twisted

By Per Nielsen

windPRO

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My issues

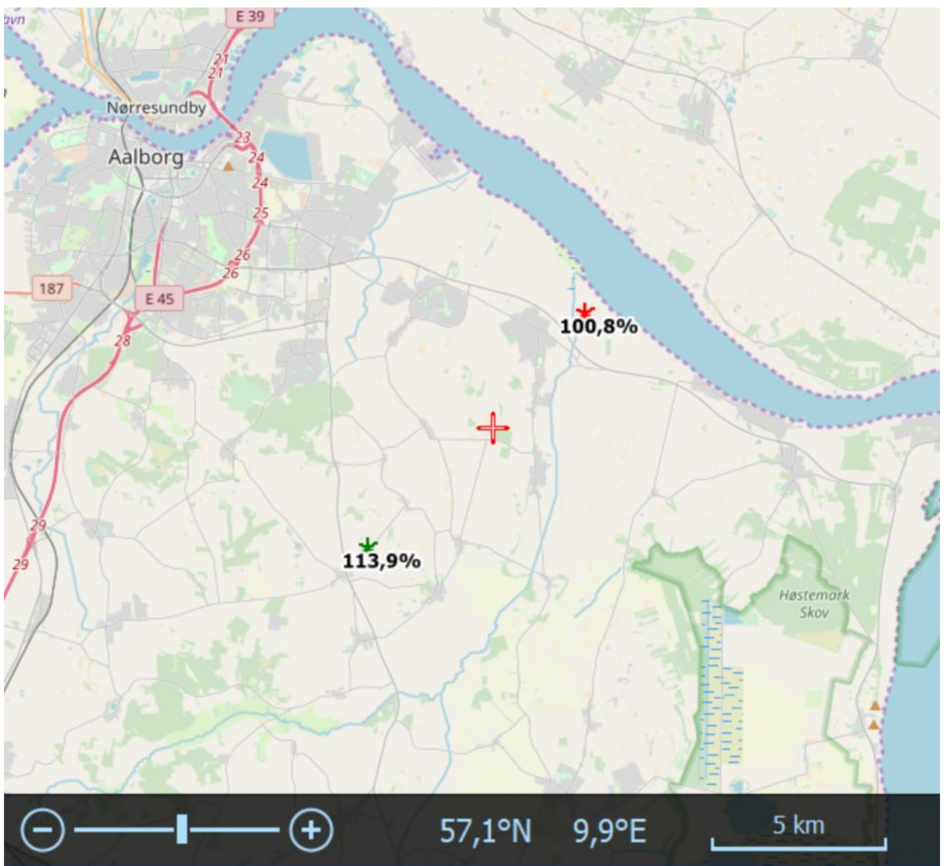
1. Old days
2. Time step calculations
3. Forest 15%
4. MESO data 15%
5. Lidar shear measurements 15%
6. Elevation 50%
7. Wake losses (featuring ”new approach” – if time allow) 5%

Focus is ”practical” AEP calculation

- How wrong can it be?

Old days

Courses in Aalborg in late 80'ties in "Wind atlas for Denmark" by DTU/Risø (1979)
150kW Bonus, 2 different sites near Aalborg performed essential different relative to calculation.



Just 10 km apart, the one performed 13% better than the other relative to calculated! At that time i believed calculation models were "near perfect", so what could be the reason ? – it had to be the turbines !

Note: *There was ONE wind statistic for all DK at that time. Calculation is reproduced by to-day "state of art" Meso data, extreme precise terrain data and the last 30y WAsP improvements, the result is the same.*
WHY ?

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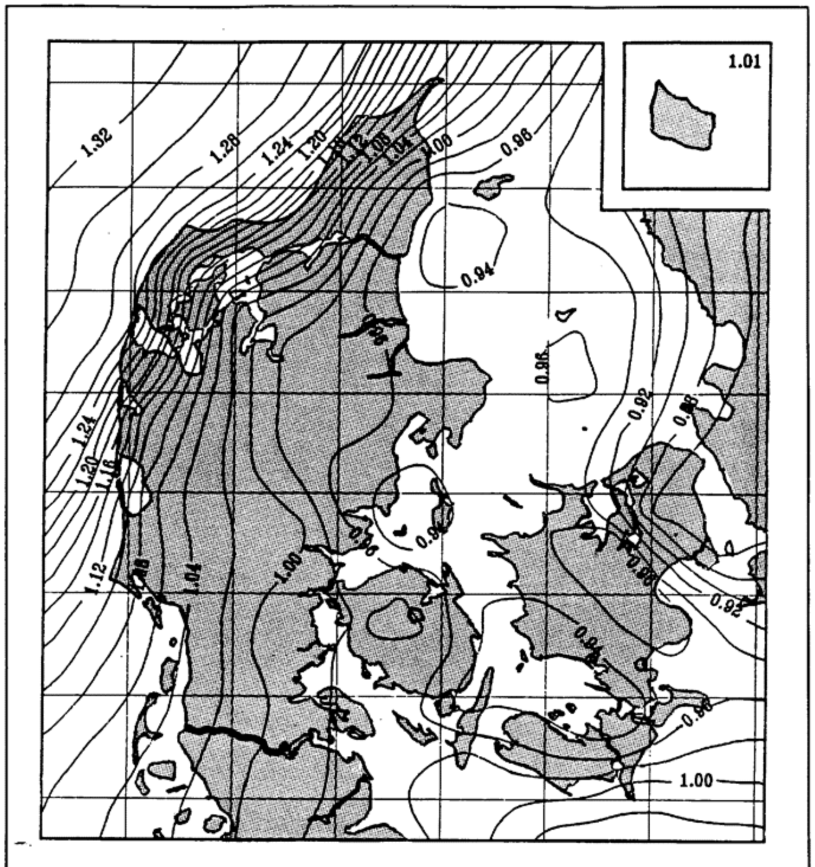
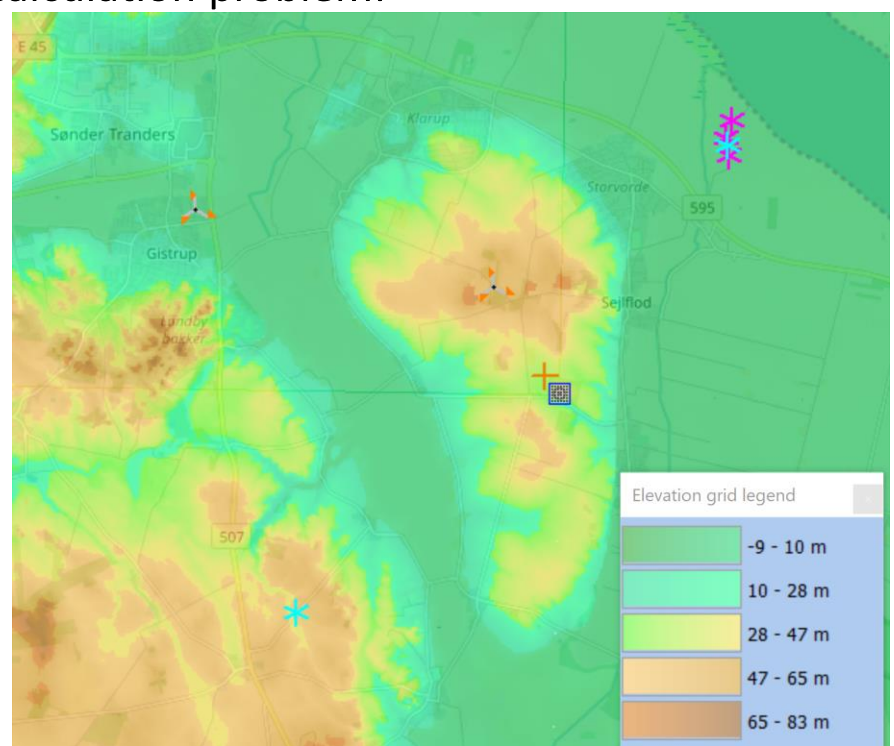
Old days

My first ”real twist”; the **regional correction curves**



- but still just **ONE wind statistic!** [1992 (*EMD/Intercon*)]. This still “holds”!

- but it did not solve previous introduced calculation problem:



50m elevation difference, ~3% calc. bias per 10m elevation difference, ”a bell is ringing” →

Time step calculation

The most important "break trough" for understanding where the calculation models or data makes mistakes. Simply because the concurrent MEASURED and CALCULATED can be compared 1:1 binned by e.g:

- Direction (Wake and terrain model)
- Wind speed (Wake and power/Ct curve)
- Season (Meso data bias)
- Day/night (Stability, TI, Shear)
- Hot/cold (WTG "performance", Air density correction)
- Turbulence (Wake model, power curve correction)

Every potential model problem can be identified and quantified – when data quality is sufficient!

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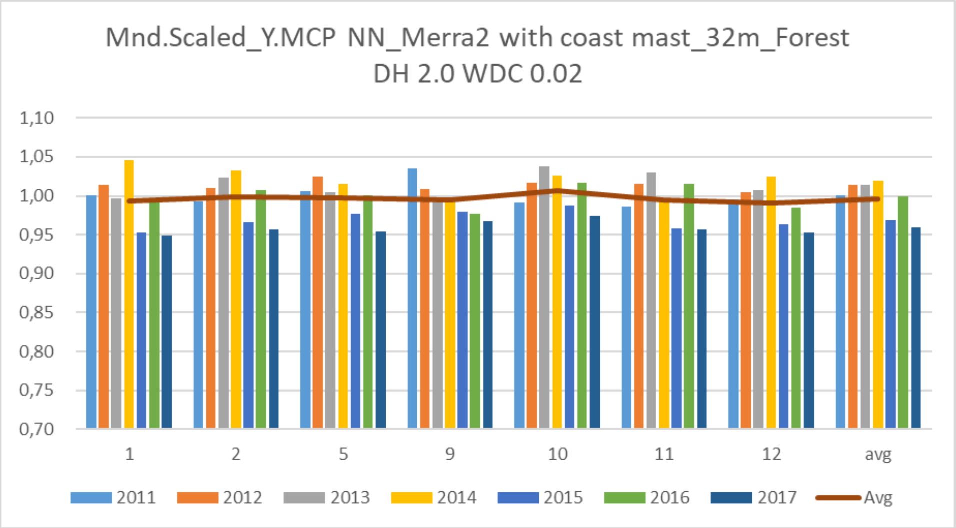
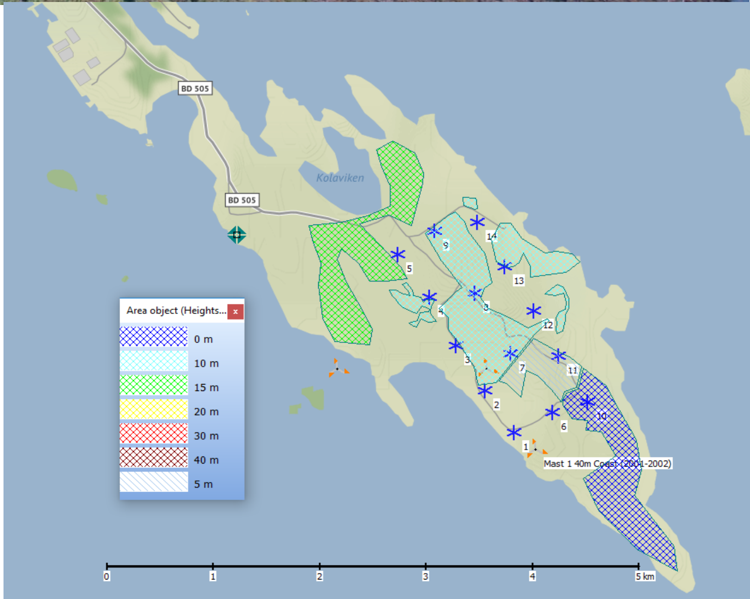
Forest

Island project with forest, finally "nailed" after 10y:

***Forest height x 2 as displacement height**, and all 14 turbines are calculated correct. The is a very high displ. height, and the deviation from "normal" is probably related to stability issues. 20% production difference within 3km in flat area, this is much. (Main wind from South)*

