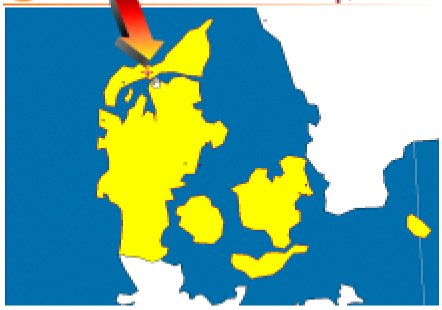
Klim, Denmark – Case study.



Abstract

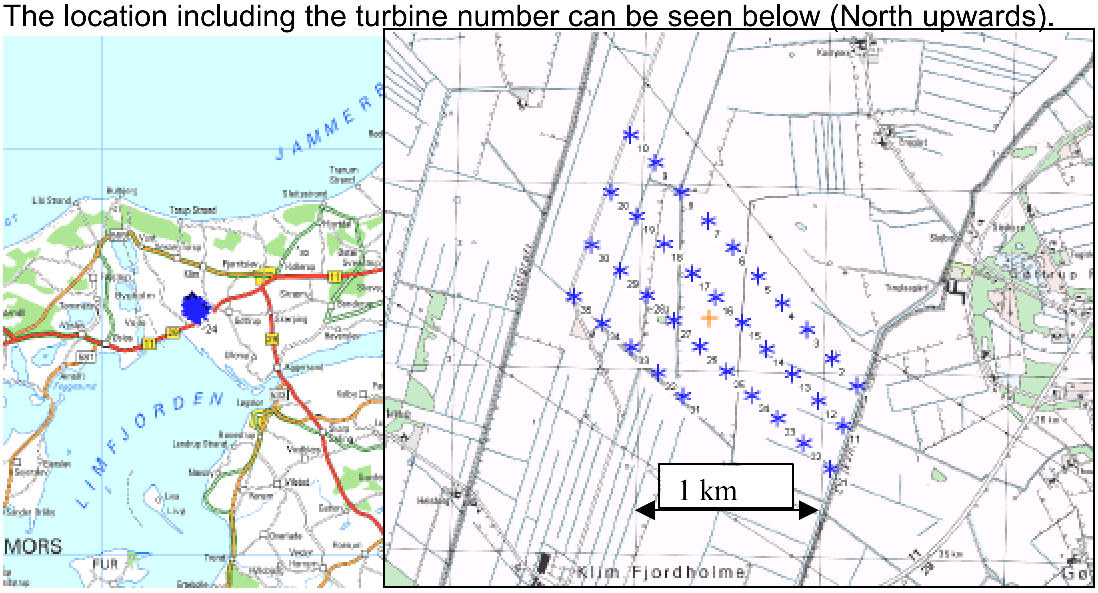
Terrain type: Flat, open, inland, close to fjord.

Project: The turbines in this project are situated in the north-western part of Denmark, 9°09' East 57°04' north, 7 km south west of Fjerritslev. The area is called Klim Fjordholme. It is a good wind location with a mean wind speed around 7 m/s at 44 m a.g.l. (Hub height). The park contains 35 WTGs, all Vestas V44, 600 kW, with typical spacing: 4.5 RD in rows and 5.5 – 7 between rows. The first 13 WTGs were erected in Sep. 96, one year after the wind farm was completed to 35 WTGs.
The main issue in this case study is to check the PARK calculation model (Wake-loss). It is unfortunate that we don't have measured wind data close to the wind farm, but instead data from Silstrup, around 35 km away will be applied. It is fortunate that we have production data as 10 min values, which gives unique evaluation possibilities. It is good that the site is in Denmark, where we in general have much experience and a well-known wind index.

Main results: Actual production for the entire wind farm is calculated very accurate – but the interesting part in this case is how the differences among the individual WTGs production is relative to what the PARK-calculation show with different assumptions. We here have an almost "unique" test site, total flat and open. The findings are that a 0.075 Wake decay constant, as usually is assumed for "open land", work very well for the two front rows of WTGs in the main wind direction. Whereas 0.04, as normally is used for off shore (less turbulent wind, higher reduction) is the better value for the rows behind. This is very surprising, because the back rows should experience more turbulence. It looks like the PARK model do NOT work correct at large wind farms – some "large farm" effects seem not to be taken into consideration. This can have large influence on the calculations of large off shore wind farms.

Detailed maps:

The location including the turbine number can be seen below (North upwards).



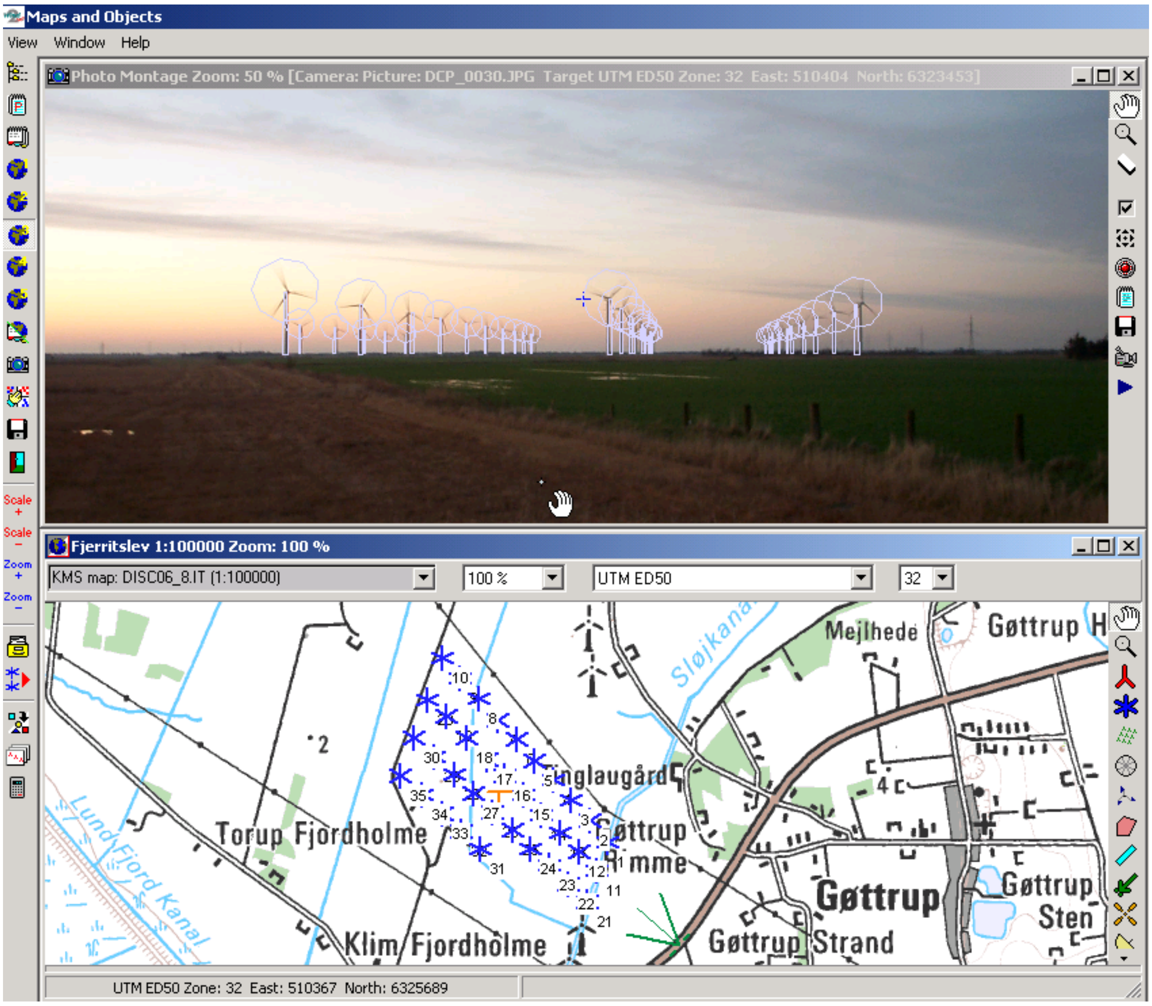


Figure 1 The wind farm seen from southeast with an overlay from the WindPRO photomontage tool, which confirm that the positions of each WTG match exact.

