Wind Denmark October 21

Verification and validation of wake models – how far are we within accurate wake modelling?

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windPRO

A little history

I made the first course in wake model calculation I 1988 in Ebeltoft (33 years ago)

- Before the PC (and far before the internet / mobile phone) ->
- The first Wind Farms were there; Ebeltoft 1985, replaced 2002:

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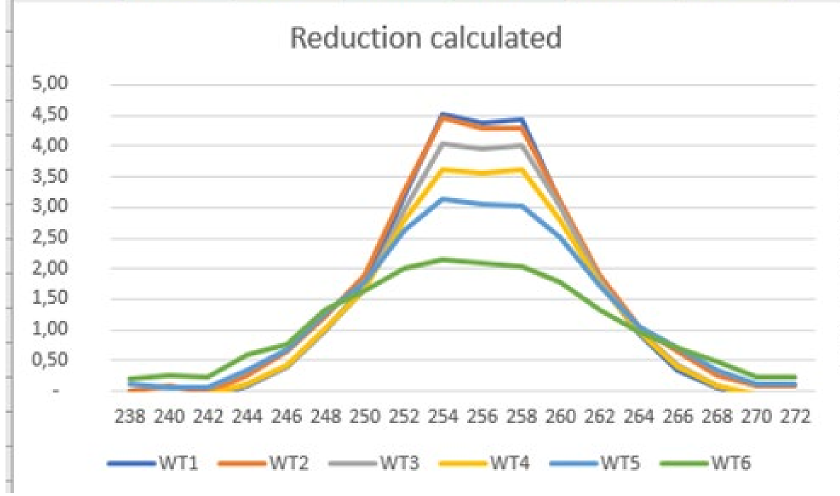
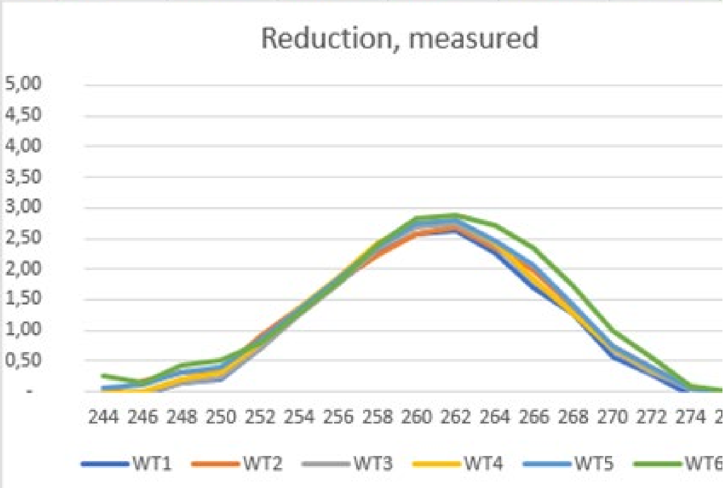
Single row wind farms

PARK1_WDC 0.04 wind speed_2015

													use scalin
Reduction calculated							Reduction, measured						offset
	WT1	WT2	WT3	WT4	WT5	WT6		WT1	WT2	WT3	WT4	WT5	WT6
238	- 0,08	- 0,00	- 0,06	- 0,04	0,11	0,19	244	- 0,12	- 0,02	- 0,07	- 0,03	0,06	0,25
240	- 0,09	0,08	- 0,07	- 0,05	0,04	0,24	246	- 0,04	0,16	- 0,03	- 0,01	0,10	0,15
242	- 0,11	- 0,01	- 0,10	- 0,06	0,05	0,21	248	0,13	0,32	0,14	0,20	0,31	0,43
244	0,08	0,26	0,10	0,12	0,35	0,59	250	0,21	0,35	0,24	0,31	0,39	0,51
246	0,40	0,65	0,39	0,44	0,67	0,76	252	0,71	0,89	0,70	0,79	0,85	0,80
248	1,00	1,23	0,98	1,02	1,28	1,32	254	1,28	1,36	1,26	1,37	1,33	1,26
250	1,72	1,90	1,67	1,66	1,79	1,64	256	1,78	1,80	1,76	1,87	1,85	1,78
252	3,18	3,27	2,96	2,81	2,64	2,00	258	2,26	2,24	2,34	2,43	2,38	2,39
254	4,51	4,46	4,05	3,63	3,12	2,14	260	2,58	2,58	2,69	2,75	2,74	2,82
256	4,38	4,29	3,96	3,57	3,06	2,08	262	2,63	2,68	2,73	2,80	2,81	2,88
258	4,44	4,28	4,02	3,61	3,02	2,05	264	2,27	2,35	2,40	2,43	2,46	2,70
260	3,09	3,11	3,01	2,79	2,50	1,78	266	1,69	1,97	1,81	1,85	2,08	2,34
262	1,77	1,89	1,80	1,75	1,74	1,33	268	1,27	1,39	1,31	1,27	1,41	1,72
264	0,93	1,05	0,99	0,97	1,04	0,97	270	0,57	0,74	0,67	0,70	0,74	0,98
266	0,34	0,64	0,42	0,41	0,70	0,71	272	0,29	0,40	0,32	0,36	0,39	0,56
268	0,07	0,24	0,08	0,08	0,35	0,48	274	- 0,05	0,07	0,06	0,10	0,05	0,08
270	- 0,13	0,07	- 0,10	- 0,07	0,13	0,24	276	- 0,20	- 0,14	- 0,12	- 0,05	- 0,05	- 0,00
272	- 0,08	0,08	- 0,11	- 0,06	0,13	0,24	278	- 0,22	- 0,16	- 0,16	- 0,13	- 0,09	- 0,06





Wind direction

Single row projects and partly 2-3 row projects has a special problem by wake modeling:

Fresh wind is added along the sides, this is NOT captured by the wake models. This can be handled (in windPRO) by increasing the Wake Decay Constant by number of upwind turbines.

But this is not the focus in this presentation, looking at larger wind farms.

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Wake models in windPRO 3.5

Wake model overview	Statistical	Time step	Blockage	Note
Original N.O. Jensen (PARK1)	x	x	x	Long time usage
Improved N.O. Jensen (PARK2)	x	x	x	Recommended
EMD variant: NO2005	x	x	x	With special tuning for e.g., single row wind farms
Ainsley 88 with DAC (Eddy Viscosity)	x	x	x	New in windPRO 3.5
WakeBlaster (external model)		x		Advanced flow modelling
Outdated: (to be removed)				
EWTS II (Larsen) 1999	x			No good for large wind farms
EWTS II (Larsen) 2008	x			No good for large wind farms
Ainsley 86	x			Outdated implementation

windPRO 3.5 cover the 3 most common/best validated wake models. Old "experimental" models to be out phased.

Blockage is included based on state of art scientific papers but have room for improvements mainly due to the lack of interaction between wind farm and atmospheric boundary layer, which could be handled by TI influence in the calculation models. (For time step calculations).

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Notes on what this presentation is about

Verification: Do the different models behave as expected (differences)

Validation: Do the models calculate as measured (needed tunings)

360 degrees, all wind speeds

Most wake model validations is about a narrow interval regarding directions and wind speeds. This is of cause important, but what is most important is how well the TOTAL wake loss is calculated, this is what matters for the investor.

Use of Meso scale wind data

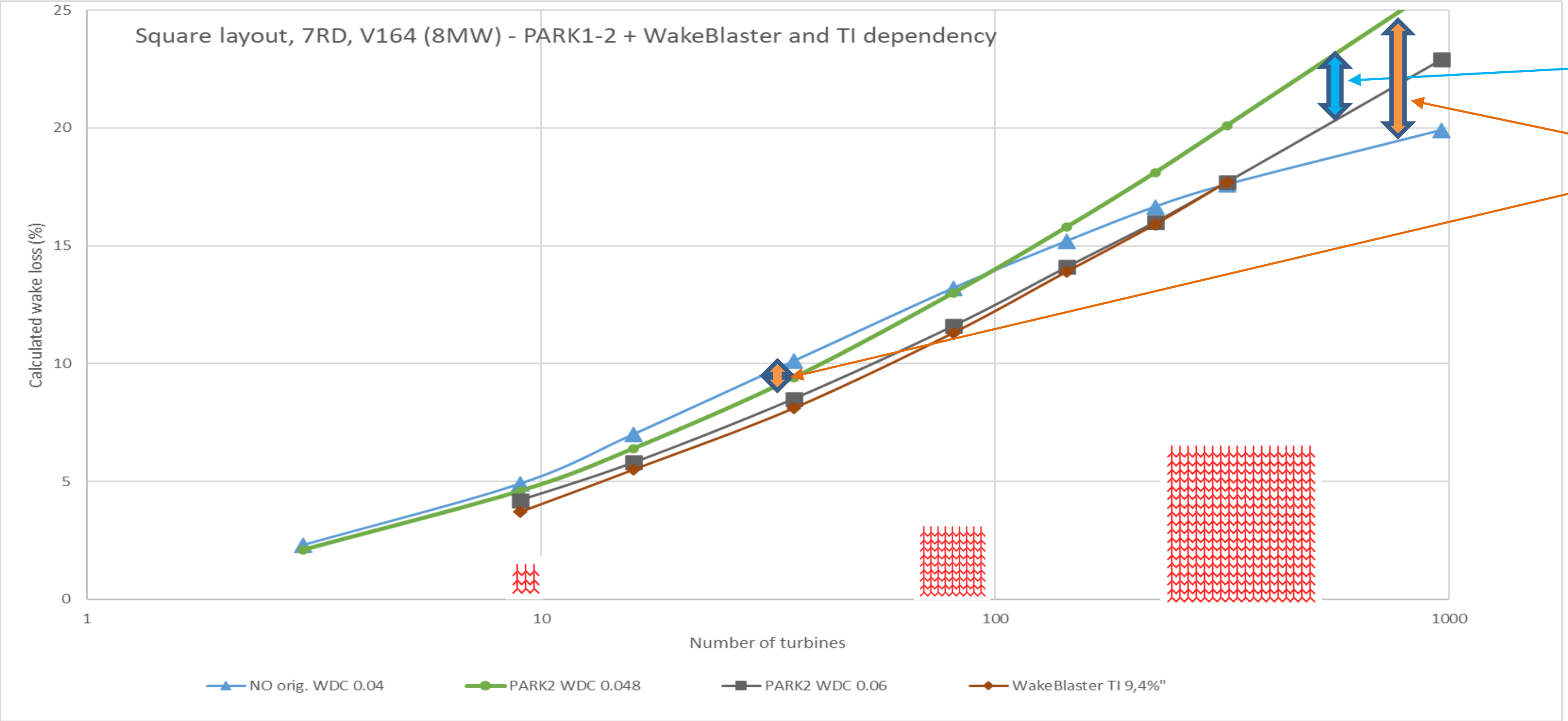
Because they has become very accurate recent years. No problems with wind measurement – which always has problems.