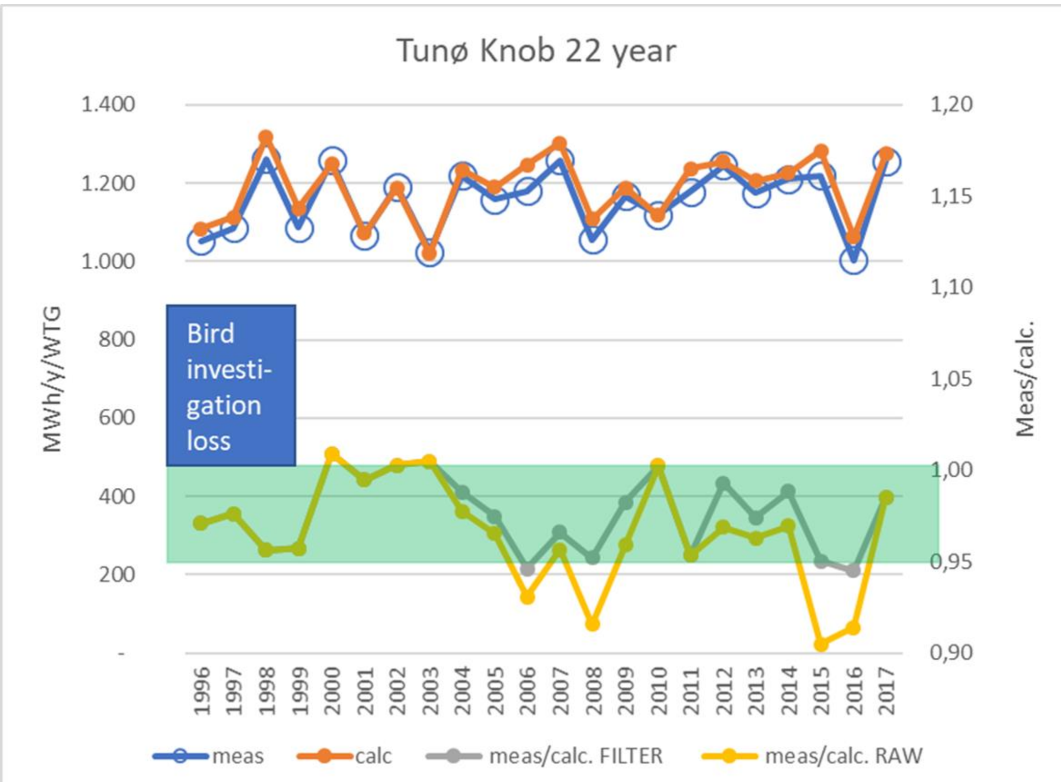
Why? Stability issues?





MESO model data

Another ”break trough” recent 5 years is the use of 3km resolution 1 hour meso wind data, a huge improvement for AEP calculations and understanding.
BUT, it can give surprises, nothing is perfect.



When filtering outliers (poor availability) on monthly basis, this project is calculated within +0 /–5% over 22 years ☺

No signs of different trend in measured vs calculated

The bias by some years probably availability caused.

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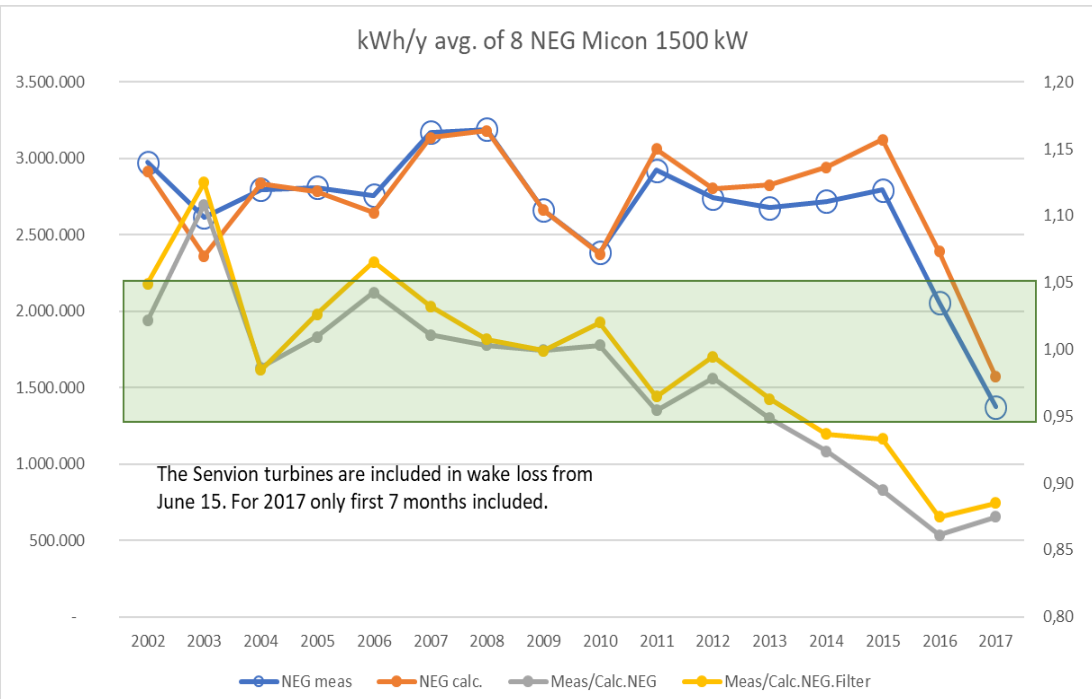
MESO model data

An example, where I do NOT trust the MESO data do it OK (not long term consistent):



A constant Meas/Calc. (Goodness) drop;

20% over 10 years, 2% per year. Is this performance degradation – or MESO data “drift” ?

Talking to turbine operators, there are no sign of degradations – and 2% p.a. over 10 y would be unusual high – unrealistic.

So what can the ”twist” be? Many many investigations to support a some ”spectacular” conclusion:

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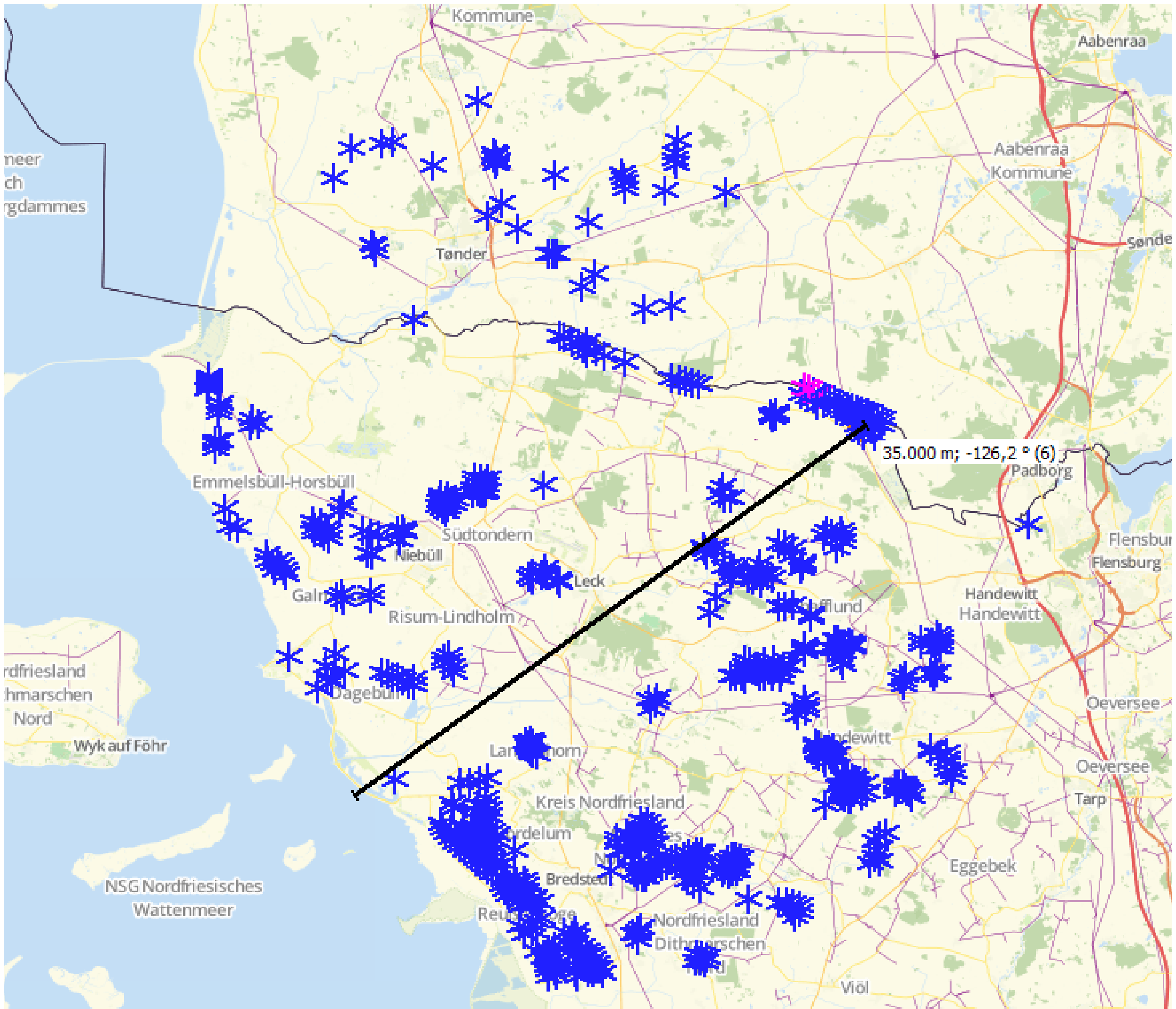
Potential MESO bias problem



The heavy expansion with turbines in main wind direction is not "known" by the MESO model data !

There might in addition be tree growing and other roughness increase features.

WTGs closer to west coast do not face problem, but other similar located do.

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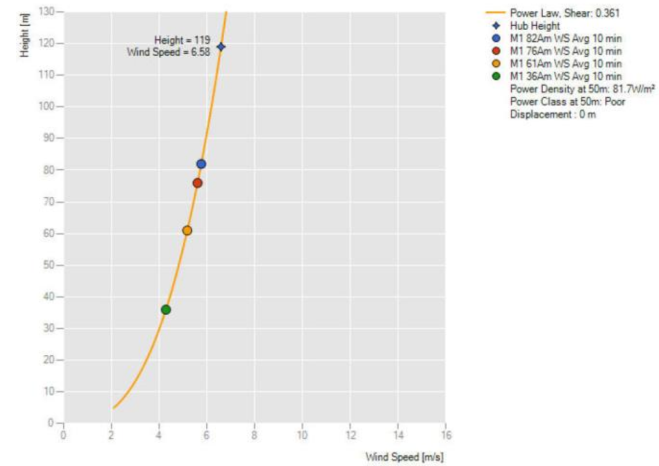
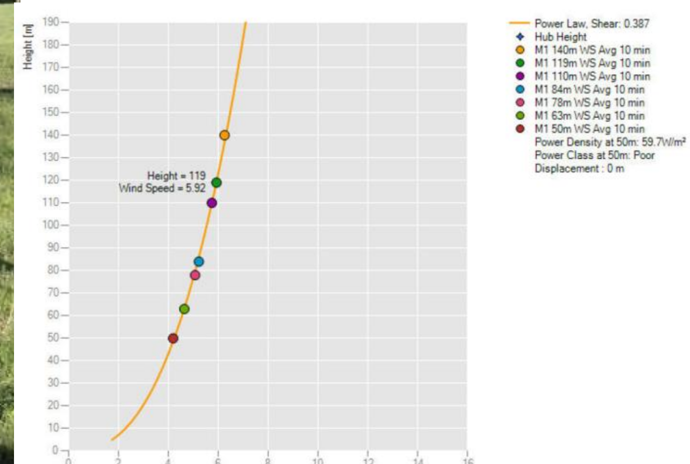
Shear by Lidar

Lidar shear: **WindCube**: 0,387, **Zephir**: 0,361 (calculated by turbine manufacturer that did the Lidar measurements – My own analyse gave exact the same.