Actual Energy production from the WTGs

Production figures have been available in three variants:

1. Monthly production data from the beginning (September 1996 up to May 2000) from the wind farm computer for each WTG
2. The complete WTG computer registration set for 1998 (down to 10 min. values for each WTG of all parameters registered)
3. The monthly energy production from the beginning until Sep. 2001 for the whole wind farm based on the utility reporting to the WTG owner association database

Based on the last information source, it can be stated with correction indexes that the long term average production is estimated to 49 GWh/year (1400 MWh/WTG/year). The mean actual production 1998-2000 was 45.4 GWh, see print below.

21000A KLIM
35 stk. VESTAS 600 kW Navhøide 45.0 m

Anlægsdata			
Rotordiameter/rotorareal/Spec. effekt	**44.0 m**	**1520.5 m2**	**0.39 kW/m2**
Amt/Kommune (kommunenr.)	**Nordjylland**	**Fjerritslev(811)**	
UTM-koordinater (Zone/Øst/Nord)	**32**	**509807**	**6323586**
UTM præcision	**Rimeligpræcis (±100m)**		
Beregnet årsproduktion (MWh pr. år/Ber. af)	**46000.0**	**FAB**	
Indkøring/data start/data slut	**Sep 1997**	**Jan 1998**	**Sep 2001**

HOVEDRESULTATER	NE-index	DMI-index
Vindkorrigeret årsproduktion (MWh)	50280.4	48579.7
VKP/rotorareal (kWh/m2)	944.8	912.8
VKP pr. kW generatoreffekt (kWh/kW)	2394.3	2313.3
GODHED	1.09	1.06

Baseretpåperioden Jan 1998- Sep2001

Månedligeproduktioner og GODHEDER (GODHED baseret på: NE-index).

År	Data	Jan	Feb	Mar	Apr	Maj	Jun	Jul	Aug	Sep	Okt	Nov	Dec	SUM	Pr. år
1998	kWh	4,414,500	6,724300	*	2,982,900	2,548,700	3,729,000	4,144,300	*	2,769,100	6,208,200	2,558,000	4,811,500	40,890,500	44,249,700
	Godhed	1.14	099		1.04	0.96	1.20	1.09		1.03	0.96	1.11	1.17	1.06	0.95
1999	kWh	5,340,700	*	4,010,160	3,687,100	3,536,400	2,346,600	1,899,800	1,362,900	2,399,400	4,312,500	4,506,170	6,176,260	39,577,992	43,289,928
	Godhed	1.18		1.23	0.94	1.26	1.18	1.10	0.83	1.01	1.06	1.20	1.13	1.11	1.10
2000	kWh	6,824,920	6,289,540	4,996,180	*	2,774,680	*	2,372,630	3,341,000	3,644,370	4,108,900	4,674,360	3,675,070	42,701,648	48,729,980
	Godhed	1.14	1.01	1.03		1.13		1.13	1.34	1.06	1.09	1.18	1.18	1.11	1.11
2001	kWh	2,998,190	4,681,170	2,845,665	2,695,450	3,202,020	3,263,150	2,360,350	3,101,390	2,020,730				27,168,114	19,134,372
	Godhed	1.10	1.11	0.88	1.02	1.16	1.29	1.34	1.17	0.79				1.08	0.77
Sum	kWh	19,578,310	17,695,010	11,852,005	9,365,450	12,061,800	9,338,750	10,777,080	7,805,290	10,833,600	14,629,600	11,738,530	14,662,830	150,338,258	155,403,984
Middel	kWh	4,894,578	5,898,337	3,950,668	3,121,817	3,015,450	3,112,917	2,694,270	2,601,763	2,708,400	4,876,534	3,912,843	4,887,610		
	Godhed	1.14	1.04	1.05	1.00	1.13	1.22	1.16	1.11	0.97	1.04	1.17	1.16		

NOTE: Pr. årerrapporteretårsproduktion. *: Produktionstalikkeangivet.

År	1998	1999	2000	2001	Gns.
Produktion (MWh)	44,250	43,290	48,730	19,134	45,423
VKP (NE) MWh	43,920	50,386	51,071	35,271	48,459
VKP (DMI) MWh	45,424	49,756	51,765	24,696	48,982

Gns.erbaseretpå3heleår: 1998-2000

Figure 2 Data for the whole wind farm from the VINDSTAT database.

For the individual WTGs there have been performed a cleaning up based on availability etc. which gives the below figure.

It is seen in figure 3 and 4 how the configuration with 10 WTGs per row in the first 3 rows and a 4'Th row with 5 WTGs gives the variations in the individual WTGs production. This is seen that the WTGs in middle of 3 first rows of 10 WTGs (5-6, 15-16, 25-26) have the lowest production figures. The same is seen for WTG 33 in middle of the row with 5 WTGs.