Calculations by time step compared to time step measurements

This gives a huge added value in validations. Having only monthly production data there will be 120 data points to use in validation with 10 years operation data. These data are available for almost all wind farms. Having 10-min. data there will be ~50.000 data points with just one year of data. Aggregations on more parameters is possible to pinpoint discrepancies.

Wake losses cannot directly be measured but having 10-min. data for each WTG in a WindFarm, it can almost.

Verification by comparing different models by Wf size



WDC choice impact

Model choice impact (PARK 1-2, low WDC)

- PARK1 (org. N.O.Jensen)
- PARK2
- WakeBlaster

The impact of the WDC choice is seen for PARK2, where the WDC 0.06 (DTU recommendation for offshore) is compared to the lower 0.048 (low TI site). The low TI site show round 1 percent point higher calculated wake loss for medium size and 2-3 percent point higher wake loss for large wind farm size. The original N.O.Jensen (PARK1) do have a slight “saturation” with very large wind farm size. This has been seen as a problem, which did require some Deep array correction for very large wind farms, e.g. the Zafarana wind park in Egypt with 700 WTGs, but is also seen at e.g. Horns Rev area, where PARK 2 handles the wake loss calculation better than Park1. PARK2 and WakeBlaster almost fully agree. Here WakeBlaster is calculated with slightly higher TI which explain it calculates slightly lower wake loss than PARK2.

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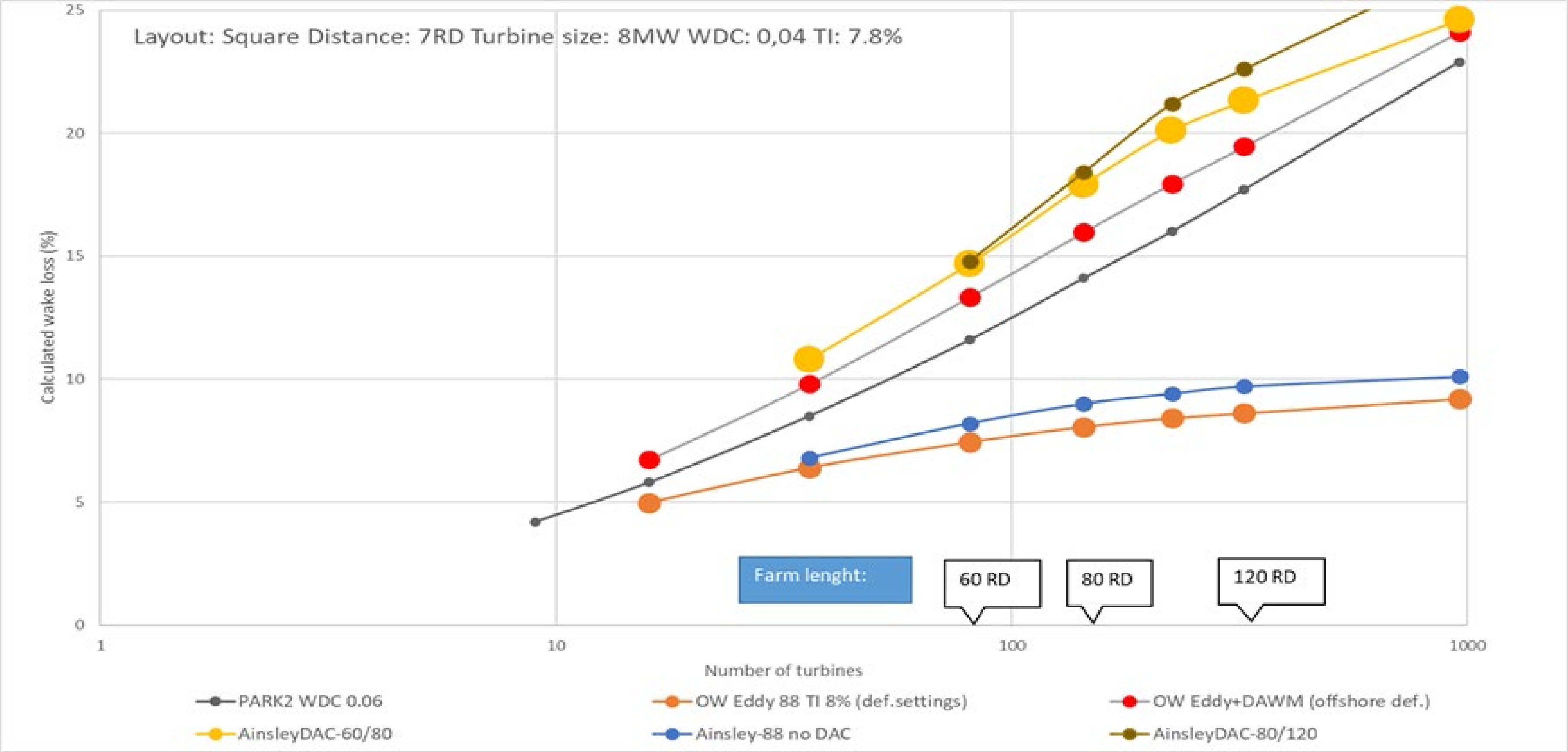
Verification by comparing different models and tools



<u>windPRO edition of:</u>

- PARK2
- Ainsley (Eddy)
- Ainsley/DAC

<u>OpenWind edition of:</u>

- Ainsley and
- Ainsley/DAWM

Above the new windPRO Ainsley 88 with DAC implementation compared to Open Wind from UL similar models.
This leaves no doubt that the Ainsley “stand alone” won’t work, even just for 6 x 6 row wind farm, it needs a deep array correction model. (DAC in windPRO, DAWM in Open Wind)
Open Wind and windPRO implementation although agree well, a little higher wake loss calculated by windPRO implementation. But there are many parameter options both in windPRO and in Open Wind, so the differences are just a question of default choices.
Following examples for Horns Rev wind farms and other shows that the higher calculated wake loss by Ainsley compared to PARK2 is related to the large WTG size (8MW) used in this example. For smaller turbines 2-3 MW, there are almost full agreement.