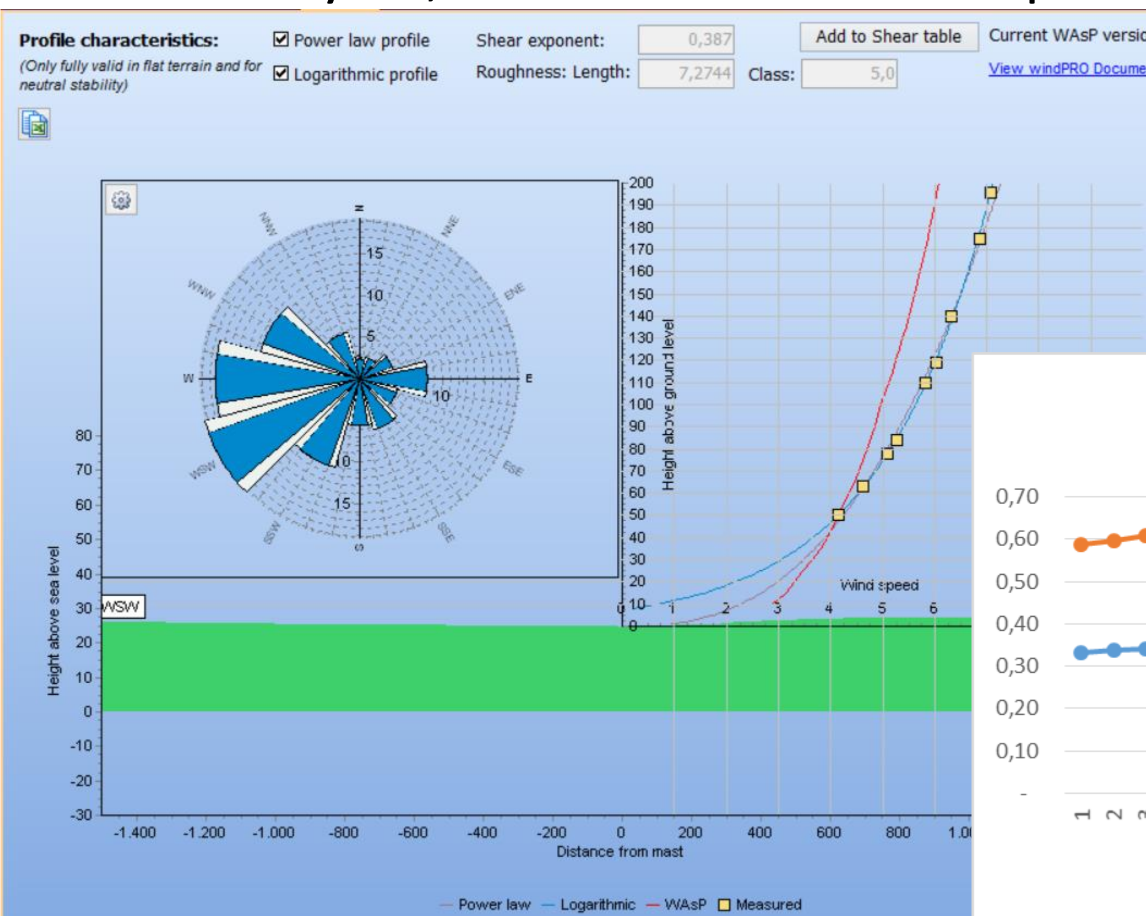


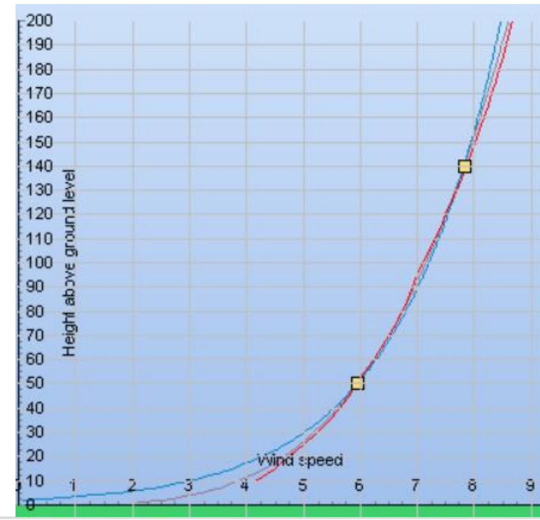


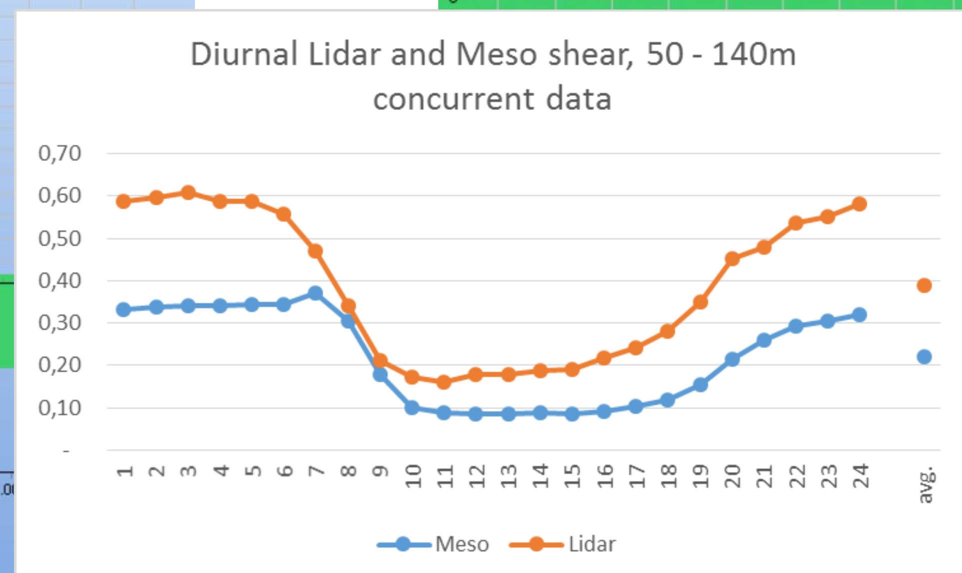
Shear by Lidar, risky!

Huge deviation to std. WAsP calc. Simple flat terrain – Meso data and WAsP agree →

0.27 all year, 0.21 in measurement period!

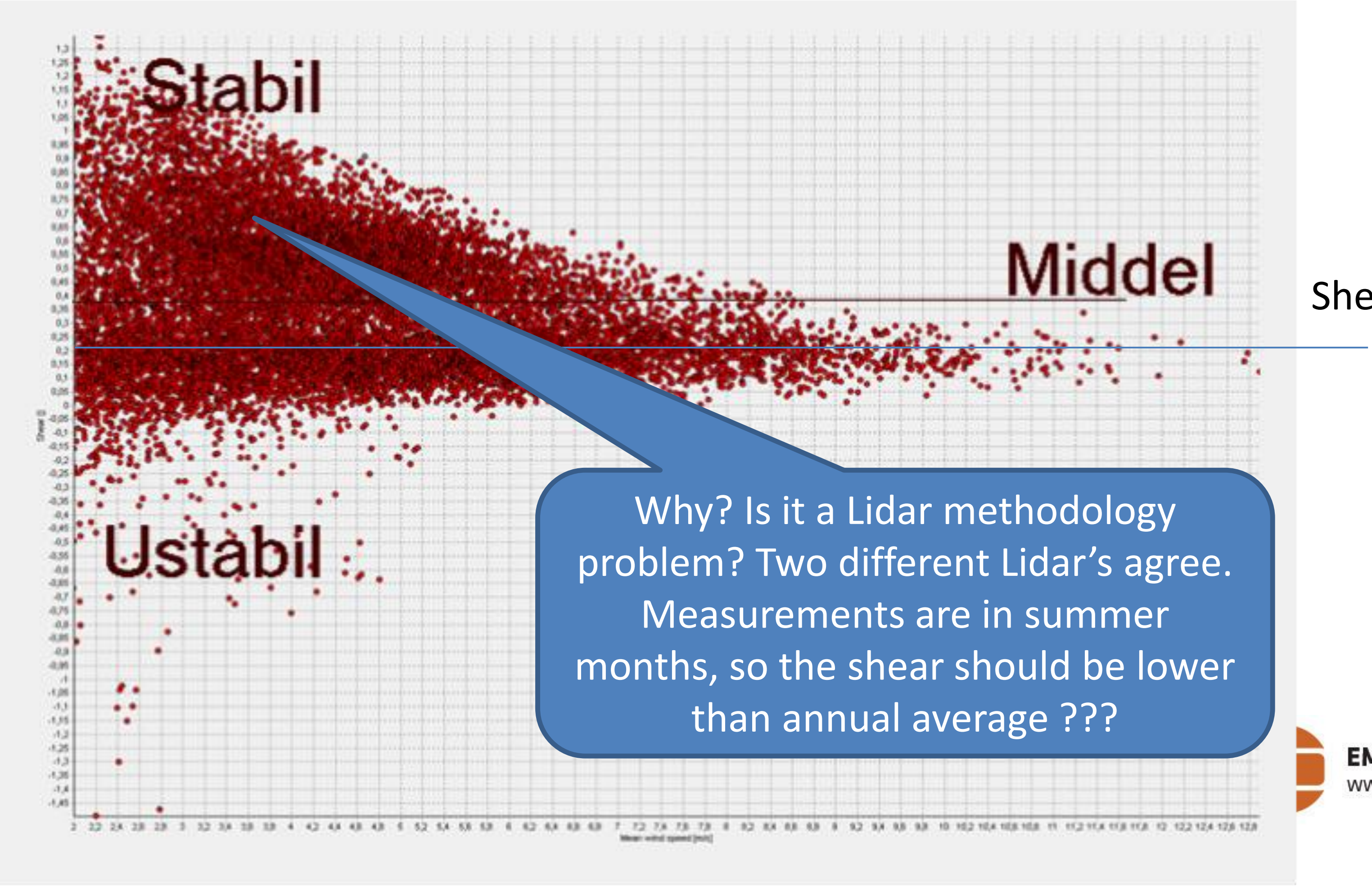






The mistake (Shear vs wind speed)

High portion of very high shear at low wind speeds ”cheats” the calculations, this did lead to at least 10% overestimation of 140m turbines ☹



Why? Is it a Lidar methodology problem? Two different Lidar’s agree. Measurements are in summer months, so the shear should be lower than annual average ???