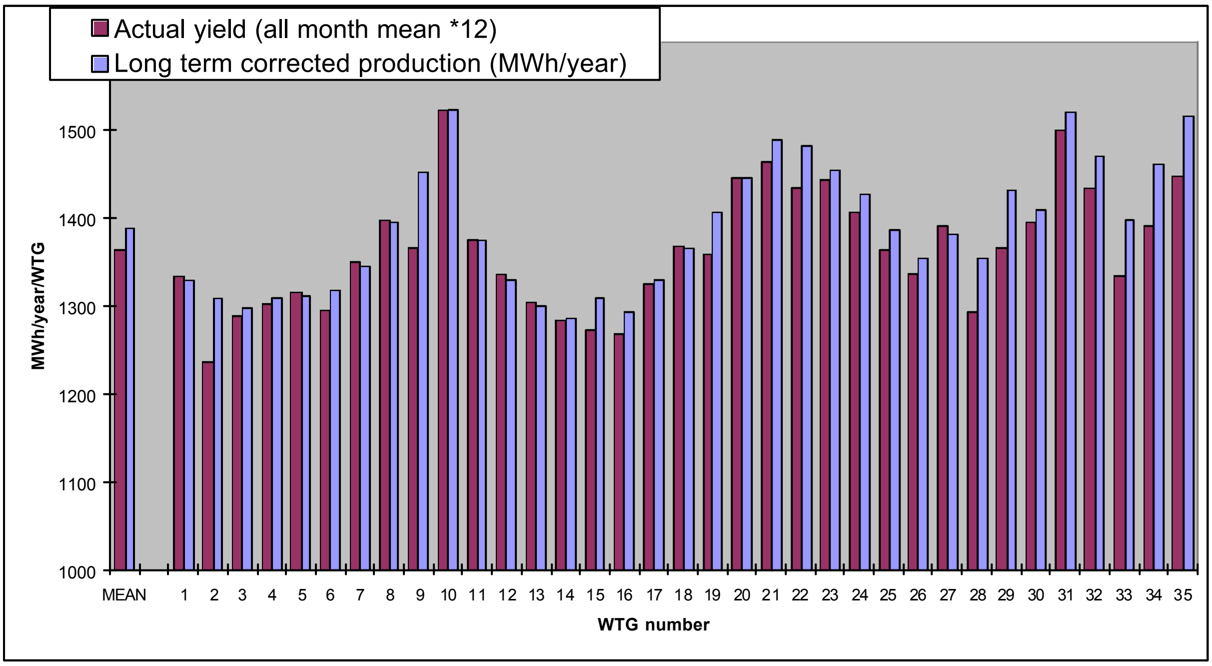


Figure 3 Actual and long term corrected energy production for each WTG

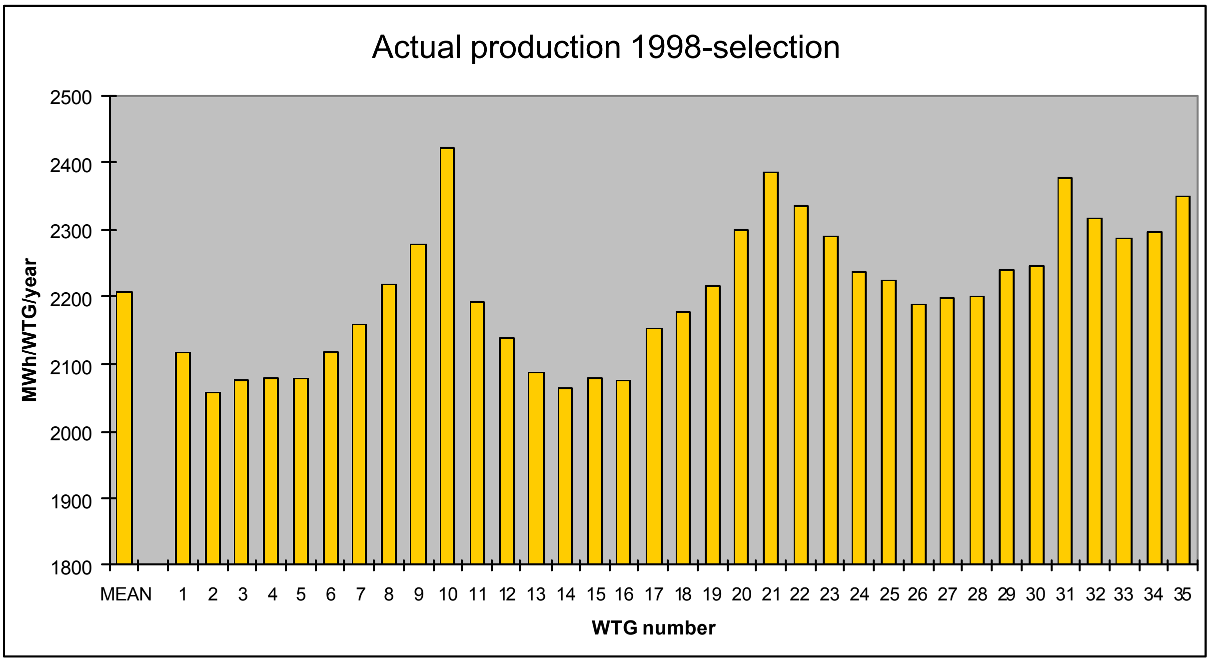


Figure 4 Production for each WTG for the selected days with 100% availability used in parallel with Silstrup measure data for same days

Finally based on the detailed database a selection of days with all WTGs in full operation from 1998 gives a more precise variation between each WTG. This is later used for parallel calculations with wind data for exact the same days.

Energy calculation assumptions – models and data

Calculation models

WindPRO 2.2 is used with the WAsP model ver. 5.1 with standard settings (Parameters) for calculation of the wind statistics based on measurements and terrain description. From the terrain description and the wind statistics the wind distributions are calculated for each of 12 directional sectors for each WTG position. WindPRO's PARK model (N.O.Jensen) and power curve calculation interface converts the wind distributions to expected annual energy yield.

Terrain assessment

The nearest 3 km in all directions are very open farmland. Further to the south the fjord begins and further to the north there is forest. Below a map shows how the roughness has been digitised from land use maps, which were the basis for generating the wind resource map of Denmark. Each 1 x 1 km^2 has been given a roughness value based on information on windbreaks etc. and the whole "patchwork" has been glued together with information on the large forests, city and water regions.

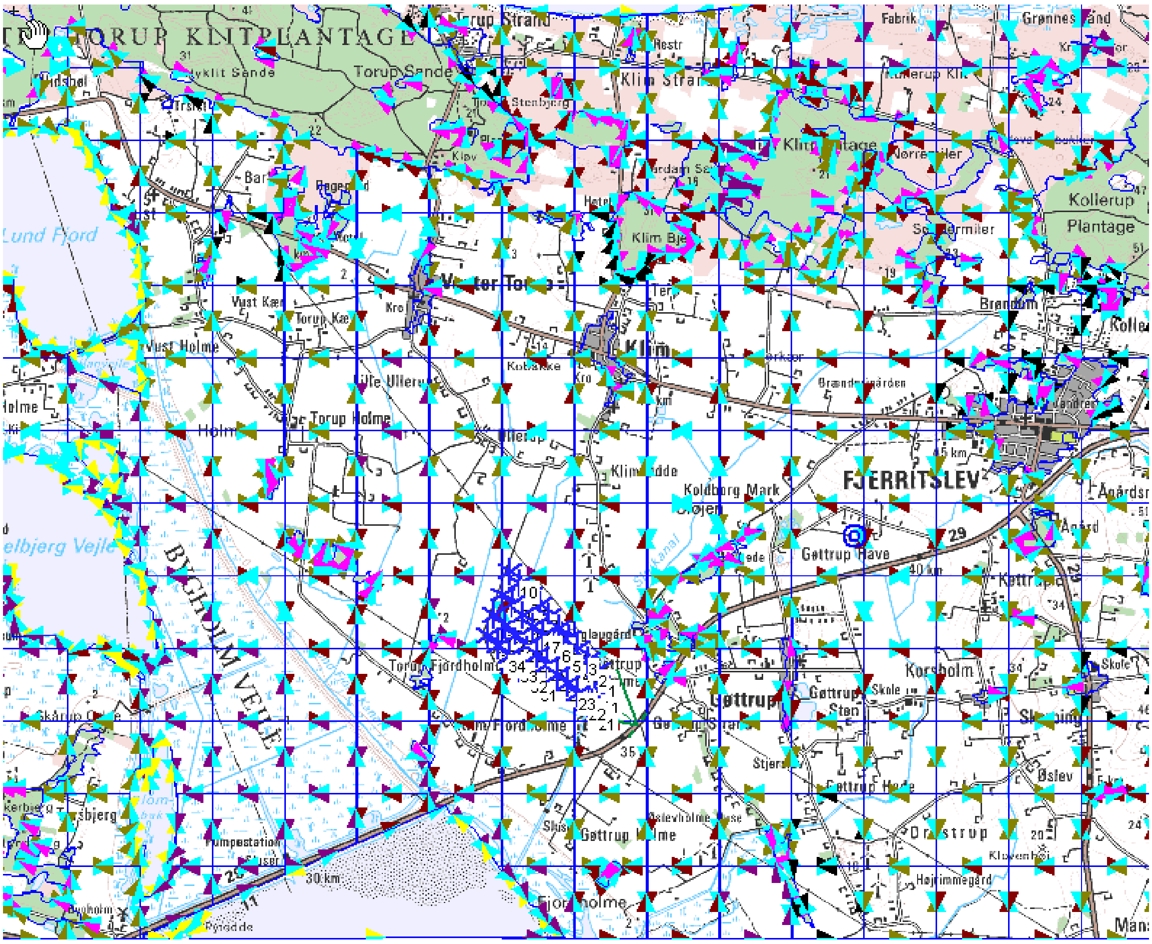


Figure 5 Roughness map, each square represent 1 km x 1 km.

As the region is totally flat, height contour line have not been taken into consideration, and local obstacles are not included.

Wind data

General wind statistic

Practically all calculations in Denmark are made with the wind statistic "Denmark '92", which is the wind statistic for Beldringe from the EU Wind atlas, combined with a set or regional correction factors. This wind statistic has been used for the preliminary calculations.
The energy rose for this wind statistic are shown below. We are aware that this wind rose probably holds too much energy in WSW and to little in W – NNW directions, when we are in the north western part of Denmark.

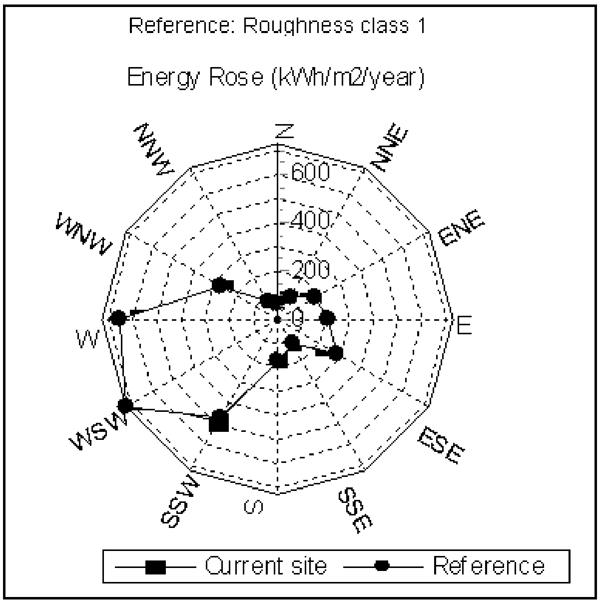


Figure 6 Denmark '92 energy rose, where the square marks refer to adjustments for the Klim site. But due to Klim is almost roughness class 1 (reference), there is almost no difference between Klim and reference.