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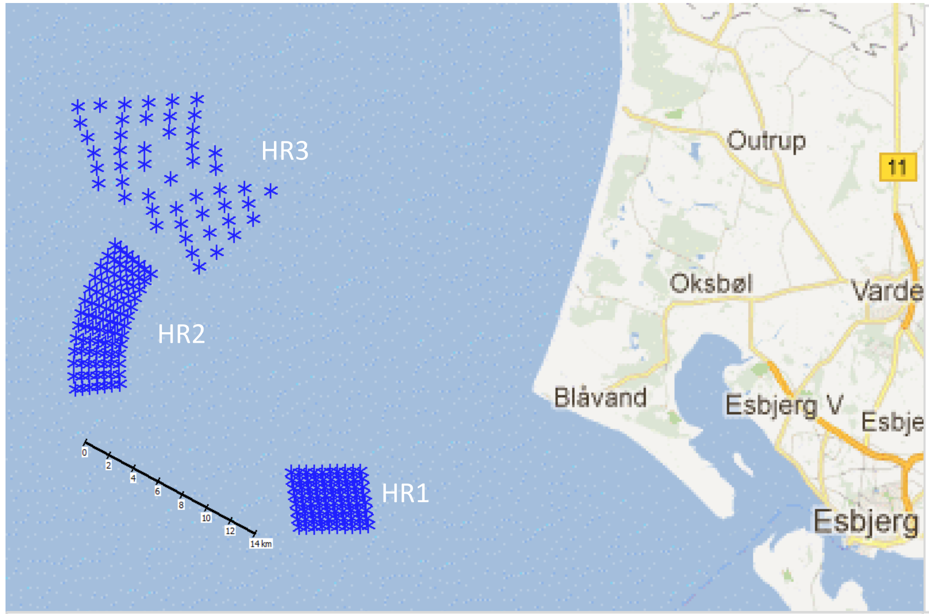
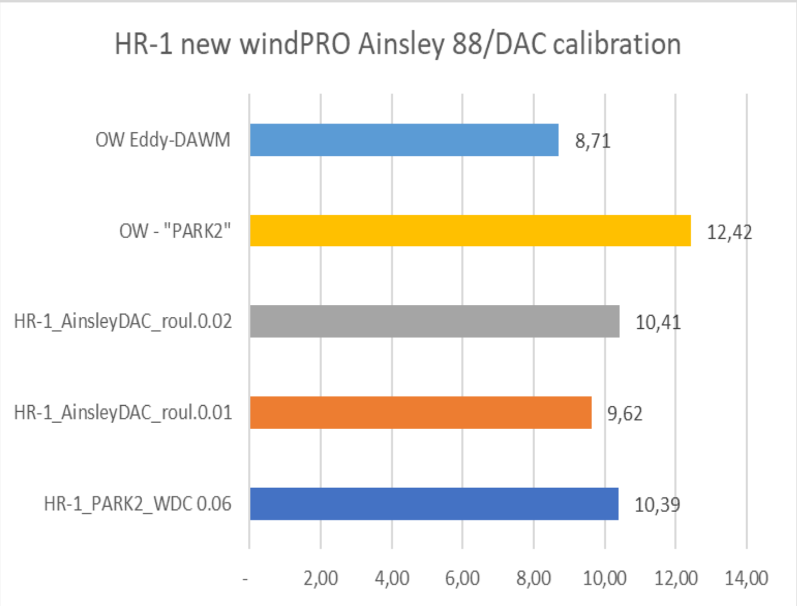
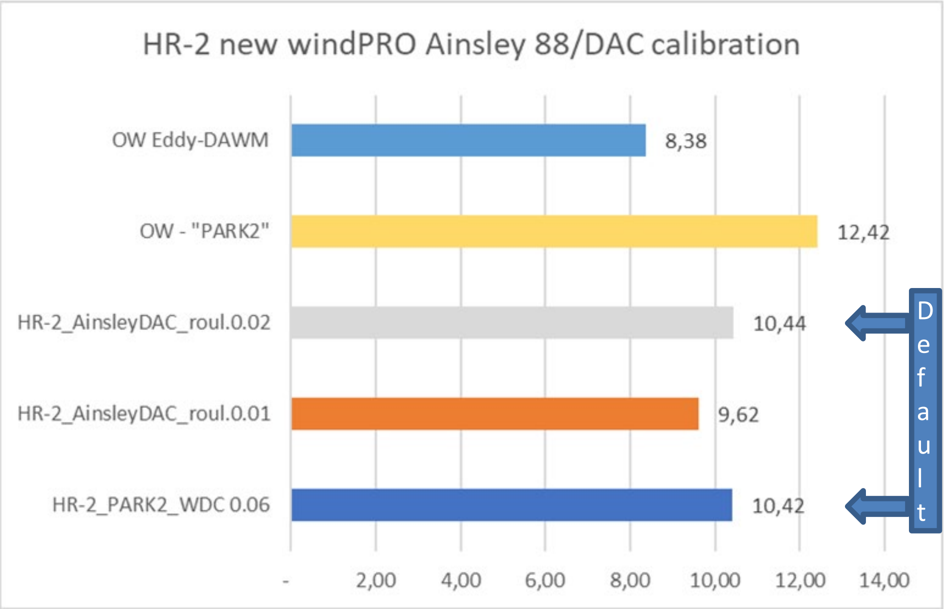
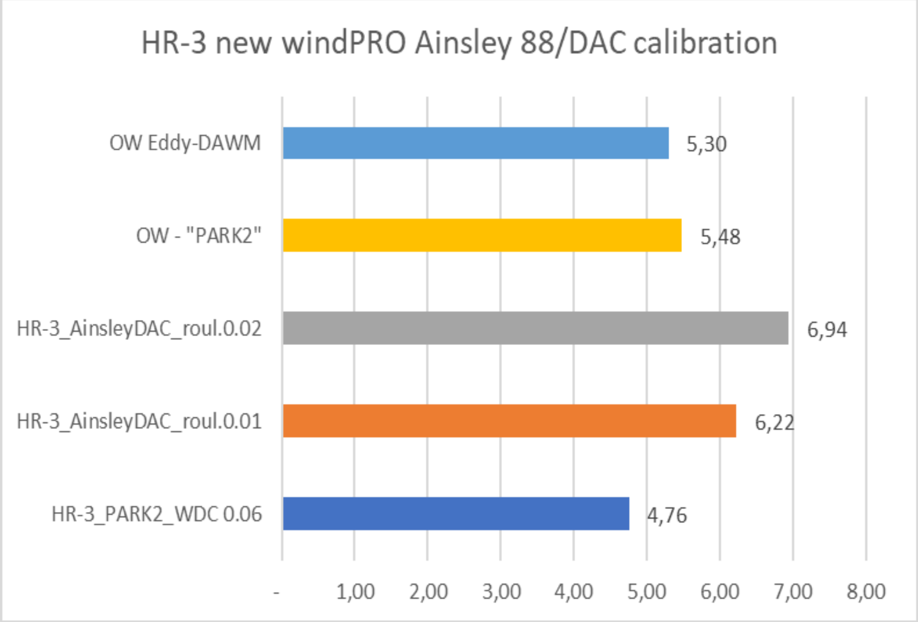
Verification PARK2 vs Ainsley (windPRO & OpenWind) @ HR







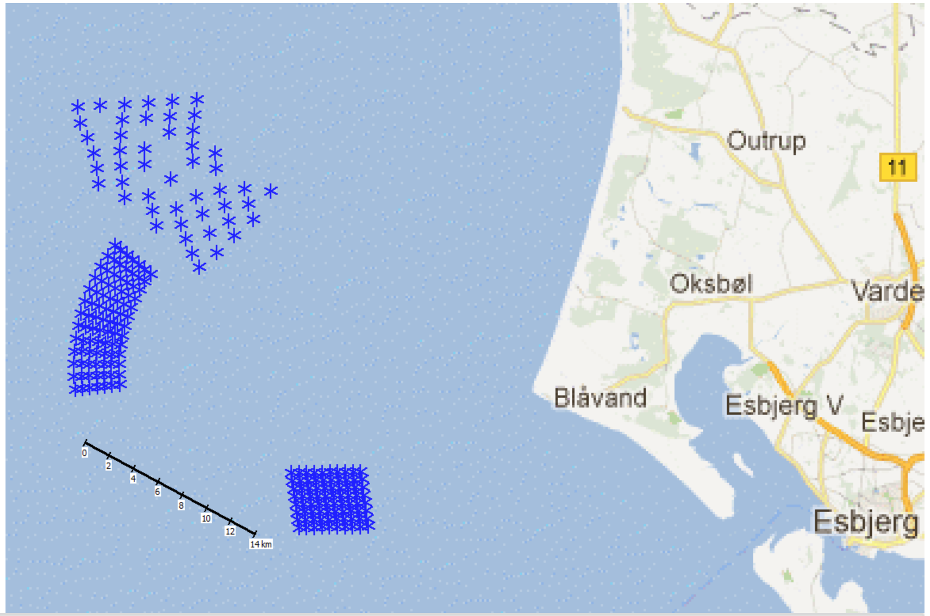


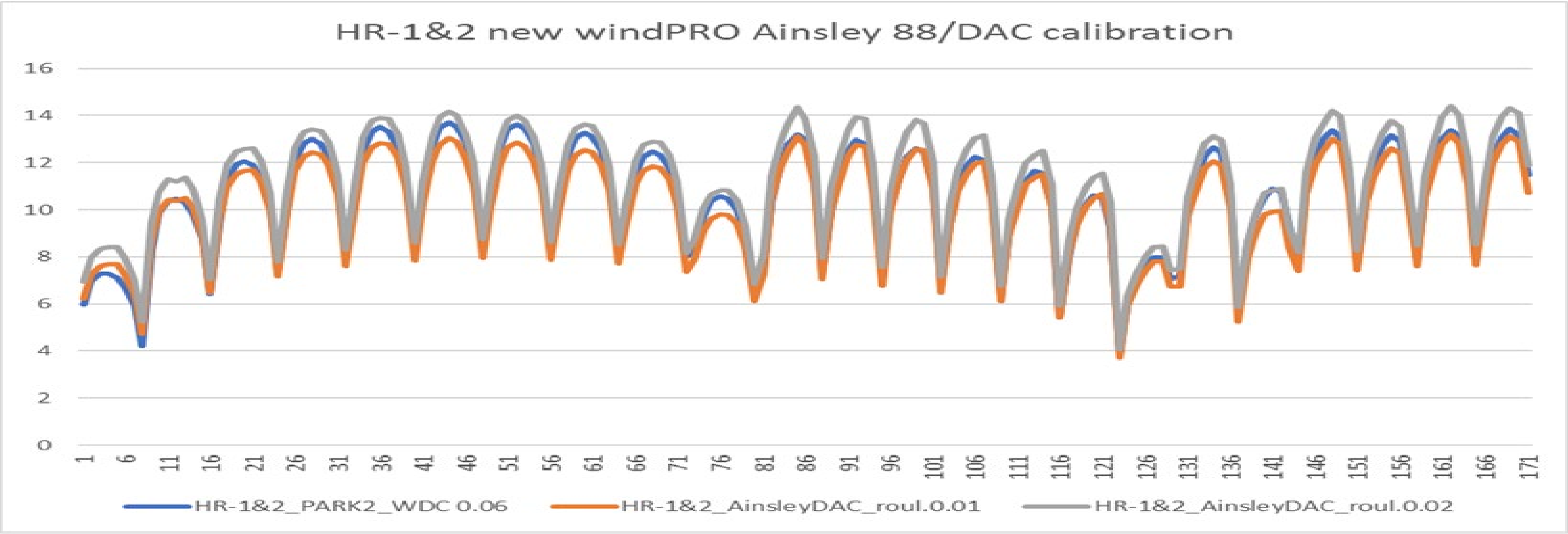
PARK2 and AinsleyDAC agree very well for both HR1&2. We know from several validations that PARK2 performs very accurate for HR1.
– OpenWind differs slightly, to the “bad” side (Their PARK2 is although not a “full” PARK2 implementation). A parameter tested in shown graphs is the added roughness in DAC, where 0.02 makes PARK2 and AinsleyDAC agree very well for both HR1&2.