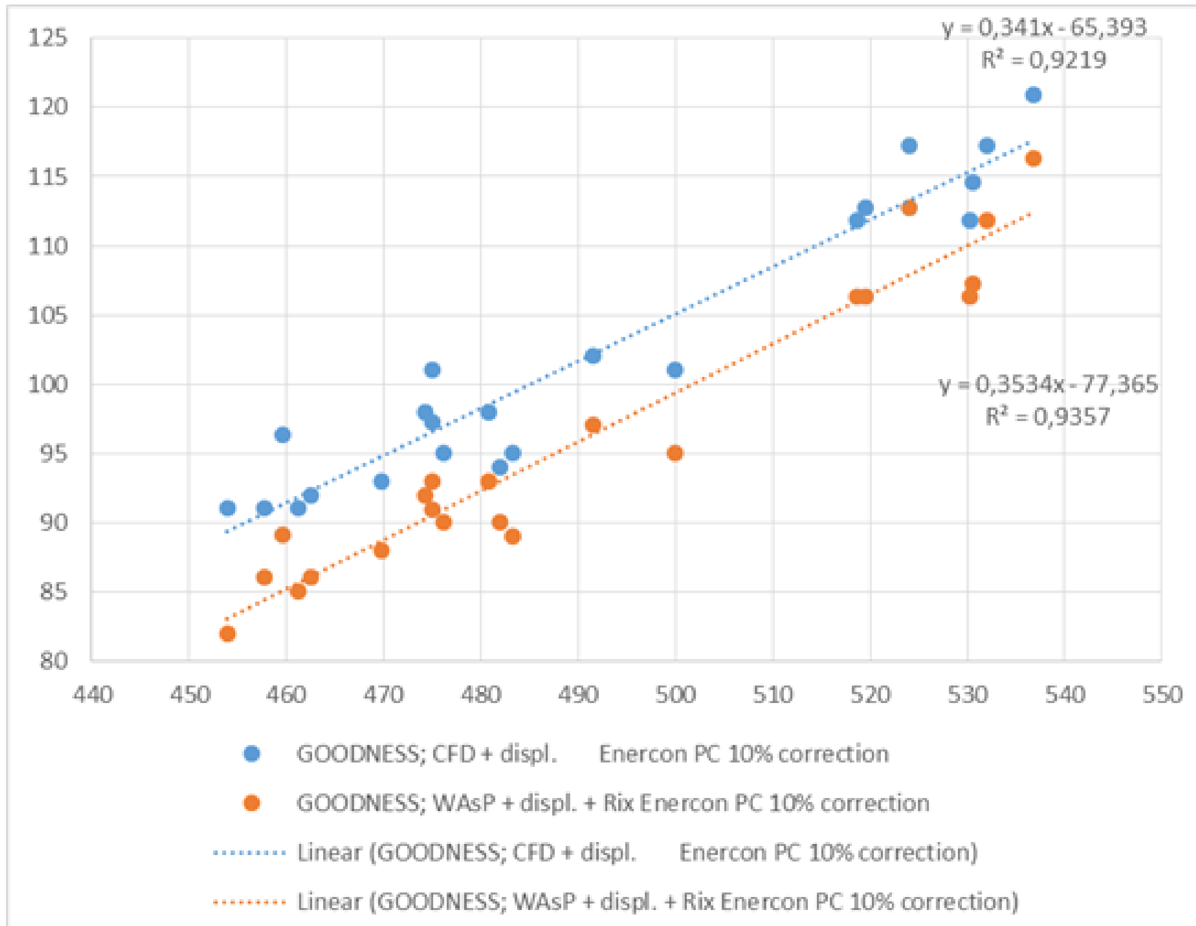
Elevation

Just ONE slide although this probably is THE MOST PROBLEMATIC MODEL ISSUE

~3% over prediction of low elevated relative to high elevated turbines per 10m elevation difference. Here with 20 km distance between high-low elevated group, but it connects with the “on site” differences!

MANY other sites with this problem seen – remember also first slide from old Aalborg site !

CFD do not solve this problem ☹
A well positioned mast at site will make average ok ☺



WAKE modeling

WDC = 0.4 x TI

TI fully coupled to z_o and height by formula:

TI = A*k/ln(h/z_o)

Where;

A = 2.5

K = 0.4

h = calculation height (z in formula ->)

z_o = roughness length

DTU research results, not used in WAsP, but it works! (but do need some twisting)

$$\mathrm{TI} \approx \left[\ln\left(\frac{z}{z_0}\right) - \psi_m(z/L)\right]^{-1}$$

$$k_w \approx 0.4\,\mathrm{TI}_h$$

http://orbit.dtu.dk/files/122284235/On_the_application_of_the_Jensen_wake_model.pdf

where z is the height above ground and TI_h the hub height TI, which can be found by evaluating equation (5) with $z = h$. These two relations are only valid for flat and homogeneous terrain and within the surface layer, thus, under stable conditions, in particular when $z/L \geq 1$, large deviations can occur when estimating wind and turbulence characteristics outside of this layer.[20] Unfortunately, it is difficult to observe, account for and estimate the BLH because of the dynamics of the atmosphere. Further, there are other phenomena, such as baroclinity, influencing the wind profile higher up.[21]

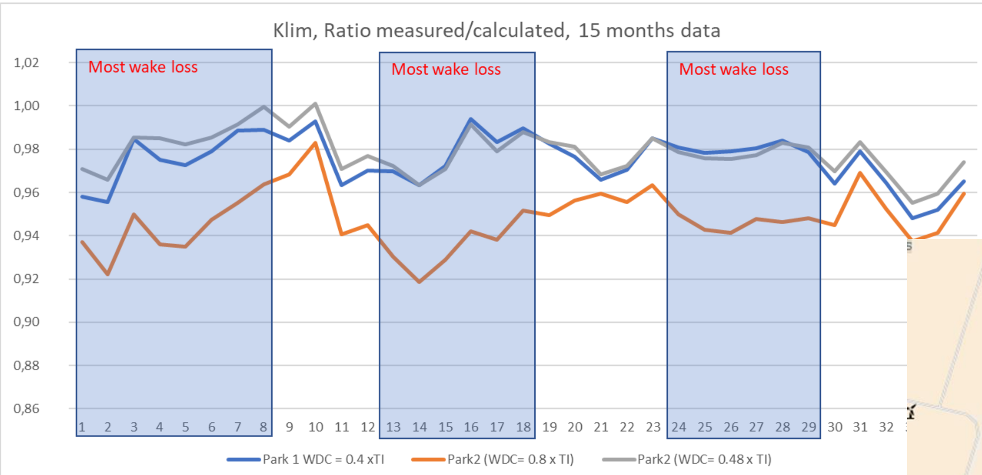
NOTE: Exceptions can occur ! Stability can “cheat”, this we will look further into!

PARK1 & 2 (N.O.Jensen)

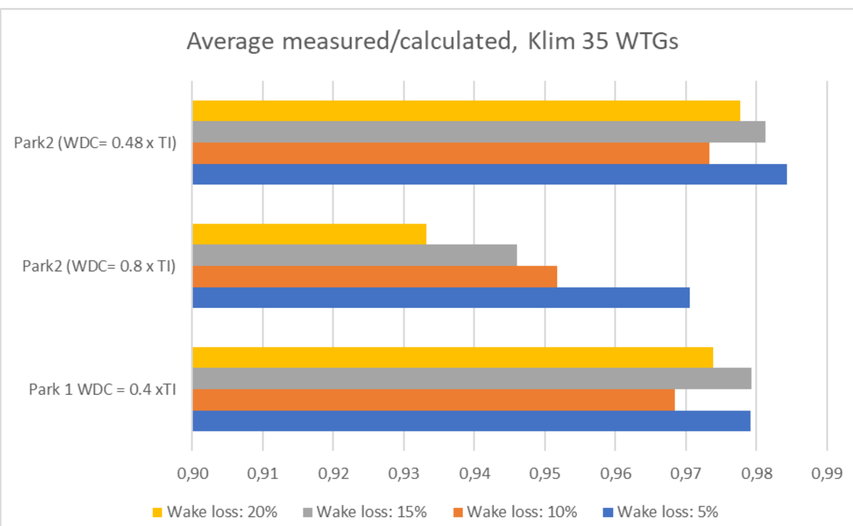
	DTU recommended fixed WDC:		EMD recommendations:	
	N.O.Jensen(PARK1)	PARK2	PARK 1	PARK 2
Offshore	0.05	0.06	WDC = TI x 0.4	WDC = TI x 0.48
Onshore	0.075	0.09		

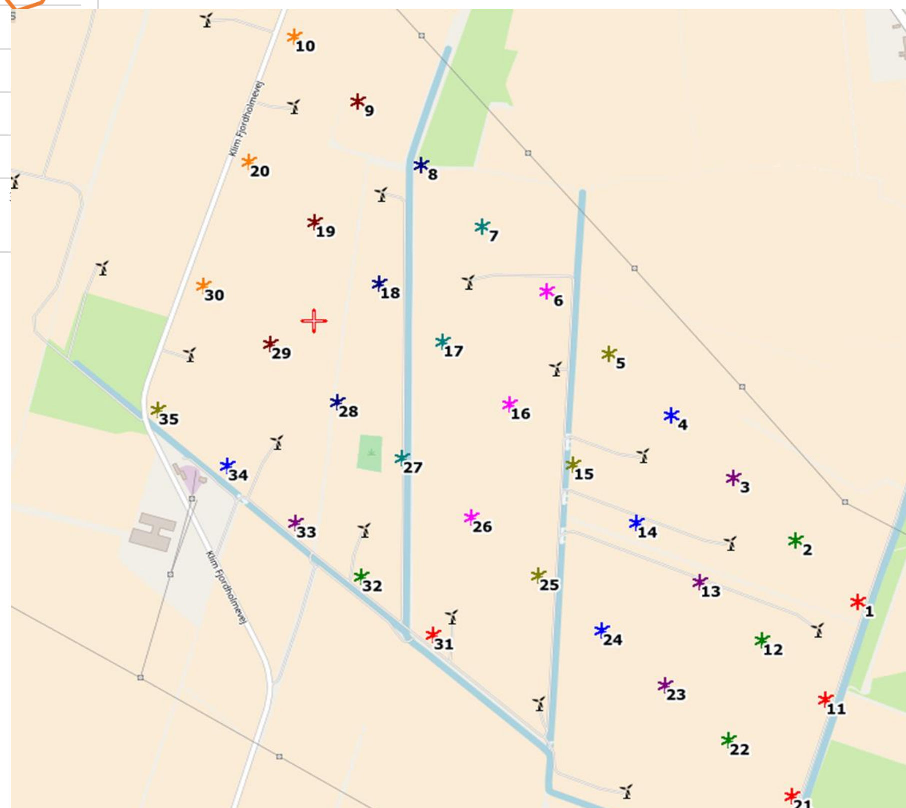
- PARK2: I was "suspicious" from start by the full linear combination model wind speed deficit weight in PARK2, but from numerous test, I must admit it is better it is VERY good! *(Think we can bury the "Deep array ghost")*
- What although NOT is "good enough" is to use a fixed WDC only dependent on onshore or offshore site, this is far to "simple" and can cost large mistakes.
- Letting the TI control the WDC makes the most, but it is not that simple as shown in above recommendations. *(low TI sites need higher factor)*
- AND it is not that simple to get access to good TI values, Meso model data seem not yet to have the required precision.
- Finally, worth to add that single row projects get too high calculated wake loss for the back WTGs due to "filling in" fresh wind from sides, not included in model.

New calibration approach
(360 degrees, 0-25 m/s)



Klim wind farm confirm **WDC = 0.48 x TI**
Also the new Klim repowered with 22 SWT 3.2 MW. TI is from Meso data.





Grouping the WTGs by wake loss gives a very clear picture if the WDC is correct calibrated (if data is good).

