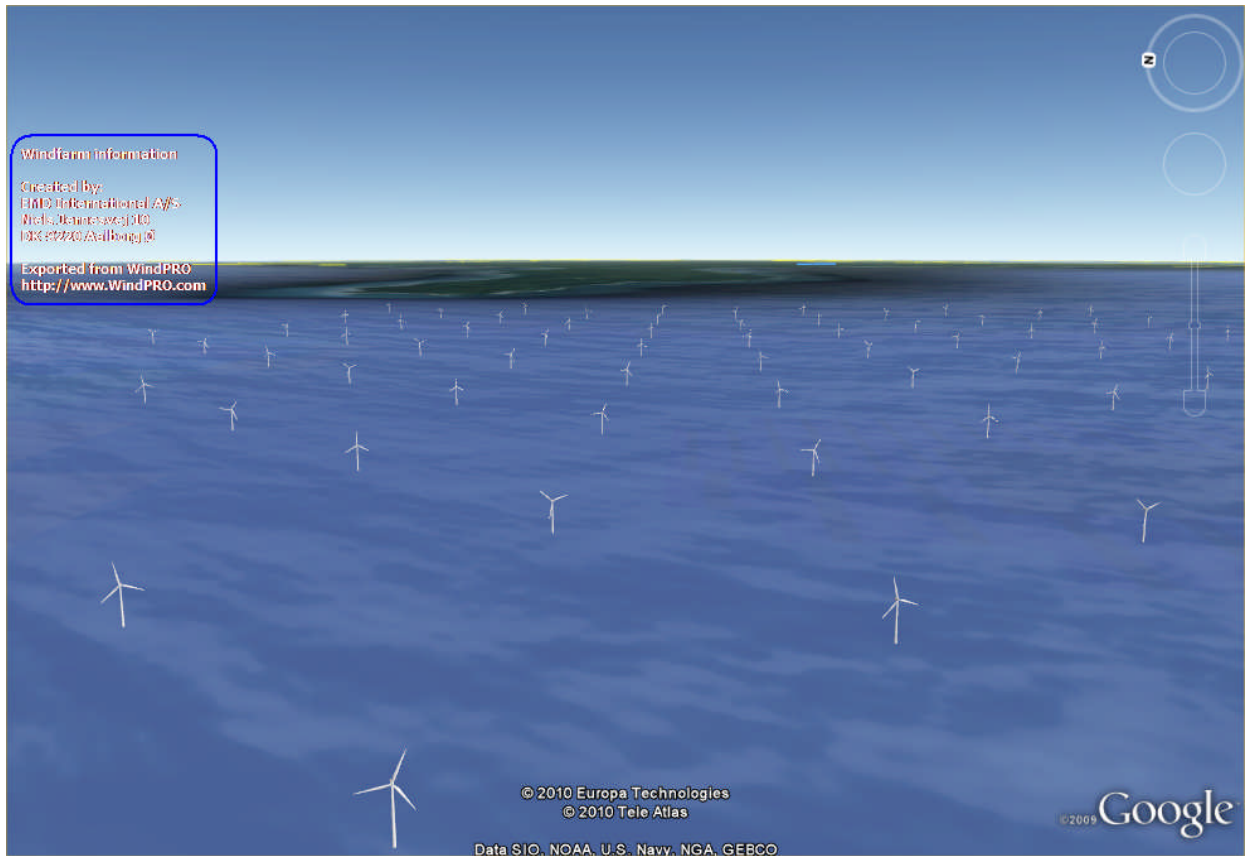


## Hiiumaa offshore wind farm, Estonia

EMD International A/S  
www.emd.dk



## TURBULENCE IMPACT ASSESSMENT



Client:	EMD:	Date: 6/9-2010
OÜ Nelja Energia	Project Manager: (Signature)	Thomas Sørensen, EMD-DK
Estonia pst. 1/3 10143 Tallinn	Checked by: (Signature)	Morten Thøgersen, EMD-DK
Att: Hannes Agabus	Document:	Hiiumaa turbulence impact EMD_kb_mlt_4.docx
	Edition	4

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Front cover page: Google Earth view from south western part of the wind farm towards Ristna.

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## ***Executive summary***

EMD has calculated the expected impact of turbulence on the coast of Hiiumaa.

The results are calculated for a typical layout of the wind farm, where results are obtained from the expected maximum number of turbines. The turbulence is calculated for 8 m/s at 10 m height on the offshore locations as this is considered a realistic regime for the operation of the turbines on this location and for sailors, paragliders, kitesurfers etc.

The presentation of the results is made in the form of maps showing the extent and magnitude of the turbulence from the turbines, and compares it to the turbulence on the coast itself.

The average turbulence intensity offshore has at Hiiumaa been measured to be 6%. The maximum turbulence contribution from a single turbine at 10 m height (and 8 m/s) is 12,8% calculated at a location directly 200 m behind a single turbine. The highest value found in any of the grid cells (calculated with a 500 m grid spacing) from the entire wind farm is 10,5%. That no higher turbulence is calculated for the entire wind farm is due to the narrowness of the high turbulence field and the spacing of 500 m between each calculation point. The very high turbulence situations are very rare. Any recognisable influence has not been found beyond 1800 m from the turbines.

By comparison the turbulence intensity on inland locations extent to 24% and the turbulence intensity when the wind direction is from land is regularly calculated to over 7% on a location located 10 km from the coast and 9,5% for locations at about 1,5 km from the coast.