Local wind data

For performing more detailed investigations on array loss calculations, there has been established a wind statistic from a wind measurement at a mast 35 km away - called Silstrup. The wind data and measurements mast is treated in the Case report "07 Silstrup". Here only the special treatment relative to this case is described.

Based on all days of 1998, with full WTG operation and fully operating measurement equipment in the wind farm (89 days in total), these days are selected in the 1998-hour value data set from Silstrup. Based on this selection of data a wind statistic is generated. Below the energy rose is shown. It can be seen that mainly the energy is associated with southwest winds in this period – but the important thing is that it represent an exact parallel period to very well verified WTG production data.

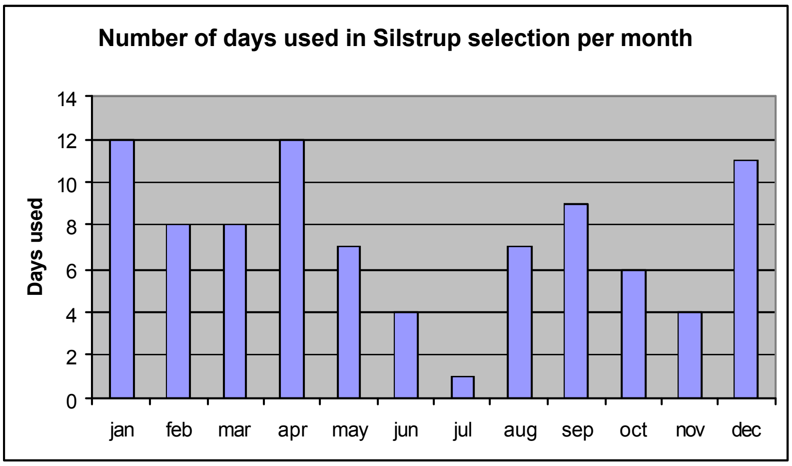


Figure 7 As well summer as winter months is included fairly equal in the 1998 Silstrup selection

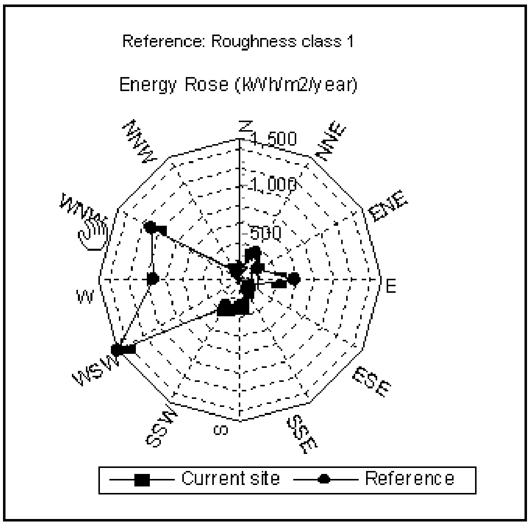


Figure 8 Silstrup 1998-selection (89 days) energy rose.

WTG data

Power curve: Manufactor 24/8-2000 1.225 20.00 0.00

Source Manufactor 24/8-2000

Source date	Creator	Created	Edited	Default	Stop windSpeed [m/s]	Air density [kg/m3]	Tip angle [°]	Power control	CT curve type
30-12-1899 00:00	EMD	20-11-2000 14:02	20-11-2000 14:03	No	20.0	1.225	0.0	Pitch	User defined

Power curve

Wind speed	[m/s]	3.00	4.00	5.00	6.00	7.00	8.00	9.00	10.00	11.00	12.00	13.00	14.00	15.00	16.00	17.00	18.00	19.00	20.00
Power	[kW]	0.00	0.00	30.00	77.00	135.00	206.00	267.00	371.00	450.00	514.00	558.00	582.00	594.00	596.00	600.00	600.00	600.00	600.00
Ce		0.000	0.000	0.256	0.363	0.423	0.432	0.423	0.398	0.363	0.319	0.273	0.226	0.169	0.157	0.131	0.110	0.094	0.081

Ct curve

Wind speed	[m/s]	3.00	4.00	5.00	6.00	7.00	8.00	9.00	10.00	11.00	12.00	13.00	14.00	15.00	16.00	18.00
Ct		0.00	0.00	0.85	0.83	0.79	0.73	0.67	0.60	0.54	0.48	0.40	0.32	0.25	0.20	0.14

HP curve comparision

Vmean	[m/s]	5	6	7	8	9	10
HP value	[MWh]	752	1,211	1,670	2,099	2,489	2,835
Manufactor 24/8-2000 1.225 20.00 0.00	[MWh]	686	1,124	1,572	1,977	2,301	2,529
Check value	[%]	10	8	6	6	8	12

The table shows comparison between annual energy production calculated on basis of simplified "HP-curves" which assume that all WTG's performs quite similar - only specific power loading (kW/m^2) and single/dual speed or stall/pitch decides the calculated values. For futher details, ask at the Danish Energy Agency for project report J.nr. 51171/00-0016, or see WindPRO manual chapter 3.5.2. Use the table to evaluate if the given power curve is reasonable - if the check value are lower than -5%, the power curve probably is too optimistic due to uncertainty in power curve measurement.

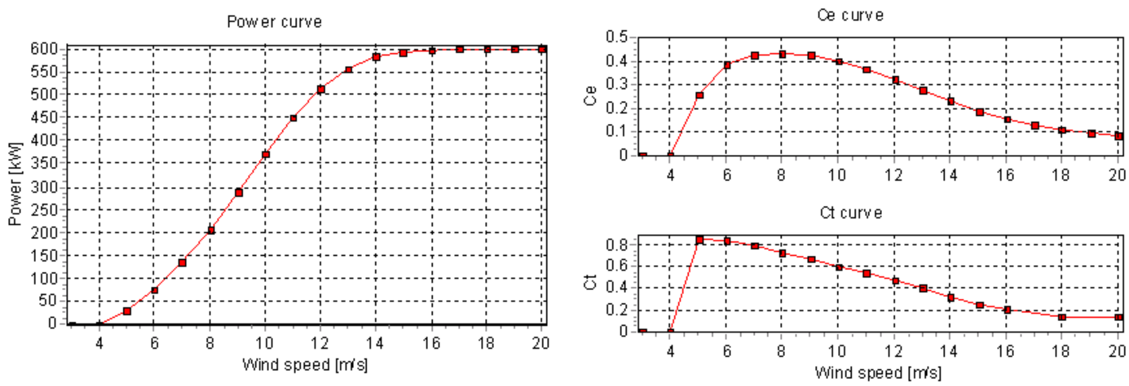


Figure 9 The V44 power curve has a pessimistic power curve according to HP-values + 6 at 7 m/s. But due to the single generator and the fact that the V44 only operates up to 20 m/s, the HP value should be high for this WTG. We estimate mainly based on case 08 Göteborg, where the WTG can be compared with others, that + 2 % is a reasonable value.

The 35 turbines in the project are manufactured by Vestas. The type is V44, with a rotor diameter of 44 m and hub height of 44 m. The turbine has one generator. The power curve is – according to HP-curves – a bit pessimistic, around 6% within the mean speed (7 m/s), where the WTGs operate. But while it is a 1-generator WTG, only operating up to 20 m/s (Where HP-corrections in general assume 2-generator operating up to 25 m/s), the + 6% is reduced to +2%.

Calculation results

With the data described in the previously chapter, the Energy production is calculated.
First the calculation is based on the "standard" wind statistic used for Denmark, next with a wind statistic based on a measurement mast 35 km away, where a selection of 89 days are taken based on the days where very reliable WTG production figures are available.

Calculation results follow in comparison with the actual normalised production data.