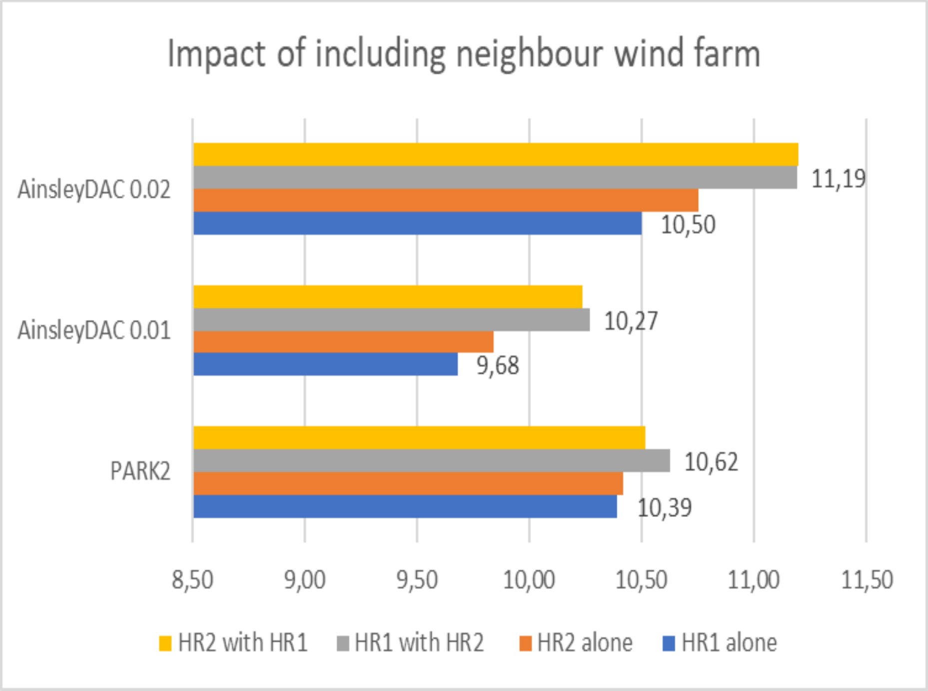
But for HR3 to the left, AinsleyDAC calculates most likely too high wake losses, even when lowering the added roughness to 0.01. The problem seem to be the large turbines (8MW) and thereby also higher spacing, which also were used in previous slide.

It is although “just” in a size order of 2 percent point that the AinsleyDAC seem to calculate too high (based on coarse operational data for HR3 PARK2 seem best).

Verification Ainslay/DAC vs PARK2 HR1+2 (interaction)







By turbine (HR1&2) some differences is seen between PARK2 and AinsleyDAC, but marginal.

To the left is seen how the AinsleyDAC adds a little more interaction losses between the two wind farms than PARK2. This is although so marginal that it even with very detailed data available for HR1 before/after HR2 it can't be seen for sure which is better. But for sure the impact of HR2 on HR1 is not higher than the 0.2 – 0.7 percent point as the two models calculates with 12 km separated wind farms.

Ainslie Model Parameter	Value
Limit of wake length [Rotor Diameters]. Default is 100.	100,0
Axial resolution of wake model [Rotor Diameters]. Default is 0.25.	0,250
Von Karman Constant. Default is 0.40.	0,40000
Length scale constant (K1) in eddy viscosity model. Default is 0.015.	0,01500
DAC-model: Correction weight. 0 is no model and 1 is full model. Default is 1.	1
DAC-model: Background roughness lenght [m]. Default is offshore 0.0002.	0,00020
DAC-model: Added roughness length inside wind farm [m]. Default is 0.02.	0,02000
DAC-model: Distance to start of recovery zone [Rotor Diameters]. Default is 60.0.	60,0
DAC-model: Distance to end of recovery zone [Rotor Diameters]. Default is 80.0.	80,0

Standard configurations for Ainslie 1988 (click to change parameters)

- Ainslie with DAC offshore class 0 (0.0002-0.02) <default>
- Ainslie with DAC onshore class 1 (0.03-0.10)
- Ainslie with DAC onshore class 2 (-)
- Ainslie with DAC onshore class 3 (-)
- Ainslie without DAC
- User defined

Park2: Few parameters
Ainsley/DAC: Many parameters

HR1 detail validation – impact of TI

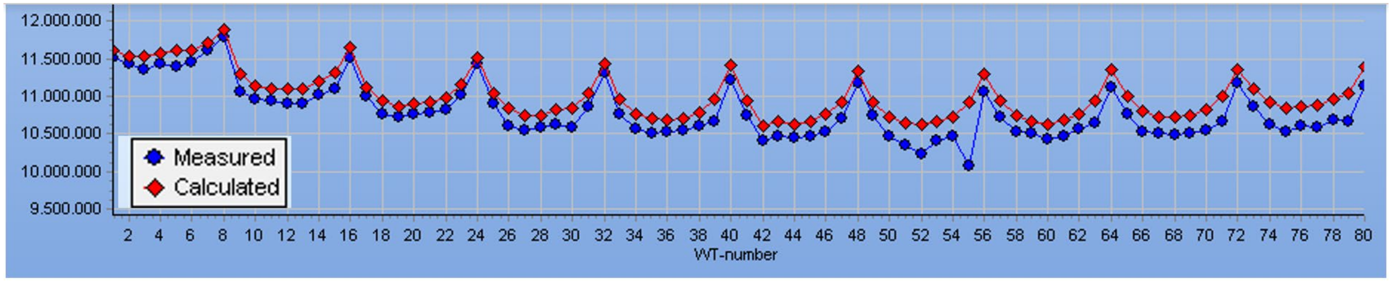


Figure 201 HR1 calculation for 2008 & 12 compared to measurements.

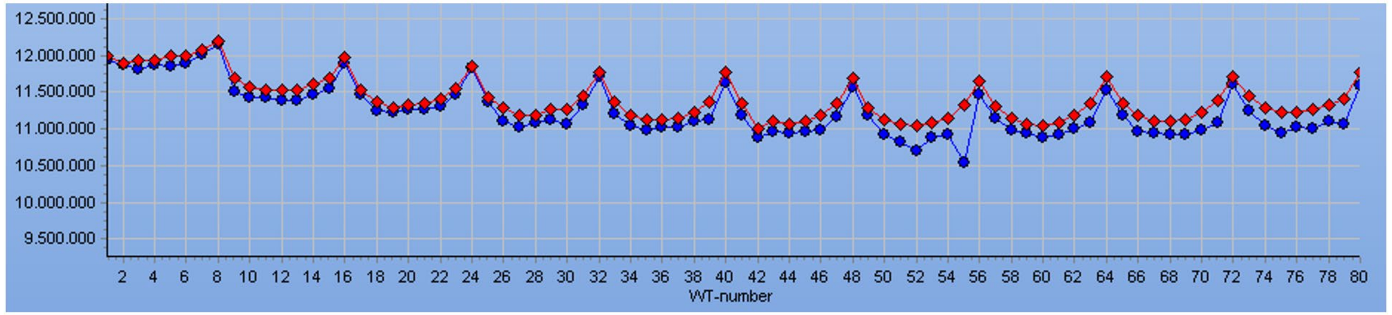


Figure 202 HR1 measured and calculated at TI>6%.

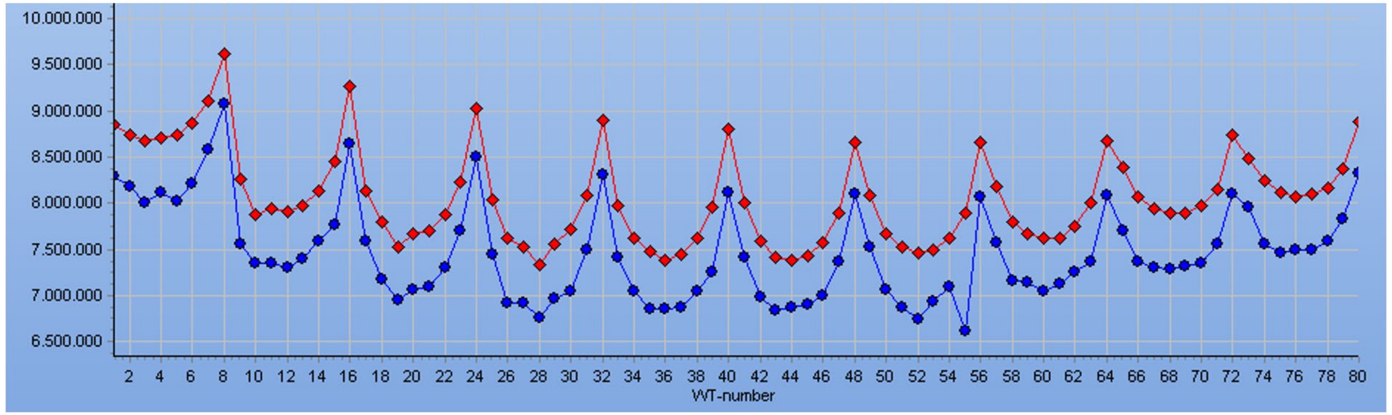
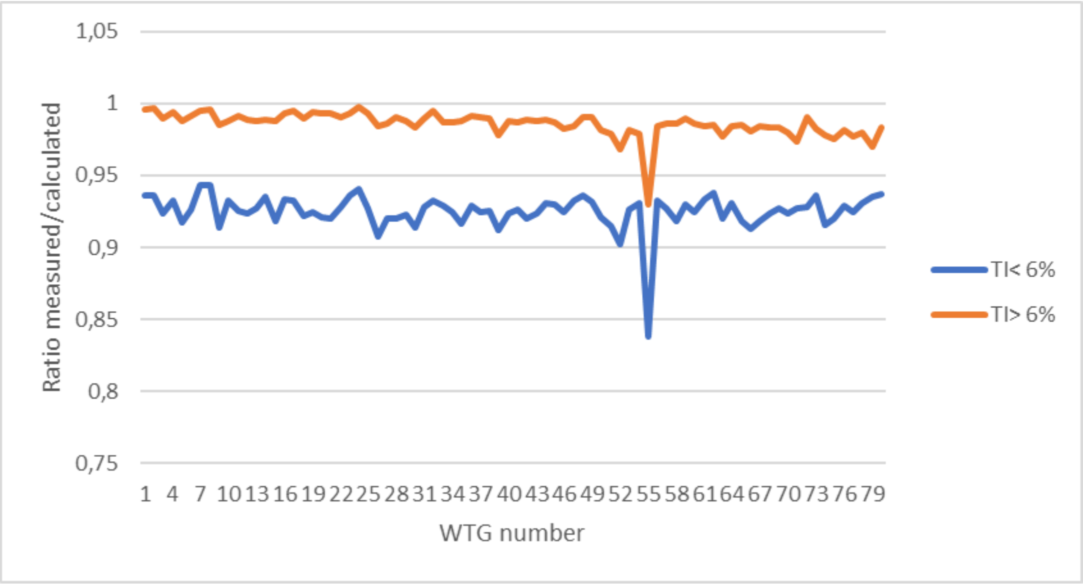