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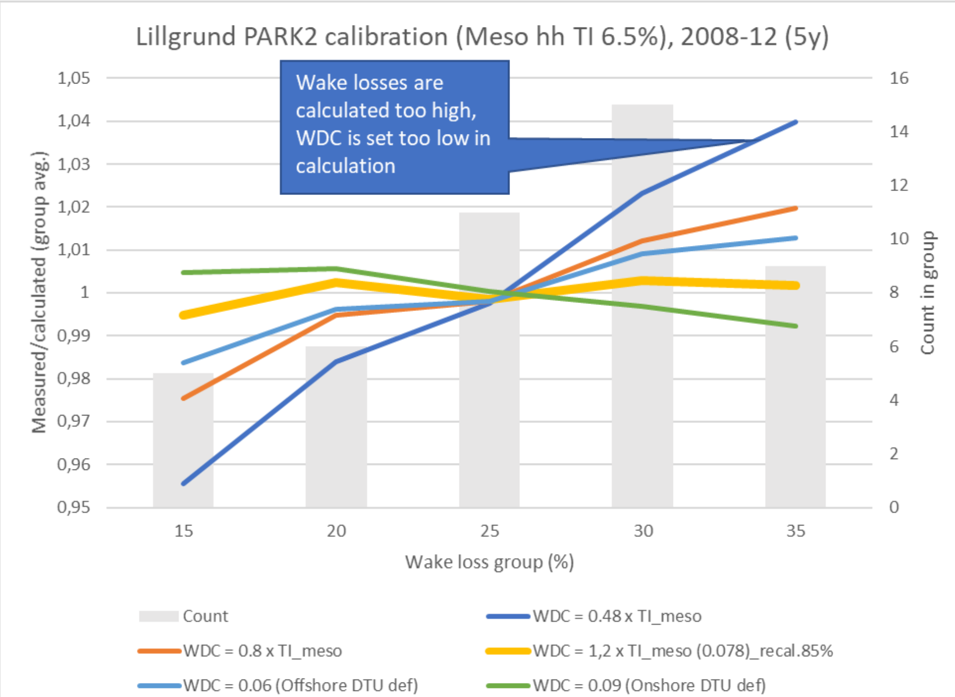
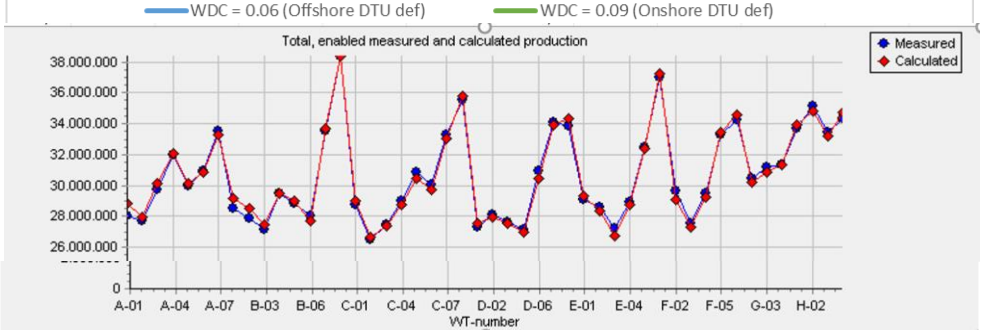
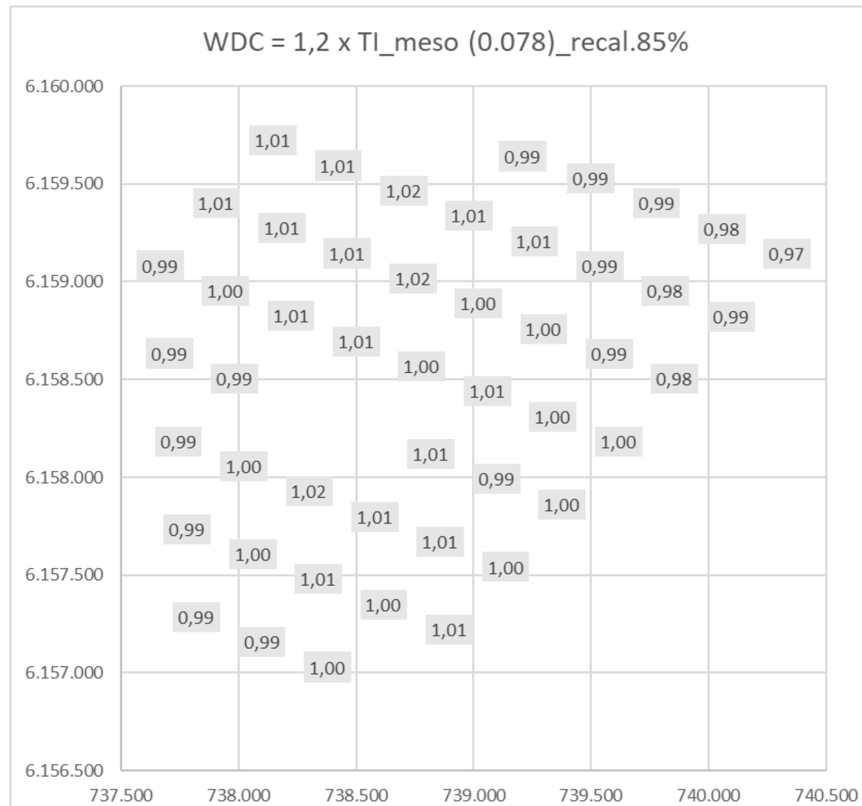
Lillgrund calibration (P2)





Calculated within +2/-3 for each WTG based on 5 year availability filtered month data. Result 26% wake loss, DTU def.: 28%.

Here the WDC = 1.2 x TI = 0.078 gives the correct wake loss calculation.
BUT TI is as low as 6.5% from Meso data, this is probably too low.
HR-1 has 7.5% TI and WDC = 0.8 x TI = 0.06 (DTU def.) works perfect here.



Collection in progress

Wake calibration collection															
														WDC= c x TI	
On/near/offshore	Windfarm	num	WTG	HH	RD	Row RD	In row RD	Data per.	Data res.	Mean ws	WDC calib	Meso hh TI	Local TI	**Factor "c"**	Calc. Wake loss
Near	Lillgrund	48	SWT 2.3MW ø93	69	92,6	4,3	3,3	5y	Month	8,0	0,078	**6,5%**		**1,2**	26,2%
On	Klim_old	35	V44 0.6MW	45	44	7,0	4,5	15m	Month	7,1	0,062	**13,0%**		**0,48**	13,4%
On	Klim_new	22	SWT 3.2MW ø113	92,5	113	5,0	2,5	3y	Month	7,7	0,057	**11,8%**		**0,48**	15,6%
Off	HR-1	80	V80 2MW	70	80	7,0	7,0	1y	10-min	9,4	0,060	**7,5%**	7,2%	**0,8**	10,4%
On (desert)	ElZayt	80	G80 2 MW	60	80	14,0	3,0	1y	10-min	10,6	0,056	14,0%	**7,0%**	**0,8**	9,1%

Next step is collection of results from numerous wind farms to get a better picture and give recommendations for new projects.
Contributions welcome !

Following is my wake “star” projects, from which a lot can be learned, but the time probably will not allow for presenting this...

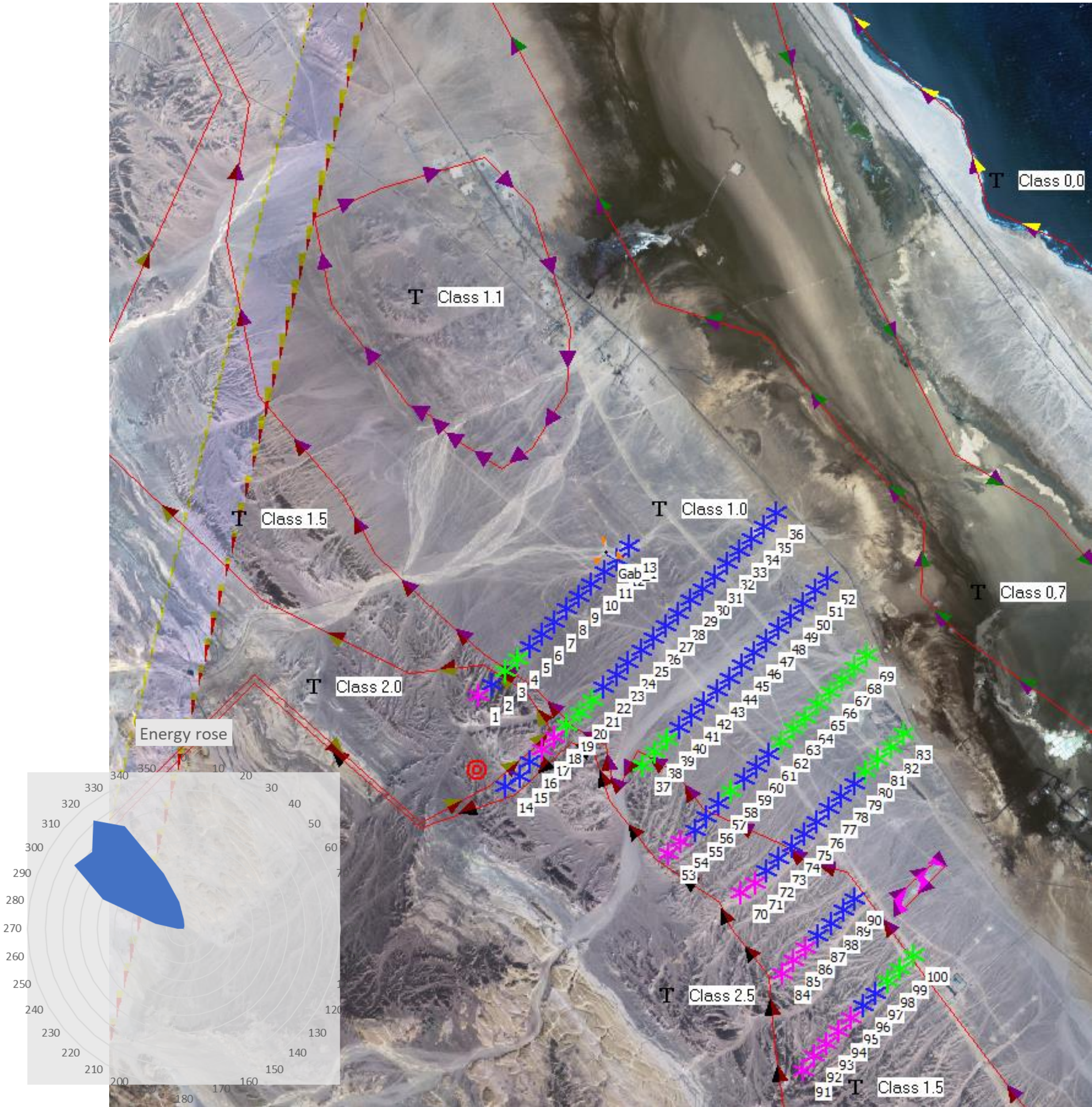
The basis

Former calibration were based on "remote mast", where the new calibration is based on site mast (Gab.1) just in front of Windfarm relative to main wind directions, 280-360 degrees.

It is surprising how important the roughness is, and therefore the wake loss calibration depend much on fine tuning the roughness classification. This is a long iterative process.

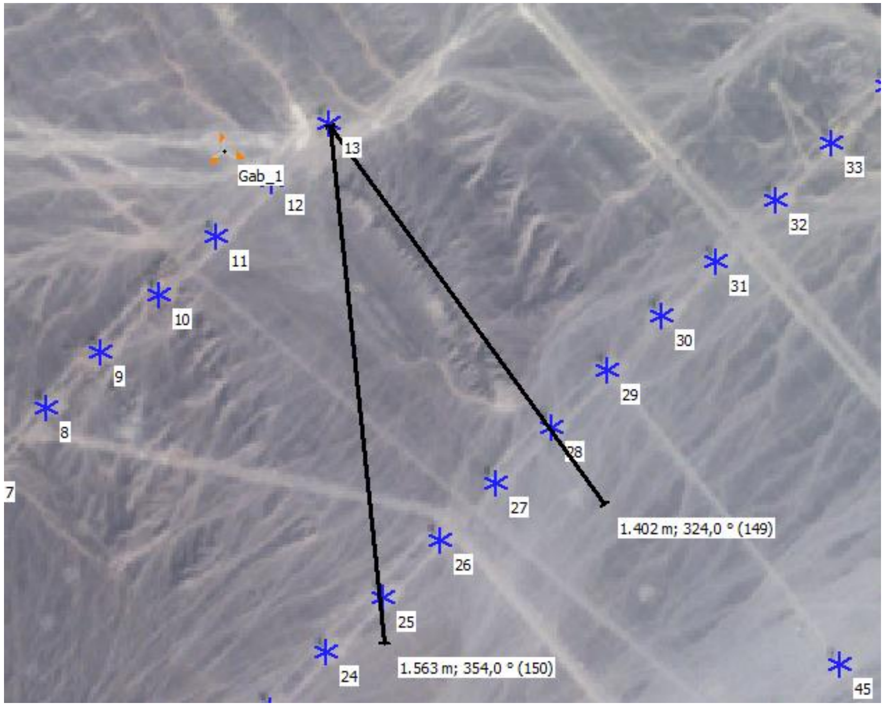
WAsP model with the new PARK2 is used via windPRO where Performance Check module do the data aggregations/analyses.