Calculation based on "standard" DK wind statistics and WDC 0.075

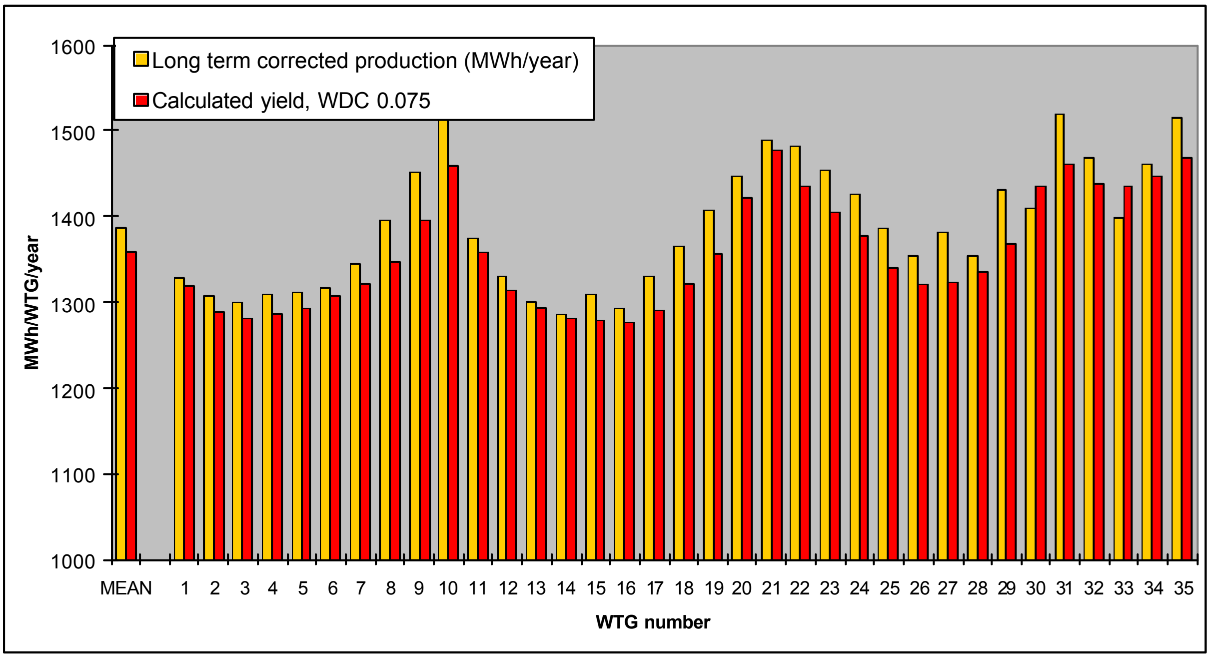


Figure 10 The "first shot" calculation simply hit the actual value. Calculation is 2 % lower than actual, before power curve correction. Power curve corrected with 2% add on to calculation, there will be exact match. So for the result as a whole the match cannot be expected better. Also the variations within the WTGs seem fairly well.

Variation of WDC –Standard DK wind statistic

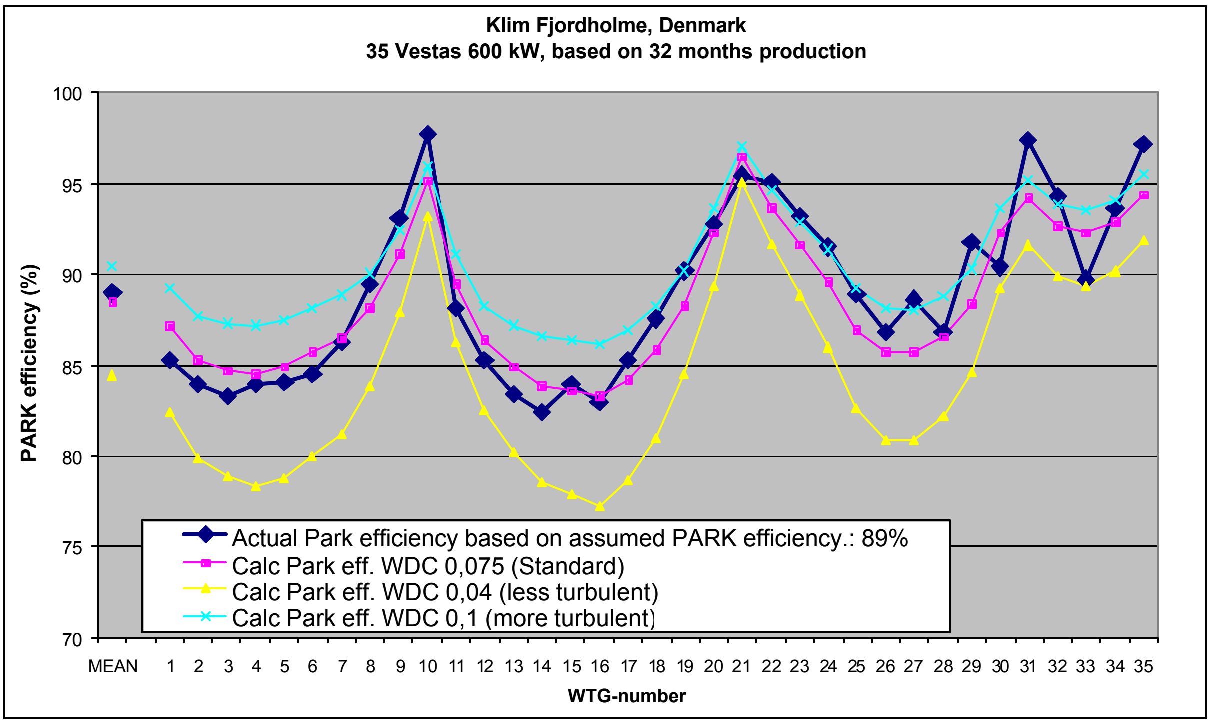


Figure 11 Varying the Wake Decay Constant (WDC) gives quite large changes. With WDC = 0.1 the PARK efficiency increase from 0.885 to 0.905 – 2 %. But at 0.04, which normally is recommended for offshore, the park efficiency decrease to 0.845, which is 4% lower than standard. From the figure above, it is difficult clearly to see what the correct value will be. We therefore continue with a shorter, but more reliable data period.