Figure 203 HR1 measured and calculated at TI<6%.

Comparing measured and calculated by time step.
Filtering by TI makes it clear how important this parameter is in wake modeling.
Using Wake Decay Constant (TI) by time step within PARK2 this handles as well low as high TI wake loss very accurate:



The seen bias by low TI is NOT wake model related, but a wind speed bias by TI in the meso wind data, possible blockage?

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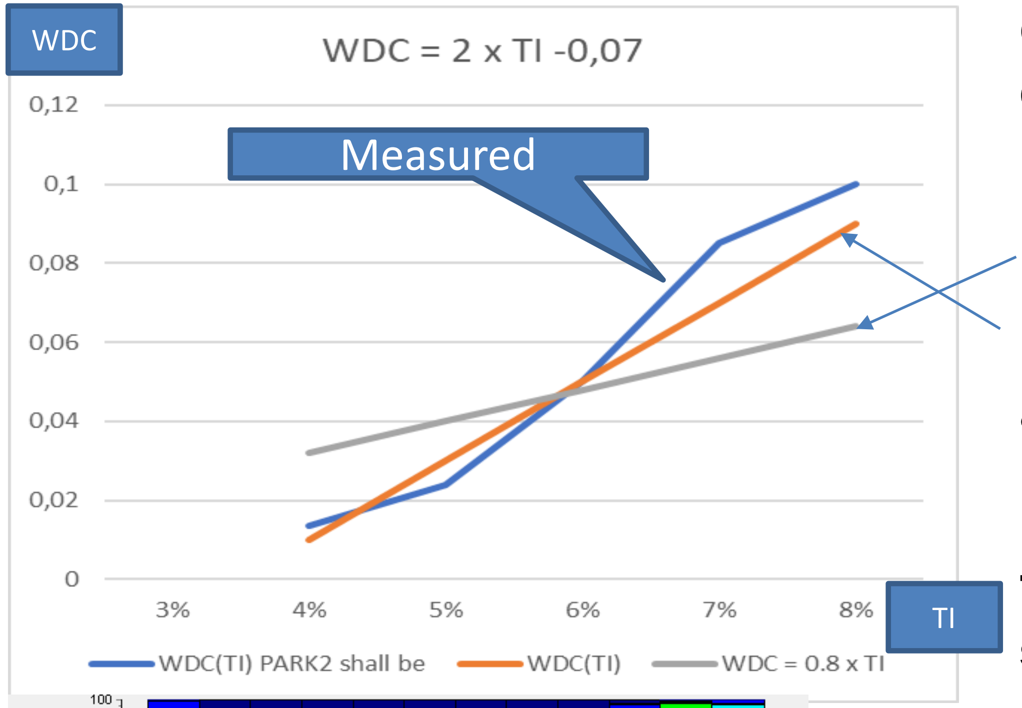
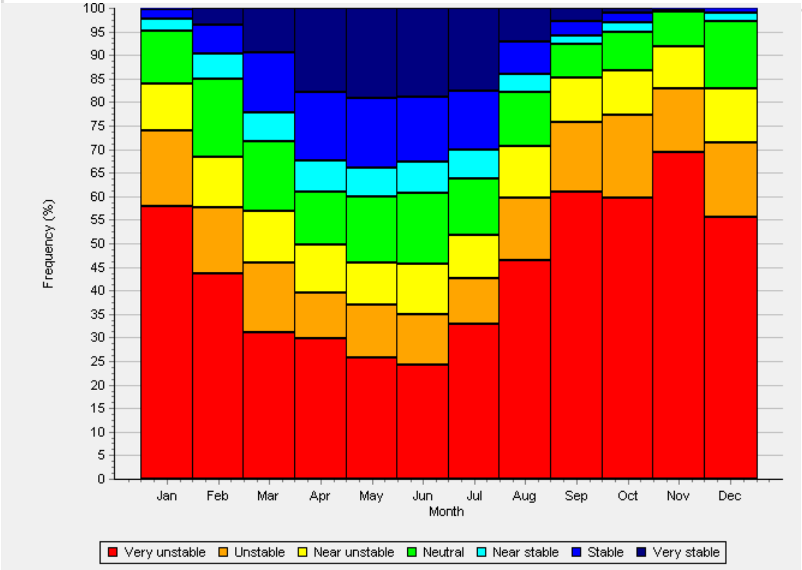
PARK 2 advanced tuning





We have through several detailed validation calculations experienced that the recommended WDC(TI) relation for PARK2 offshore (and low TI onshore):

(1) **WDC = 0.8 x TI**, work very well. It can be tuned further to:

(2) **WDC = 2 x TI – 0.07**, which lead to higher calculated wake loss at low TI and lower calculated wake loss at higher TI.

This is found by comparing measured back row/front row ratios to similar calculated for TI bins for more large wind farms.

<- There is a much higher share of stable wind in spring/summer offshore due to colder water than air. This results in lower TI ->> higher wake loss. This is captured much better by (2) than (1).

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PARK 2 advanced tuning – long term month data

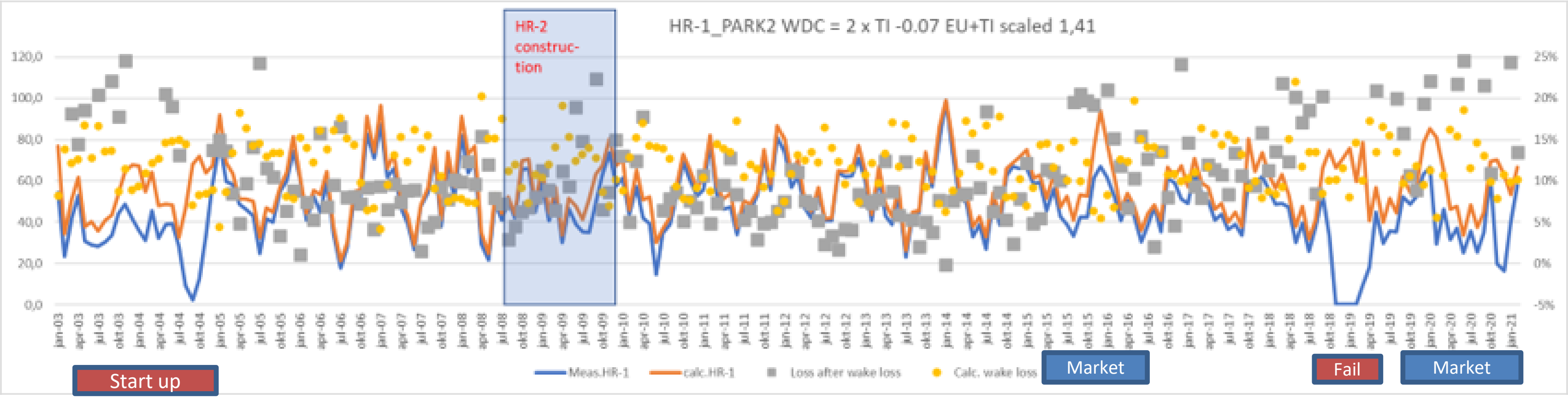


Figure 205 Long term calculation of HR1 compared to measured.

With the advanced wake model settings, round 20-year operation can be calculated and compared to monthly measurements. A very fine agreement is seen, but also that there are some months with quite high losses. From 2018 we know that one turbine has been taken out of operation permanent due to a lightning damage.