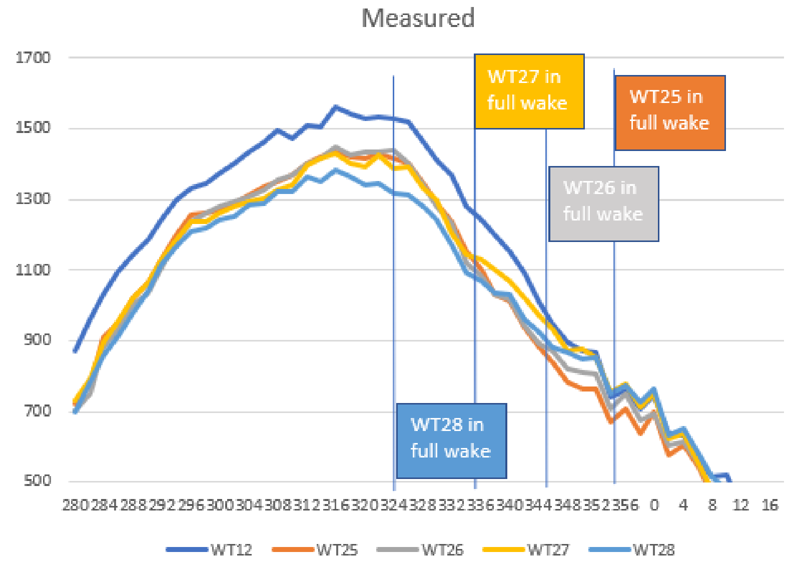
All based on 1 year 10min data for each WTG. (5.3 mio. data records!)

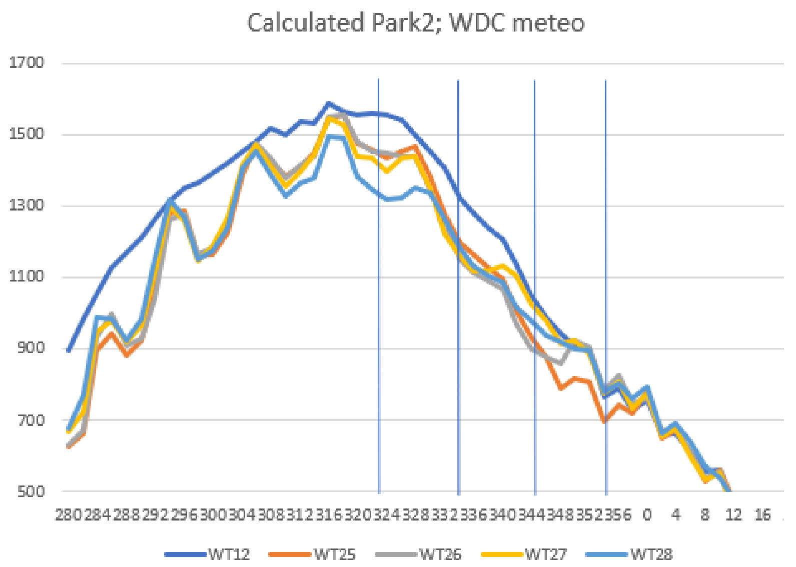


The method – step 1

Step1: Checking the direction calibration.
By comparing when the wake appear in measurements and calculations to the directions measured on map (blue lines), it can be validated that direction calibration is correct.
The measurements has more smoothened reductions by angle than calculations, but the patterns validates the direction calibration.

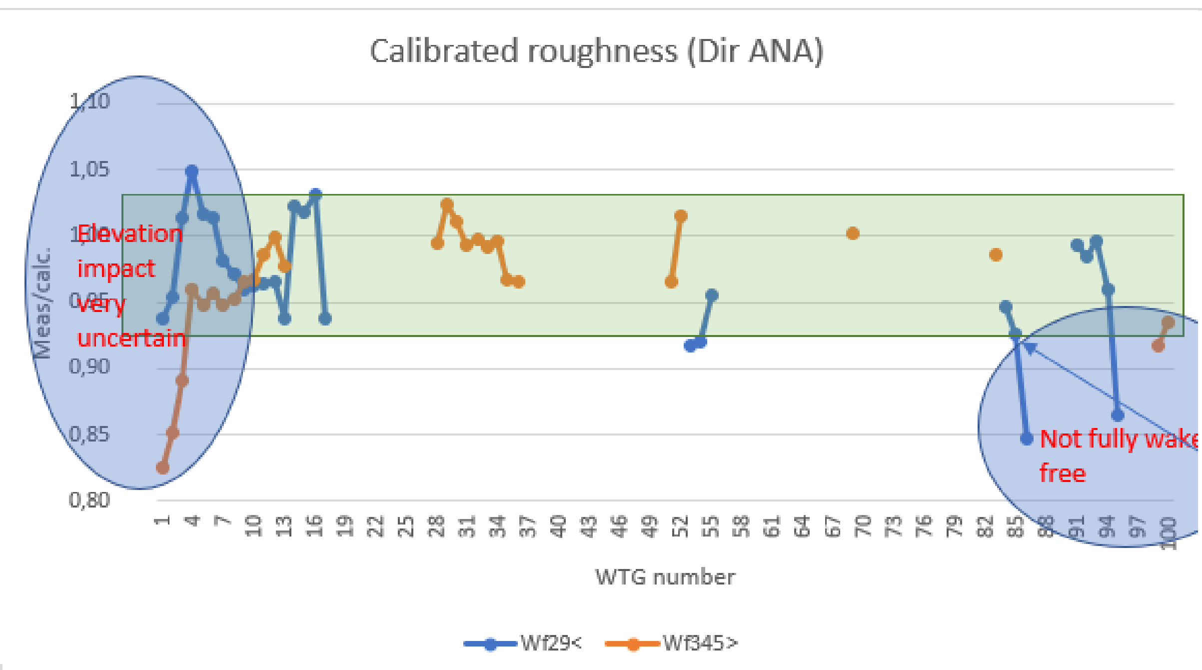


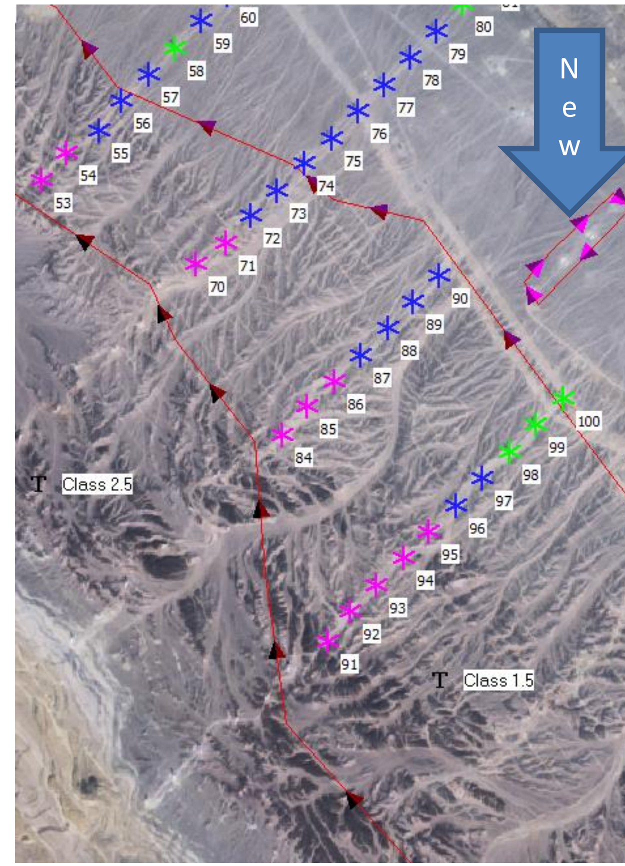




The method – step 2

Step2: Calibration of the roughness model.
This is far the most complicated – in a dessert, it could seem simple, but desserts are not just smooth sand. Due to relative few data in the wake free directions, the roughness calibration is improved later based on “pattern study” having all WTGs included.

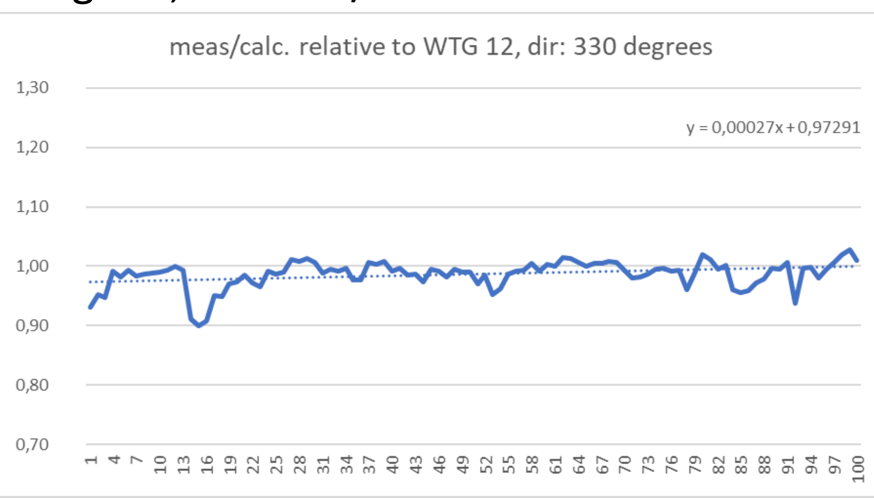


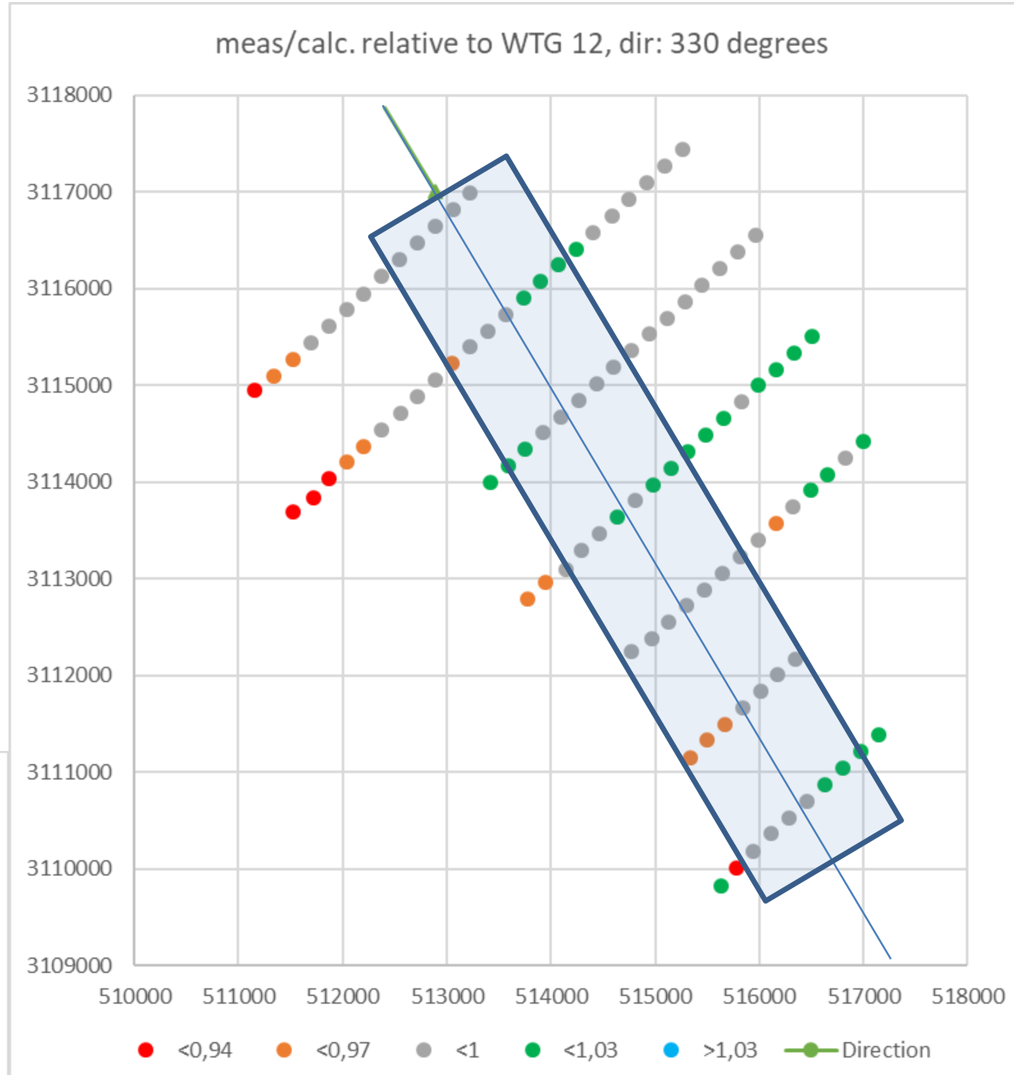


For sure the more complex surface towards west (mountains) acts as roughness increase, which could be fine tuned further, but this is extreme time consuming ⌛

The method – step 3

Step 3, the Wake model calibration
When roughness worked "satisfying", the WDC was tuned by 10 degree sectors by looking at the performance of the "most in wake" turbines, see example to the right, 330 degree +/- 5. Below ratio meas./calc. by WTG, this must be a "straight line", but important to focus most on the ones having most wake givers, less on the ones with less or no wake. Grey and Green is Very Very good, within +/-3%!