Calculation based on parallel selection of Wind and WTG production data

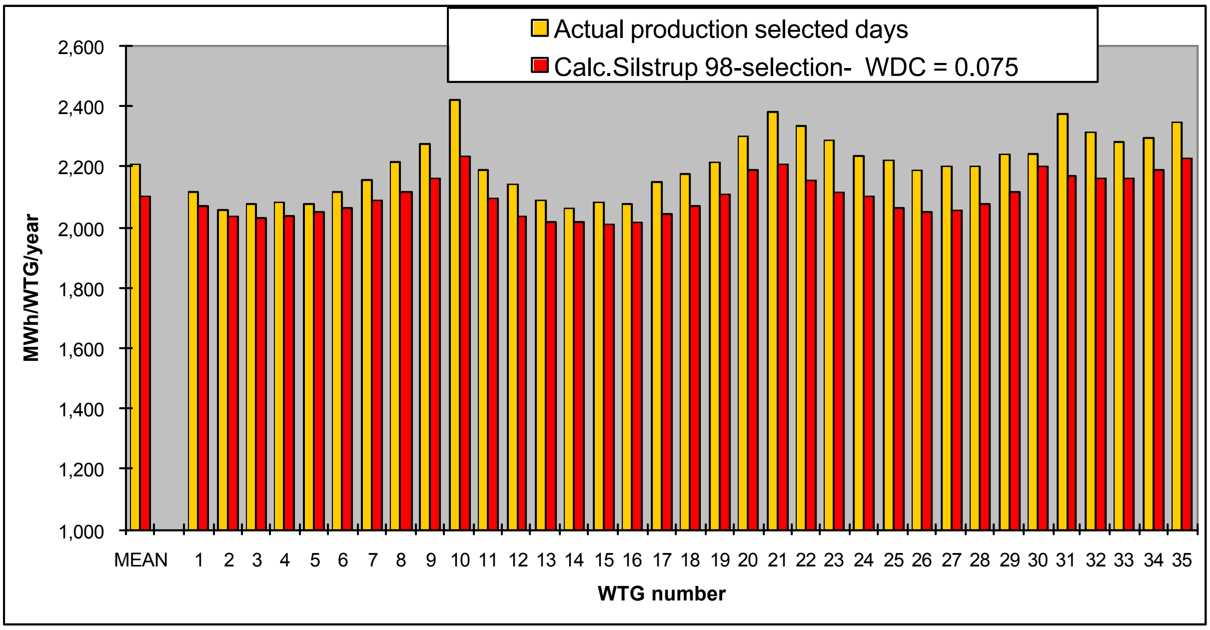
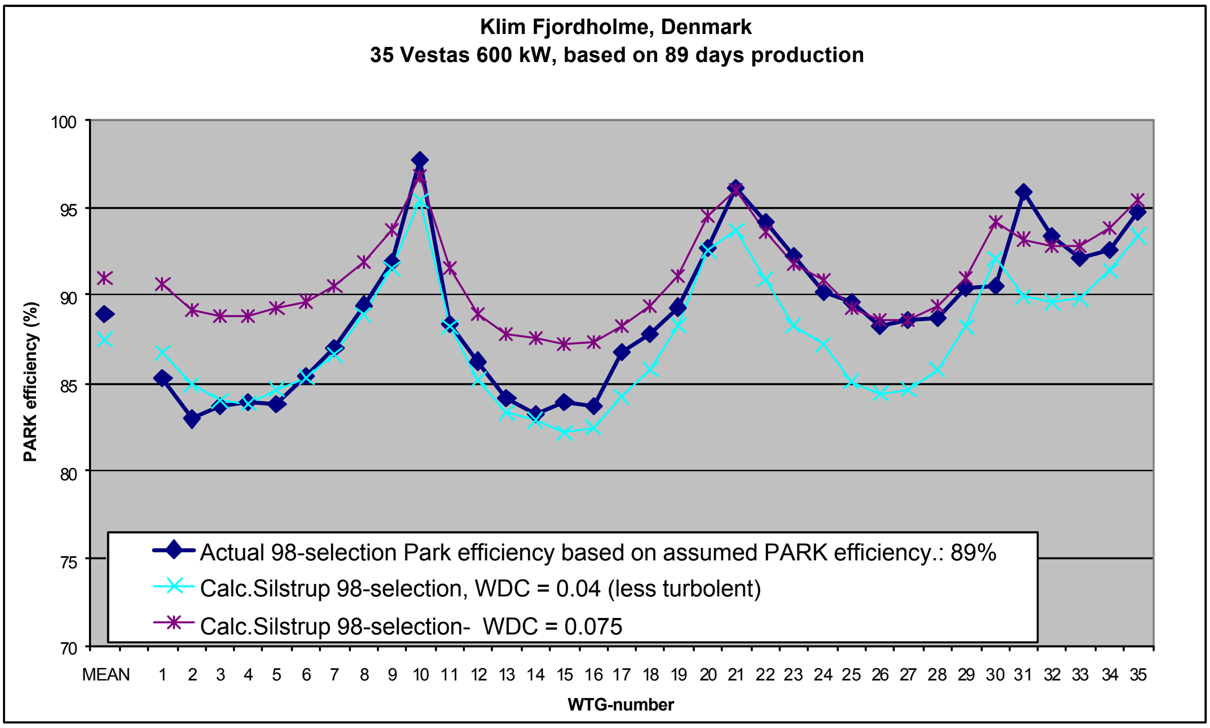


Figure 12 Here we see a much more "soft" set of graphs. But we also se a clear tendency in that the higher WTG number (more south-west), the higher production relative to calculation. To study this more cl ose, see nest figure.

Note that the calculated production is much higher than in previous calculation, this is due to the selection of the more windy days in 1998. But there is still good correlation between calculation with the 98 selection and actual wind data based on Silstrup. But do not put to much importance in the absolute values – the measured wind data are 35 km away in a region with relative high changes in geotrophic wind. The main task here is to look at the variations in-between the individual WTGs.



Here it seem quite clear, that at the northeastern rows (WTG 1-20), use of WDC = 0.04 match very well, while use of WDC = 0.075 mach very well at the southwest rows.

This is a surprising result. The main wind is from southwest, which means that the northeast WTGs most of the time are the back row, with most turbulence and therefore a higher WDC should be a better choice.

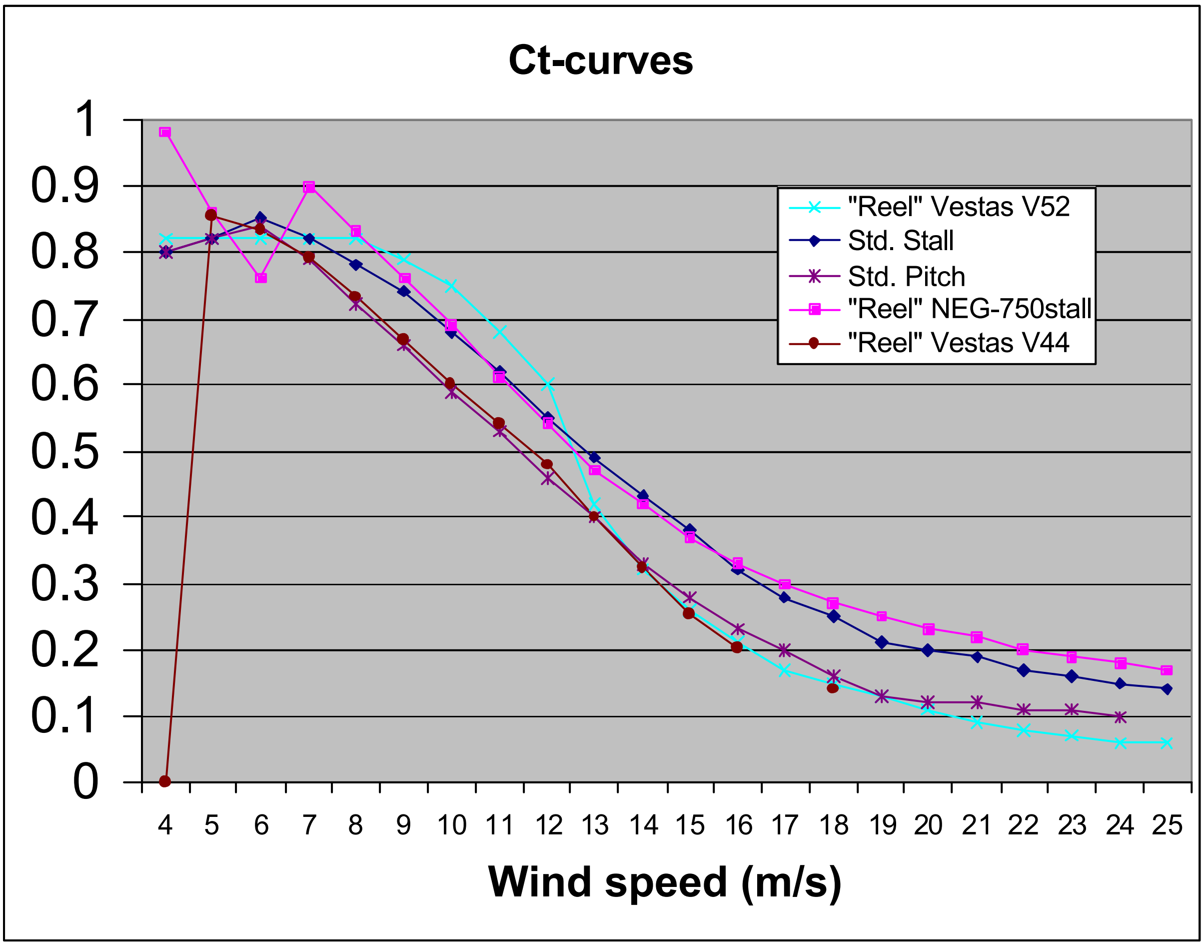
The explanation although speculative is probably that there is physics lacks in the PARK model. That the wind disturbed by the first rows holds less energy than the model predict – and by coincidence it just match lowering the WDC.