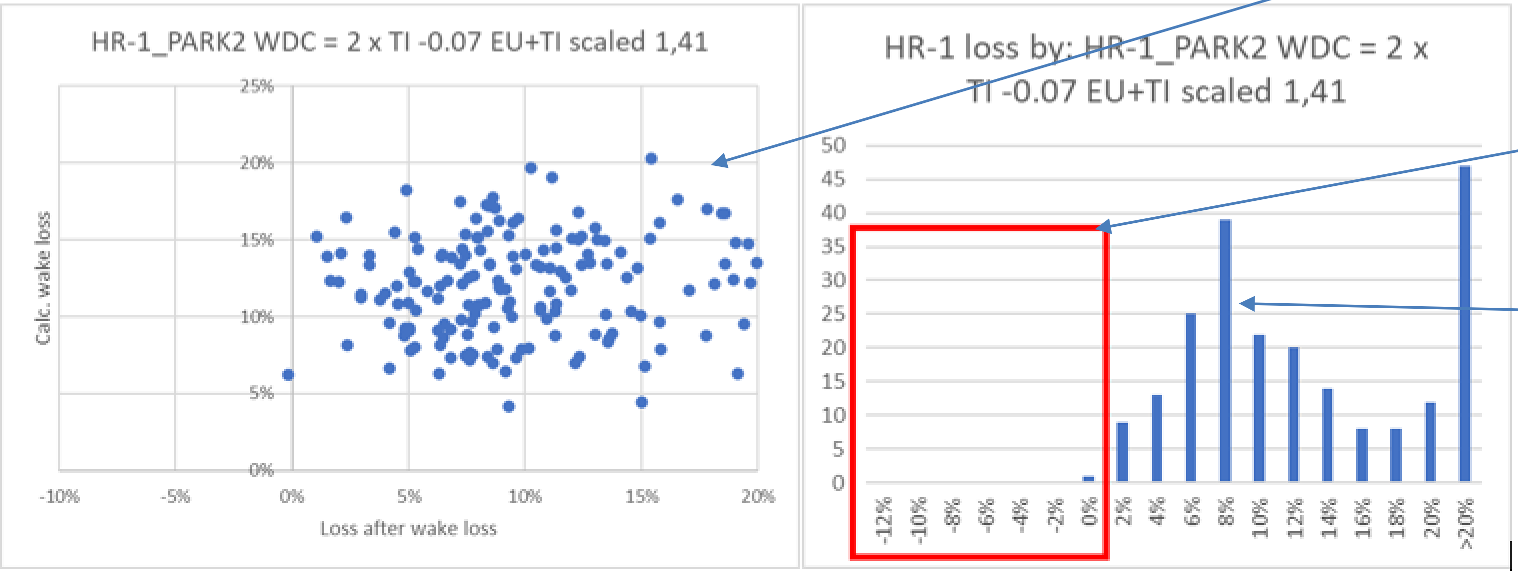


Figure 206 The calculated wake loss vs loss on top of wake loss and binned loss.

How to evaluate wake modeling based on monthly production data:

Calculated production month by month is compared to measured.
A calculation with "no wake model" is used to find the calculated wake loss by month.
Then as well the calculated wake loss as the loss on top of wake loss can be analyzed.

There should not be a trend when plotting calculated wake loss against loss on top of wake loss – this would indicate wrong calculated wake loss.

There should not be any months with "negative loss", apart from what meso wind bias might bring, but this seems marginal.

The loss on top of wake loss should be normal distributed, apart from the extreme loss months due to major failures or large Market regulation.

PARK 2 advanced tuning – will this always work?

For dense spaced turbines and very large wind farm complex's, detail calibrations are performed, and it is seen that the best results can be obtained by smaller adjustments, which are the VERY advanced tunings:

- ❑ "Normal" offshore wf: WDC = 2 x TI -0.07
- ❑ Dense wind farm: WDC = 2 x TI -0.05
- ❑ Large wind farm complex: WDC = 2 x TI -0.09

Below example for dense spaced, Lillgrund, Sweden offshore with just 3.2-3.4 RD spacing. By Plotting the goodness (measured/calculated) by WTG versus calculated production we can see If wake modeling is biased:

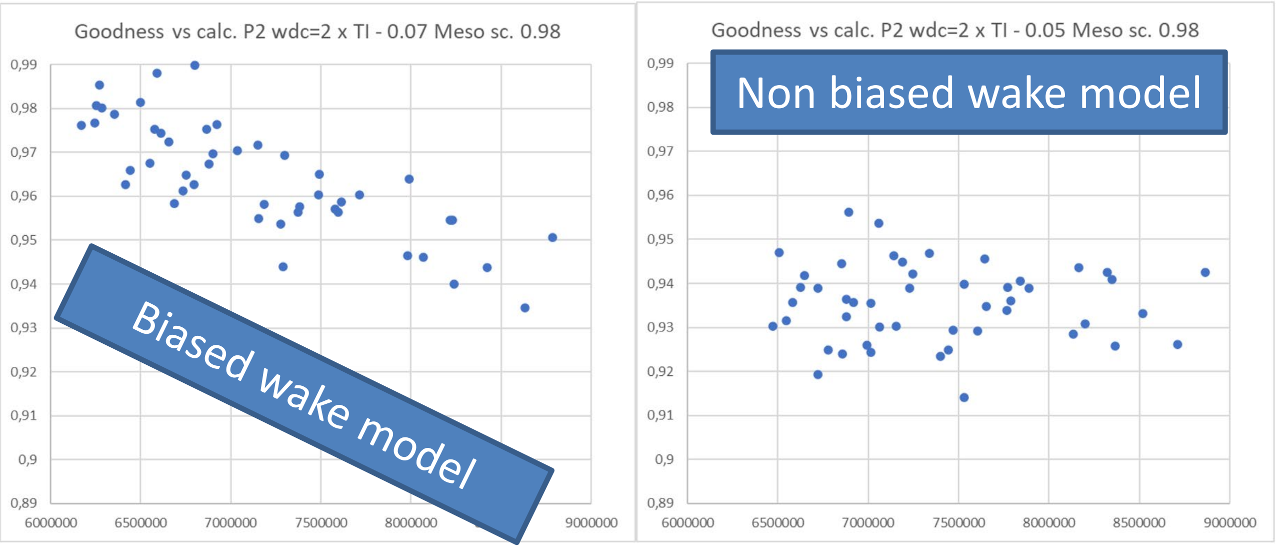
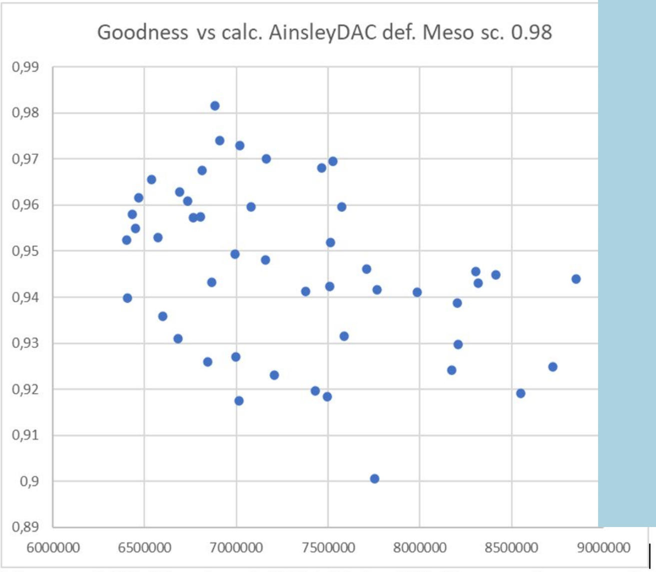


Figure 214 The calibration tool: goodness vs calculated, Park2 adv. default (left) and tuned (right).