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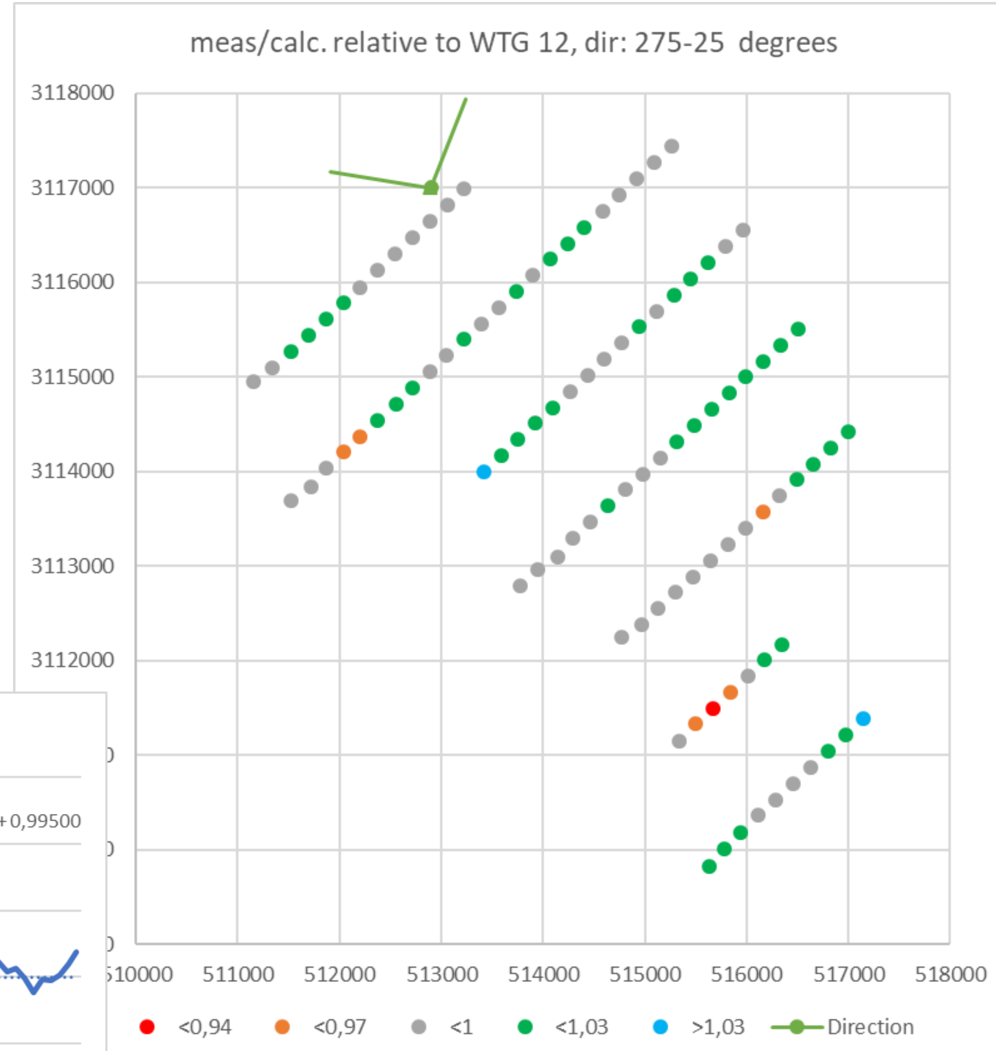
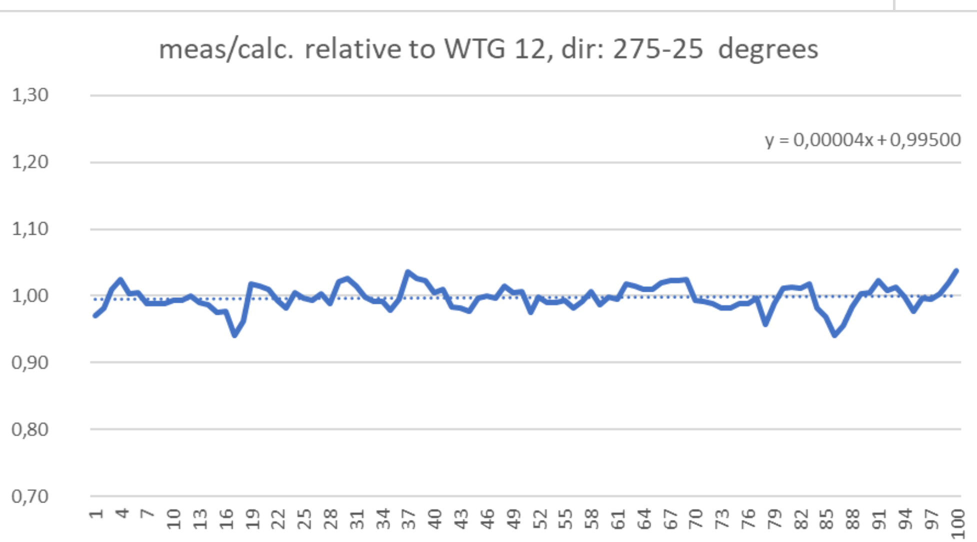
The results – 275-25 deg. 1 year

Each WTG, filtered for error codes, are calculated within +/-10% of measured relative to WTG12 at the met mast for each 10 degree wind direction sectors (where mast is wake free).

92 of 100 WTGs are within +/-3% as average. This is an extreme high accuracy, and thereby the wake loss calculation also is judged very accurate.





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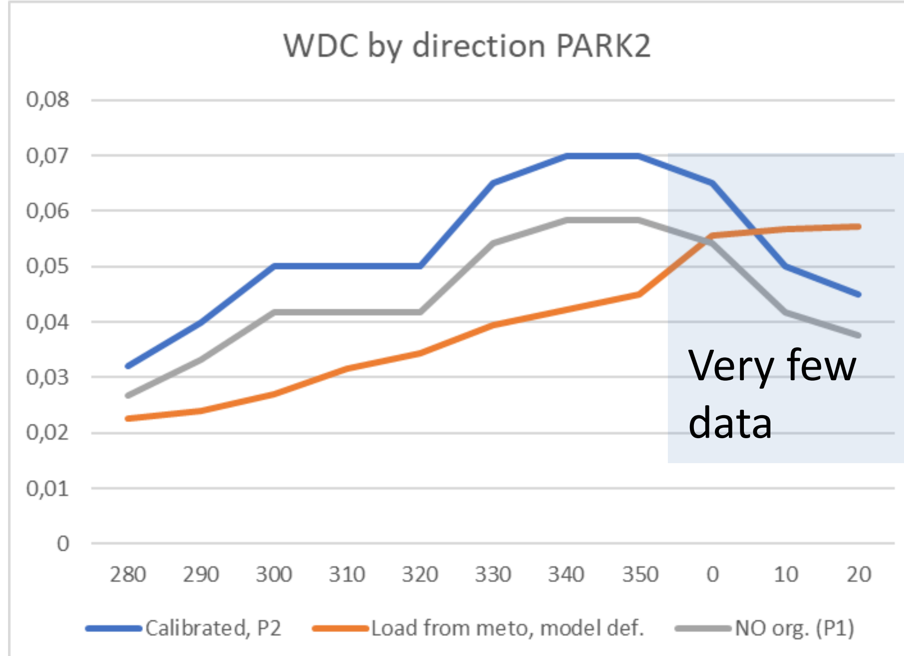
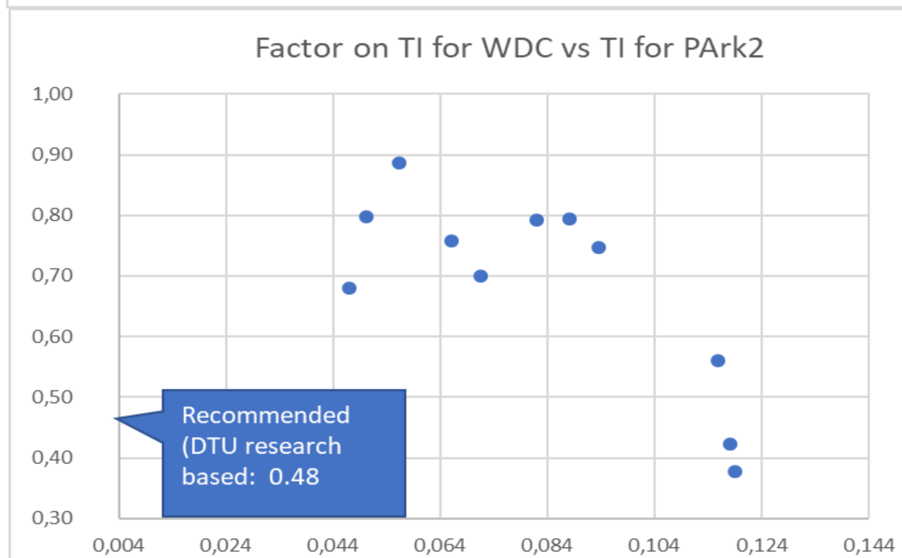
Wake loss settings

The new "concept", letting the TI(Turbulence Intensity) control the WDC by
WDC = 0.48 x TI (PARK_2) and
WDC = 0.40 x TI (PARK_1 (org. NO.Jensen), is tried out. First as fixed sector values, later by time step.

TI from measurements are loaded by 10 deg. directions within 5-15 m/s. There is seen a clear trend that the factor 0.48 is too low, like **0.8 seem to work here as average** (see later).

But no doubt that the TI is a very important "controller" of the WDC. At this site the lower TI in westerly directions (night wind from mountains) gives essentially higher wake losses.