Main conclusion:

Actual production for the entire wind farm is calculated very accurate – but the interesting part in this case is how the differences among the individual WTGs production is relative to what the PARK-calculation show with different assumptions. We here have an almost "unique" test site, total flat and open. The findings are that a 0.075 Wake decay constant, as usually is assumed for "open land", work very well for the two front rows of WTGs in the main wind direction. Whereas 0.04, as normally is used for off shore (less turbulent wind, higher reduction) is the better value for the rows behind. This is very surprising, because the back rows should experience more turbulence. It looks like the PARK model do NOT work correct at large wind farms – some "large farm" effects seem not to be taken into consideration. This can have large influence on the calculations of large off shore wind farms.

Additional analyses – Ct curves

Having so good data for a large wind farm in very simple terrain, gives good opportunities to check the influence of the selection of Ct curves. Normally the selection is limited to a standard stall or standard pitch. But it has the recent years become more common, that actual calculated or measured Ct curves are used. Below we look at a few examples.



The "real" Vestas V44 is very close to the "Standard pitch" (which are found in the WindPRO WTG catalogue, and which is based on measurements back in the early 90'ties). But the V52 has much higher values for 8-12 m/s – even higher than the Stall curves.

The Standard Stall is compared with the NEG Micon 750 kW. These are almost identical, except from the region 4-8 m/s, where the 2-generator system makes the real curve toggle more.

When we bring in these curves in the calculation, following results appear.

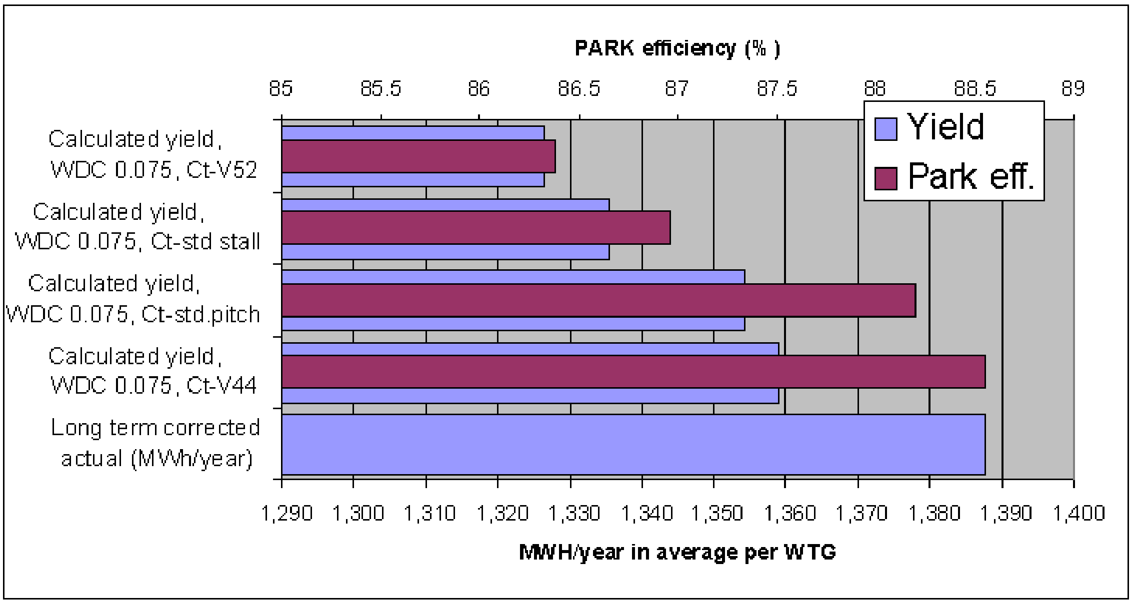


Figure 13 It is seen that the "real" V44 Ct curve perform best relative to actual production, but this can be a coincidence since the differences are very small, far below the uncertainties.

What is interesting to see is, that the V52 Ct gives calculated array losses that are even higher than the stall Ct curve. But we are talking of less than 1% and the total difference between highest and lowest calculated value are only 2.5% - at a wind farm with 35 WTGs with relatively close spacing.

Below we look at the individual WTGs with different Ct curves.

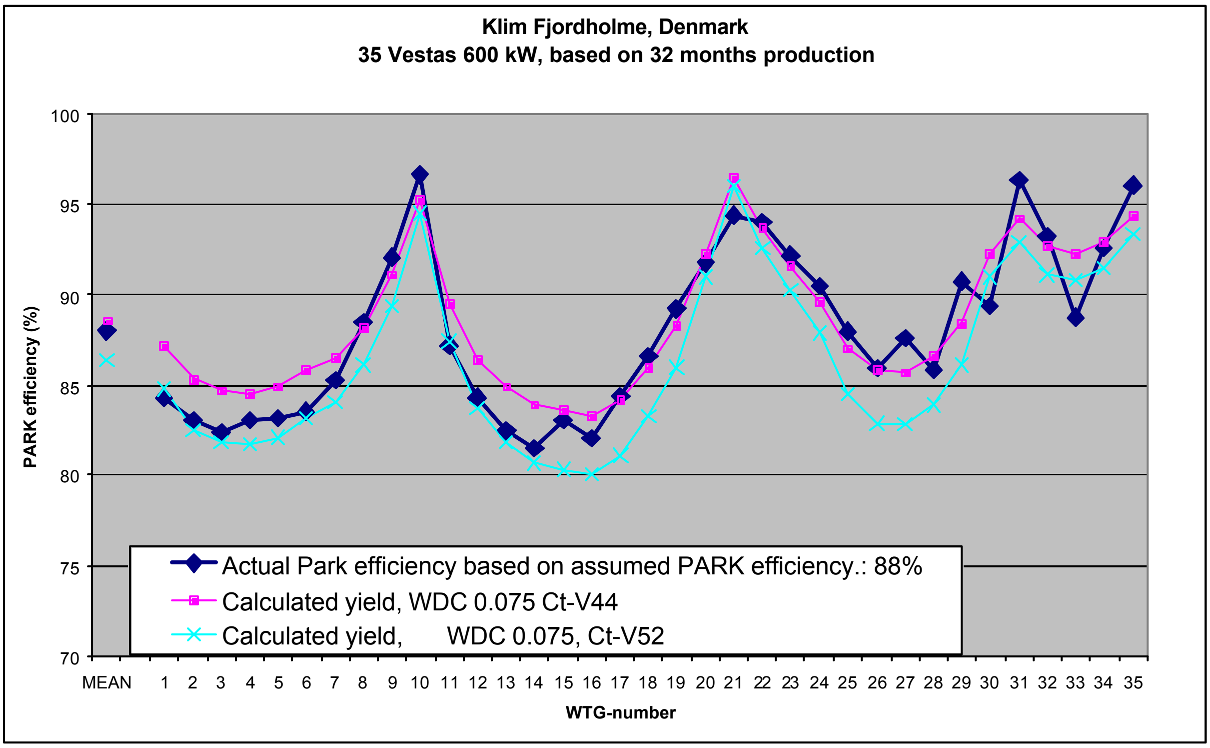


Figure 14 We se the same trends as by varying the WDC – the back rows, relative to main wind direction, WTG no. 1-20, follow the pattern from the most reducing Ct curves best, while the front rows relative to main wind direction follow the less reducing better.

If we turn the visualisation of the rows, and look at the northwestern 4 WTGs as row 1 etc. the pattern look so.