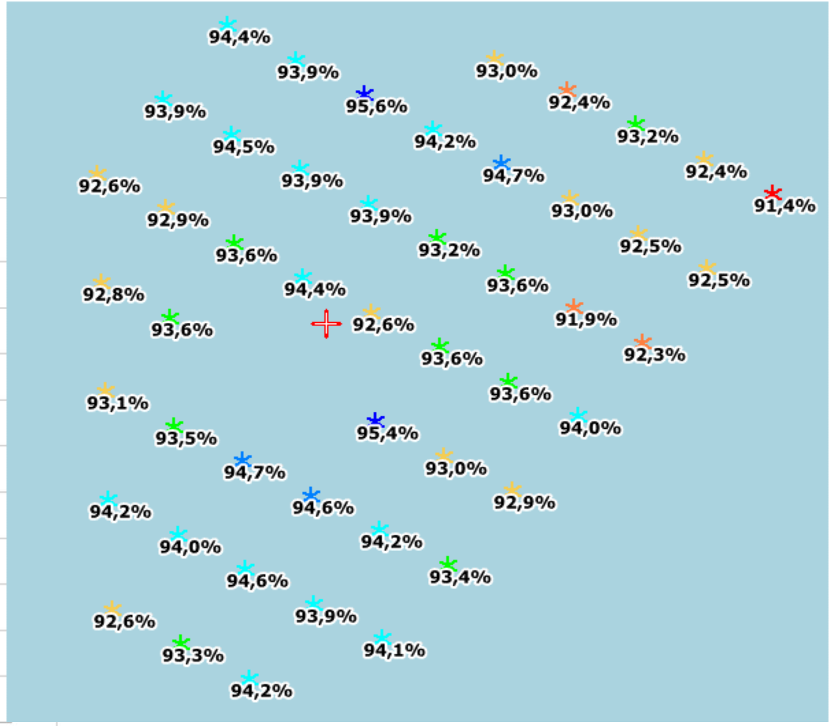
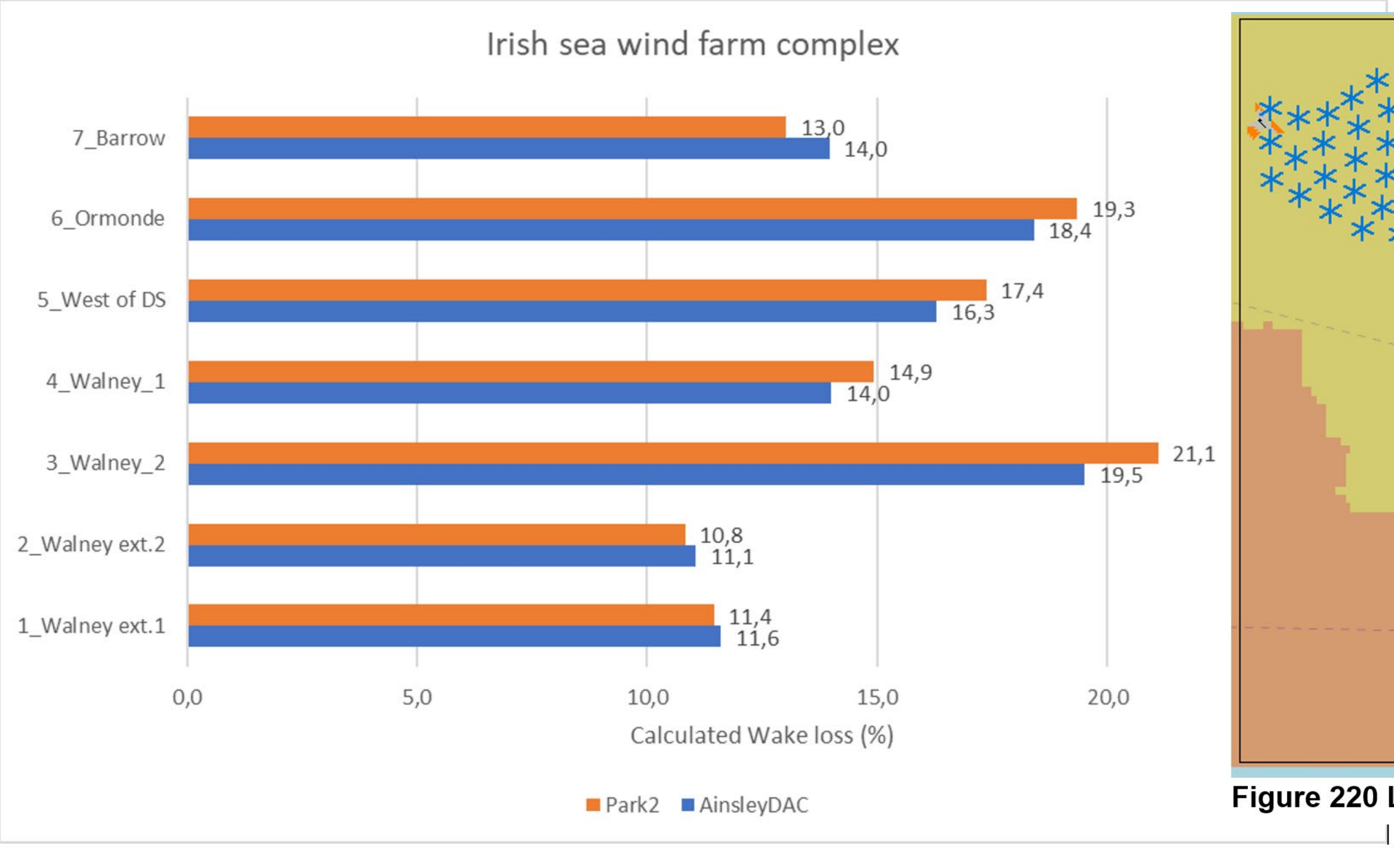


Figure 216 Ainsley hit WTG by WTG goodness slightly poorer than PARK2.

PARK 2 advanced tuning – will this always work? (2)

For a very large offshore wind farm complex, based on monthly production figures from www.ref.org.uk, wake modeling is tested for different periods with different number of wind farms operating. This test case has a great validation potential and show that wake modeling here also work very well, although best with slightly lower WDC by TI for PARK2: WDC = 2 x TI – 0.09.
Below calculation with PARK2 and Ainsley compared, quite well agreement for the different wind farms < 1.5 percent point difference!



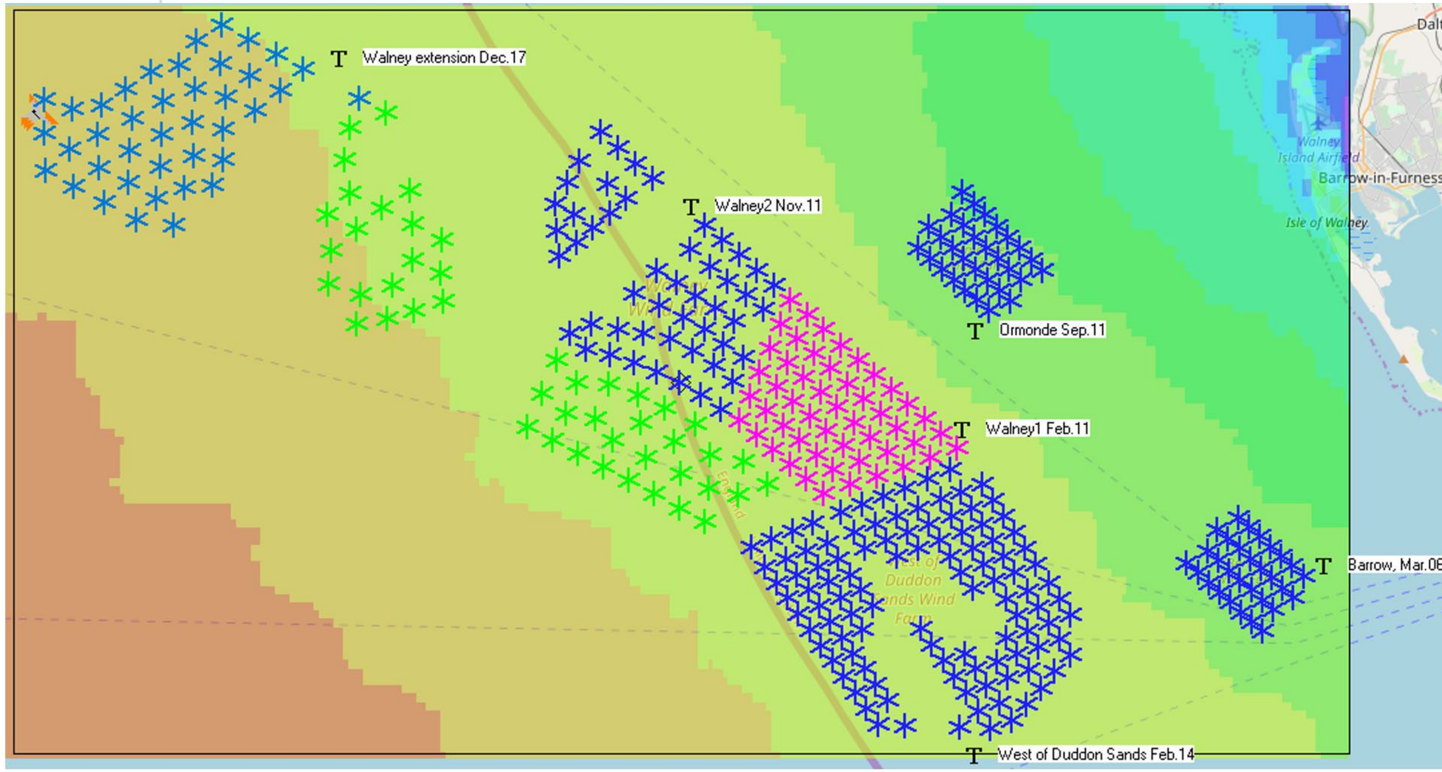


Figure 220 Large wind farm complex covering 45 km east-west.

Figure 227 Calculation for 20y all wind farms running full time, compare PARK2 and Ainsley.

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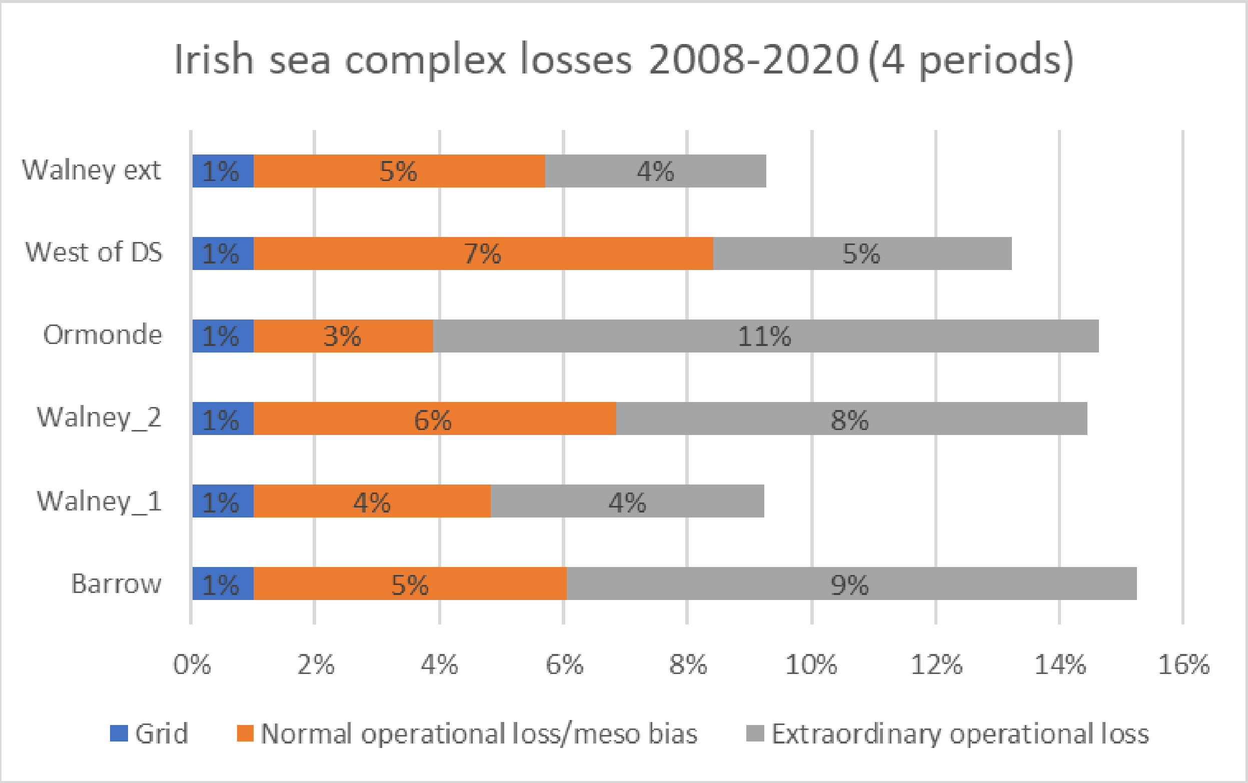
A little more on offshore wind farm non wake losses

Having well working wake models and good meso scale model data, it is possible to identify losses by "type", here we arbitrary set Grid losses (only internal cabling) to 1% and extract from the calculations the "normal operation losses" as the months with less than 15% loss. This leaves a remaining loss from months where there are obvious major operation problems.