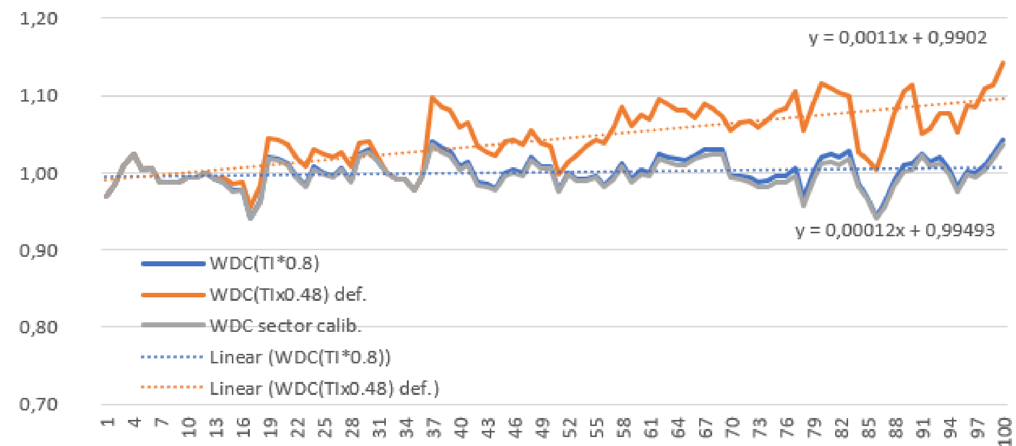
Wake loss analyses

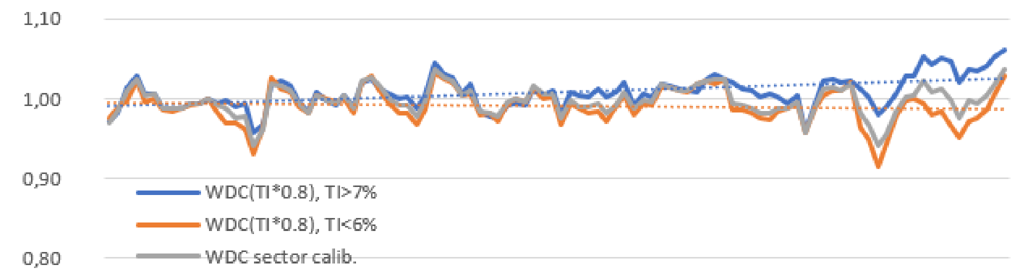
Letting the TI(Turbulence Intensity) control the WDC by TIME STEP is tried out. Here shown with:
WDC = c x TI (PARK_2) with c= 0.48 (default) and c= 0.80 (the one that works) →

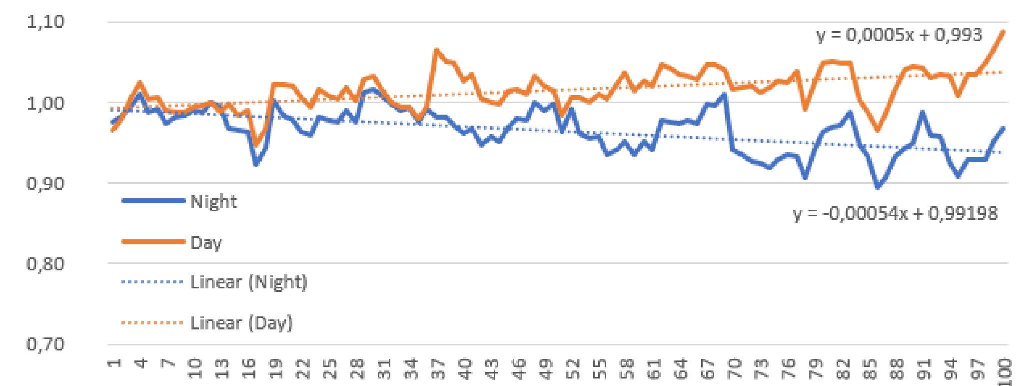
By this approach, it is possible to divide the data in low and high TI to judge how well the "simple" TI to WDC conversion works. As seen slightly too high calculated wake loss at high TI and to low at low TI (similar seen on other windfarms) →

The spread day/night in Non time step TI "calculation performance" is much higher, showing a larger potential error by "just" having a sector WDC, not by time step→

… although the "basic problem" in any of the concepts is to know how to link WDC to TI. This requires test-test-test.



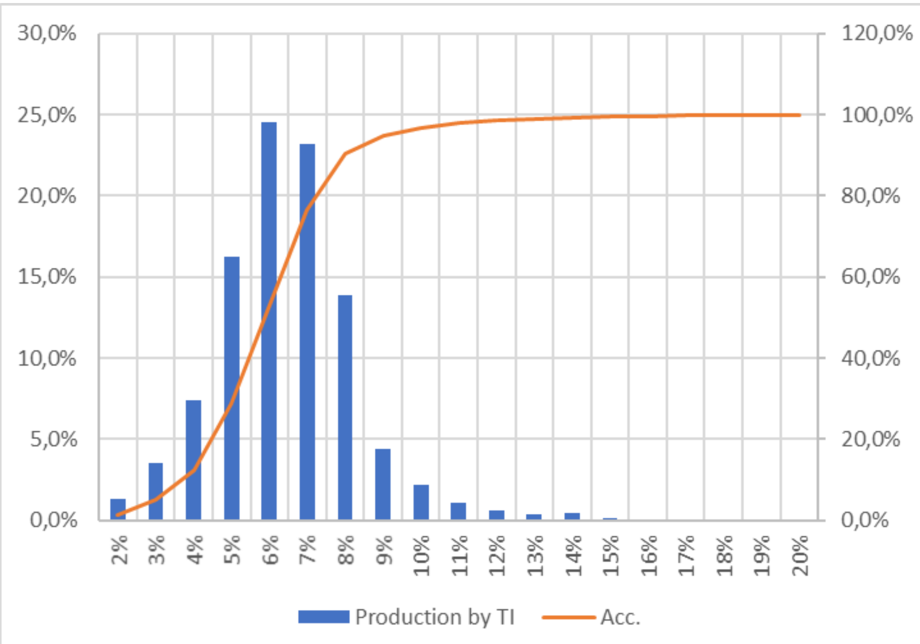


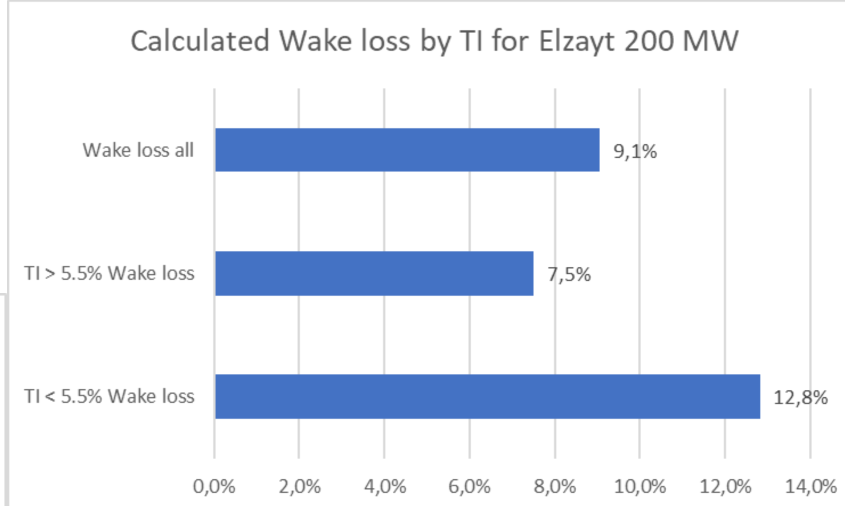


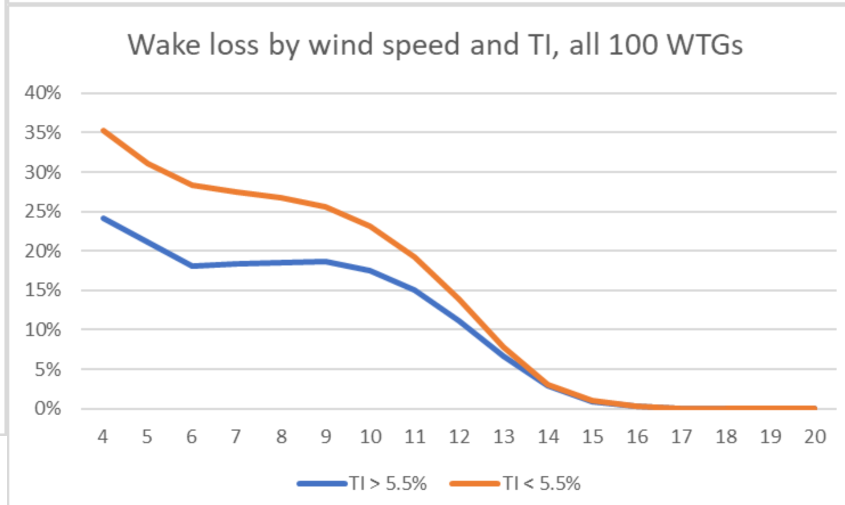
X-axis: WTG number Y-axis: meas./calc.

Usefull informations

With this very accurate calibrated wake loss calculation, many information's can be extracted from the 10 minute based calculations:





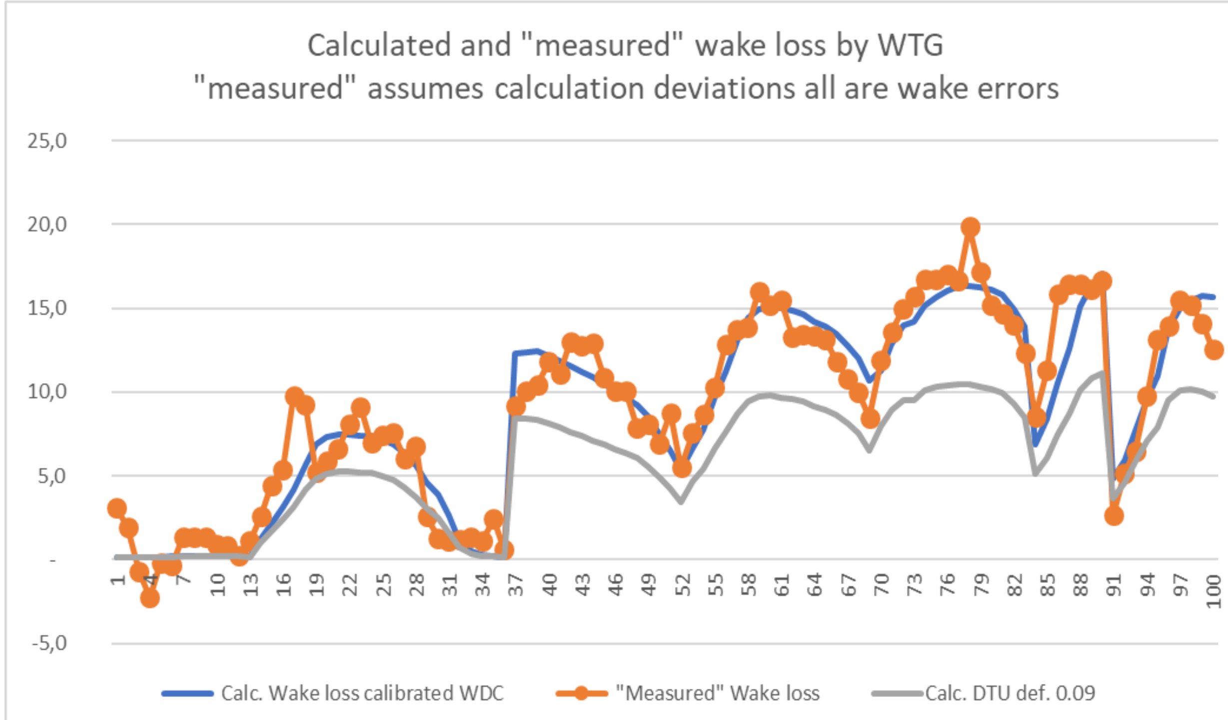


The TI really mean a lot. At this site round half the production is seen at TI < 6%, wake losses are essential higher than at other onshore sites with typical higher TI.

Conclusions

Wake loss round 9%
Up to round 18% for one WTG
No "sign" of deep array effects for this 7 row wind farm with dense spacing in row (3 RD) and row spacing of 14 RD.

Let the TI decide the WDC is the main message.
Unfortunately not as simple as WDC = TI x 0.4 as can be found pure "formula" based research:



http://orbit.dtu.dk/files/122284235/On_the_application_of_the_Jensen_wake_model.pdf

$$\mathrm{TI} \approx \left[\ln\left(\frac{z}{z_o}\right) - \psi_m(z/L)\right]^{-1}$$

$$k_w \approx 0.4\,\mathrm{TI}_h$$

	DTU recommended fixed WDC:		EMD recommendations:	
	N.O.Jensen(PARK1)	PARK2	PARK 1	PARK 2
Offshore	0.05	0.06	WDC = TI x 0.4	WDC = TI x 0.48
Onshore	0.075	0.09		

EMD recommendations will be updated when several more wind farms are tested comprehensively. But no doubt from tests so far that the factors will be increased. **In this case, using DTU def. 0.09; calculated wake loss is 6%, EMD def. 12%, the real answer is 9% !**

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