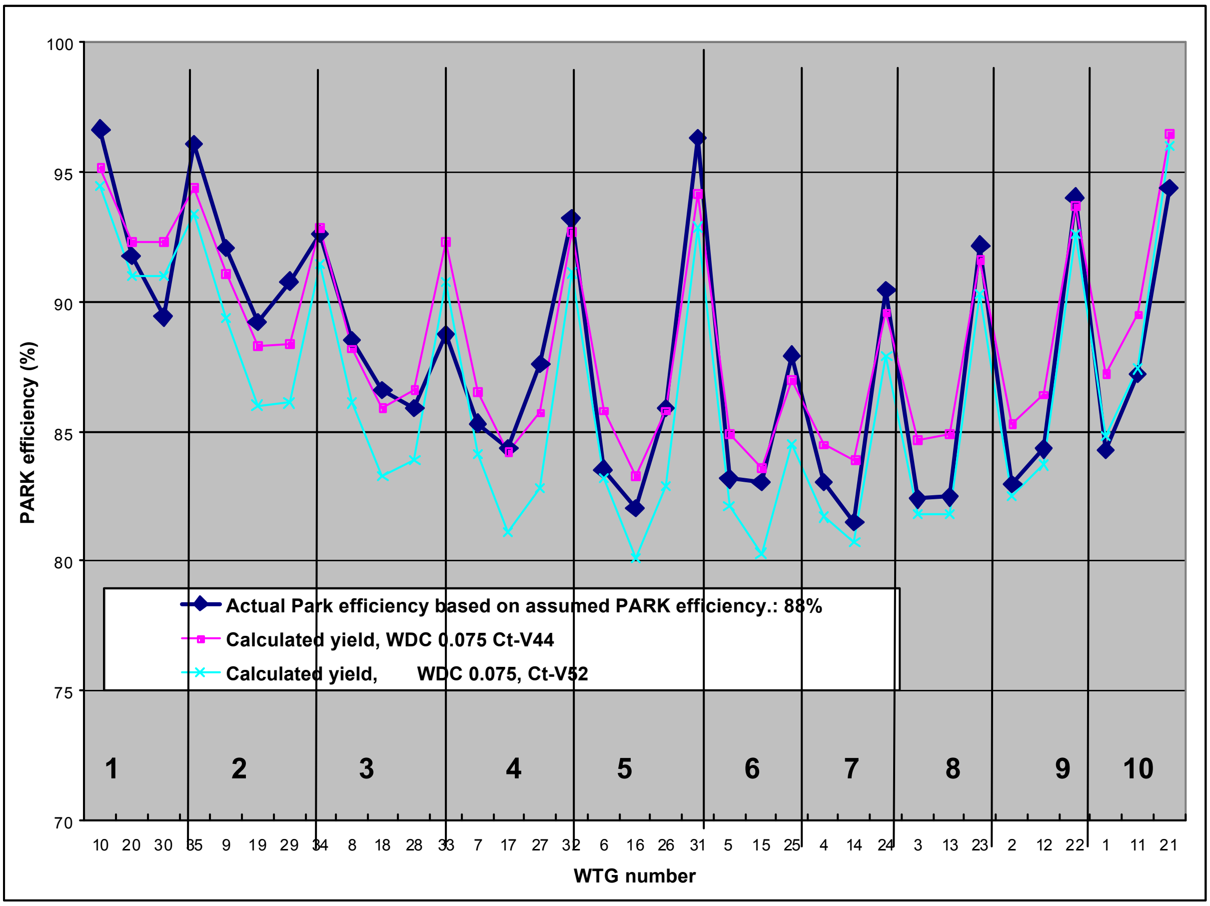


Figure 15 Here it is even clearer, that the back rows (assumed prevailing West-northwest wind) follow the most reducing Ct curve very well. Comparing to the below shown comparison by calculating with different WDC, we have to admit that adjusting the Ct value to a more reducing value gives a better match to actual production for the 5 eastern rows that adjusting the WDC.

So all in all, a combination of adjustments on WDC and Ct might give better match between actual and calculated values for the individual WTGs. But we still believe, that it is the calculation model, which has to be adjusted.

Additionally analyses – Windfarmer Eddy Viscosity wake model comparison

Finally, we have got a calculation using the Windfarmer tool from Garrad Hassan, which can operate with more different models, where the "Eddy Viscosity" model is said to be more precise. This we have tested on the Klim case with the 1998 data selection.

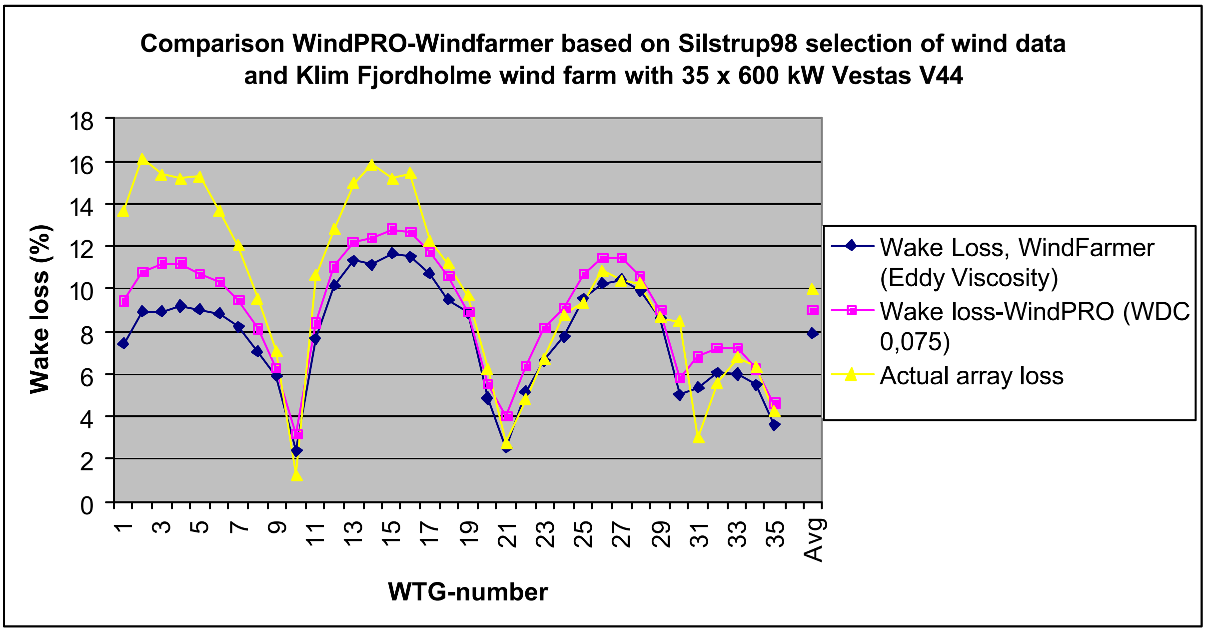


Figure 16 The Eddy Viscosity model in the standard set up perform poorer than the N. O. Jensen model (used in WindPRO and WAsP) in standard set-up based on the Klim test data. It calculates 1percent point less losses than WindPRO, where it is obvious that the real losses is higher eventhoug the wake losses not can be measured direct, the patterns gives a quite good idea. If the loss level were decreased 1 percent point, WTG 10 would have no Wake loss at all.

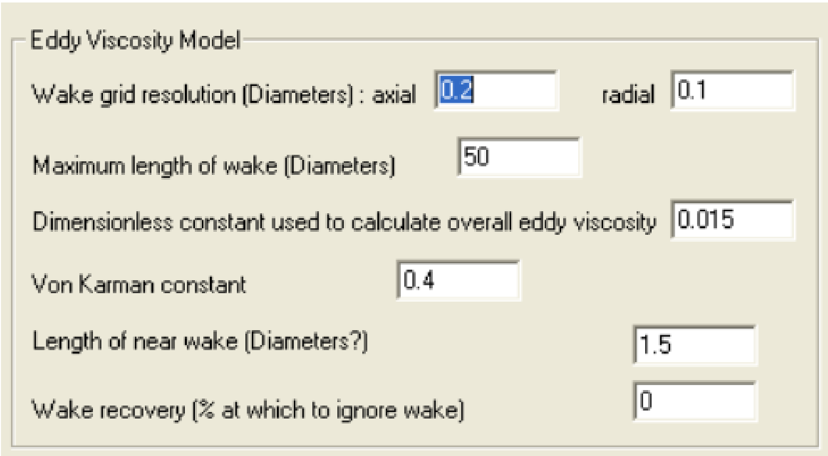


Figure 17 The used set-up of the Eddy Viscosity model in Windfarmer. No parameter variations have been tested within this model.

Data delivery and acknowledgements

Thanks to Vestas and Nordjyllandsværket (Power plant for Northern Jutland which own and operate the wind farm) for being very helpful and for delivering data.

Thanks to Kevin Romuld, EAPC, North Dakota for helping with Windfarmer calculations for comparison.