3-7% "normal operation loss/Meso wind bias" and 4-11% "extraordinary" from months with major operation problems (for DK also Market regulation, that for some periods are quite large, explaining higher loss, for UK less). This is some scary.

	Apart from "extraordinary"		Start up months excl.	
	Average if < 10%	if < 15%	All data	Extraordinary
HR-1	6,6%	8,3%	17,2%	8,9%
HR-2	6,4%	7,9%	11,2%	3,3%
HR-3	5,3%	7,1%	8,1%	1,0%

Part of loss in table above, 1-2% is internal cabling (grid) loss and stepUp transformer loss.

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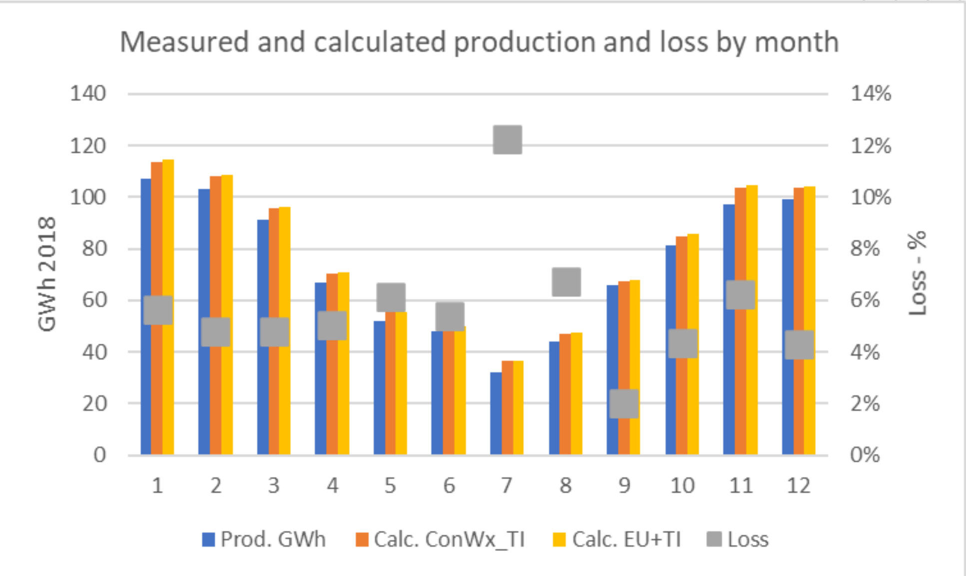
Is the losses really that high, or is it “just” meso wind bias, non captured wake and blockage losses?
This some most likely will claim.

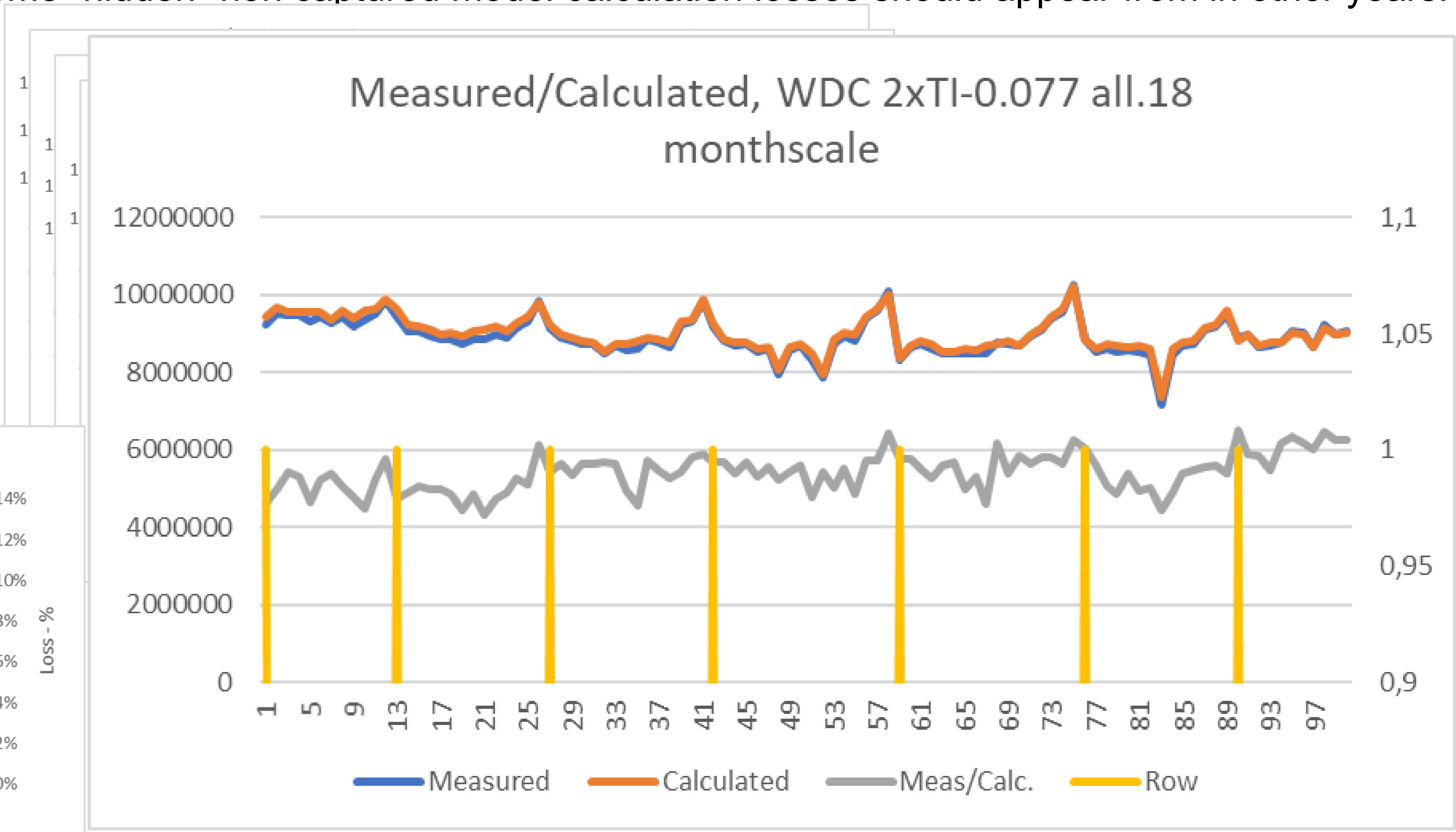
Discussion

BUT, for HR-1 example (and several other large windfarms), we see that when having detailed 10-min Scada data for each WTG, where stops and suboptimal performance is filtered, the measured production is calculated within +/-1% year by year with the used model setup.

This makes it difficult to see where some “hidden” non captured model calculation losses should appear from in other years!

Example to the right, an offshore wind farm with 100 WTGs is here calculated month by month compared to 10-min. measurements WTG by WTG (x-axis) for filtered data. Meso wind speed is scaled to “best fit” every month: Min. 0,94, Max.: 1,04, average: 0,99.





Conclusion on wake model issues:

3 fully different Wake model concepts:

- **PARK2 (DTU)**
- **Ainsley (Eddy Viscosity) with DAC or DAWM (deep array correction)**
- **WakeBlaster (ProPlanEN)**

- reproduces "measured" wake loss within +/-2 percent point, even for very large offshore complexes (45 km) – and all models agree well on size order, although some differences depending on layout and turbine sizes.

So are we good ?

☹ For all models, the Turbulence Intensity (TI) decides. This is not always accessible in a good quality.
😊 We have although now a new source for this worldwide, the Global Atlas Siting Parameters (GASP) data set from DTU/EMD (downloadable from windPRO) and for some regions, PreRun Meso scale data like EMDWrfEU+ (Europe) with time series TI.

☹ There are parameters to set, that require some experience.
😊 We try our best to help the windPRO users to get those right – and keep on validating.

Yes, I'll say we are good within wake modeling – marginal improvements is of cause possible, the "hunt" continues!

About **blockage**, the models implemented in windPRO typically deduct 0.5%, which is impossible to detect even in the best validation data sets. Much ongoing research on this topic. *We are part of the GLOBE project, the "flagship" within blockage.*
Probably next generation of blockage models will be TI (and or stability) dependent and thereby more accurate when calculating in time domain.

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