Beyond a few hundred meters from the turbines the turbulence impact from the wind turbines is therefore negligible compared to turbulence from land.

The reduction of wind speeds has been examined as well. The wind speed loss extend further than the turbulence impact. At the perimeter of the wind farm (700 m from closest turbine) the wind speed loss is up to 30% in the direction of the turbines. 4 km away on the Ristna peninsula the wind speed is reduced up to 11% in the direction of the closest wind turbine.



# 1. Introduction

4Energia has requested EMD International A/S to conduct a study on the turbulence impact from the wind farm. In addition the wind speed loss in the wake of the wind farm is examined.

Some sailors and other recreational users of the coast of Hiiumaa consider increased turbulence levels to be a potential problem.

# 2. Site and locations

The Hiiumaa offshore wind farm is located off the coast of the island of Hiiumaa. The locations of the wind farm sections are shown in Figure 1. The actual turbine locations and turbine type may not be the precise final type and location, but the selected layout for this study is a typical scenario with a large number of turbines. Different turbine types will not dramatically change the result and conclusions drawn from this study.

The total size of the wind farm in this layout is 636 MW, distributed on 212 units. The turbine type used in this calculation is a Vestas V90-3,0, which has a nominal power of 3 MW, rotor diameter of 90 m and a hub height of 80m.

Technical specifications on this turbine type can be found in appendix A.

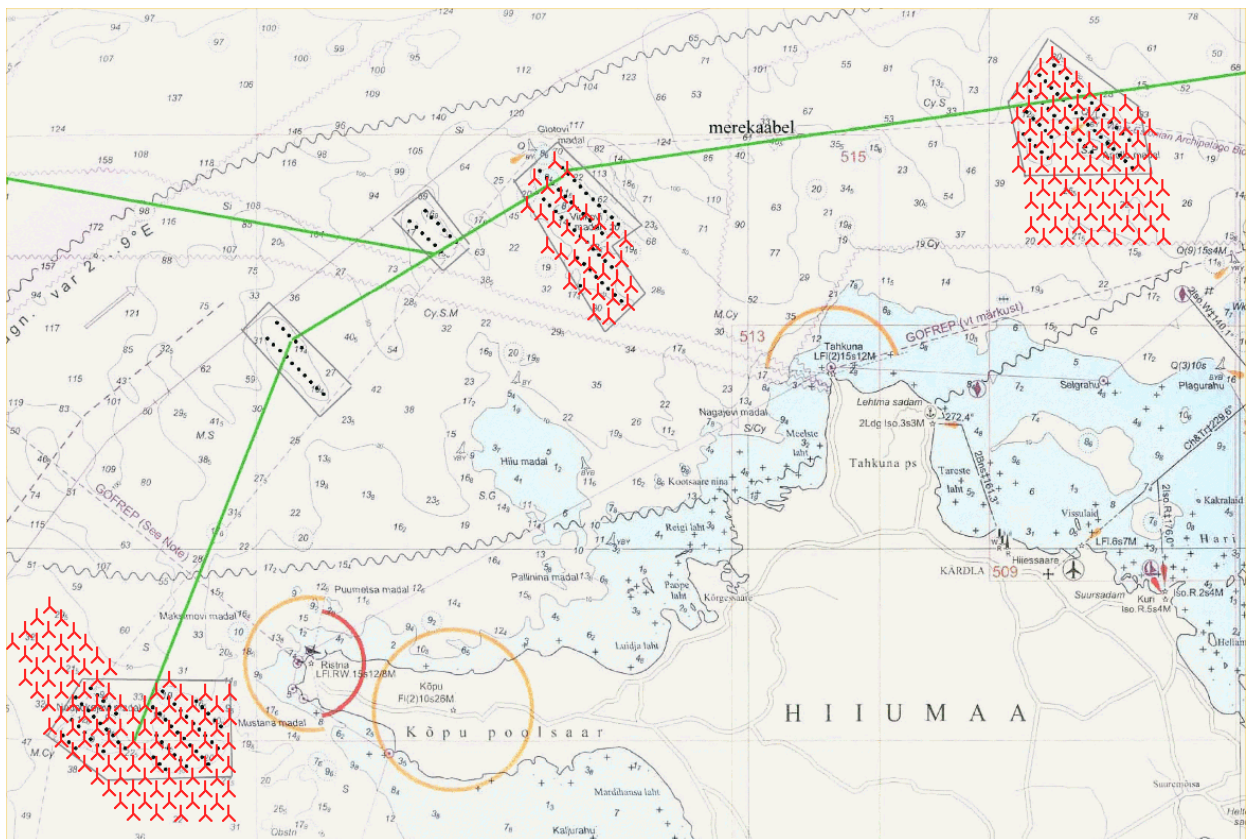


Figure 1. Map of Hiiumaa offshore wind farm. Red symbols mark the layout of the current study. The black dots and boundaries mark locations not relevant for the current project.

### 3. The calculation method (Turbulence)

#### 3.1. Turbulence intensity

Turbulence is the fluctuations in wind speed. The more extreme the wind speed changes, the higher the turbulence. Some turbulence is felt as quick, soft changes. These are small scale and typically caused by small elements in the terrain and while they are fast they also quickly disappear. The big gusts we experience in the wind are large scale gusts. They typically originate from meteorological phenomena or very large terrain elements like mountains and the like. As they lose energy they become smaller and smaller in scale. Figure 2. Example of turbulence on many scales (MIT Open Courseware). show examples of turbulence of different scale.

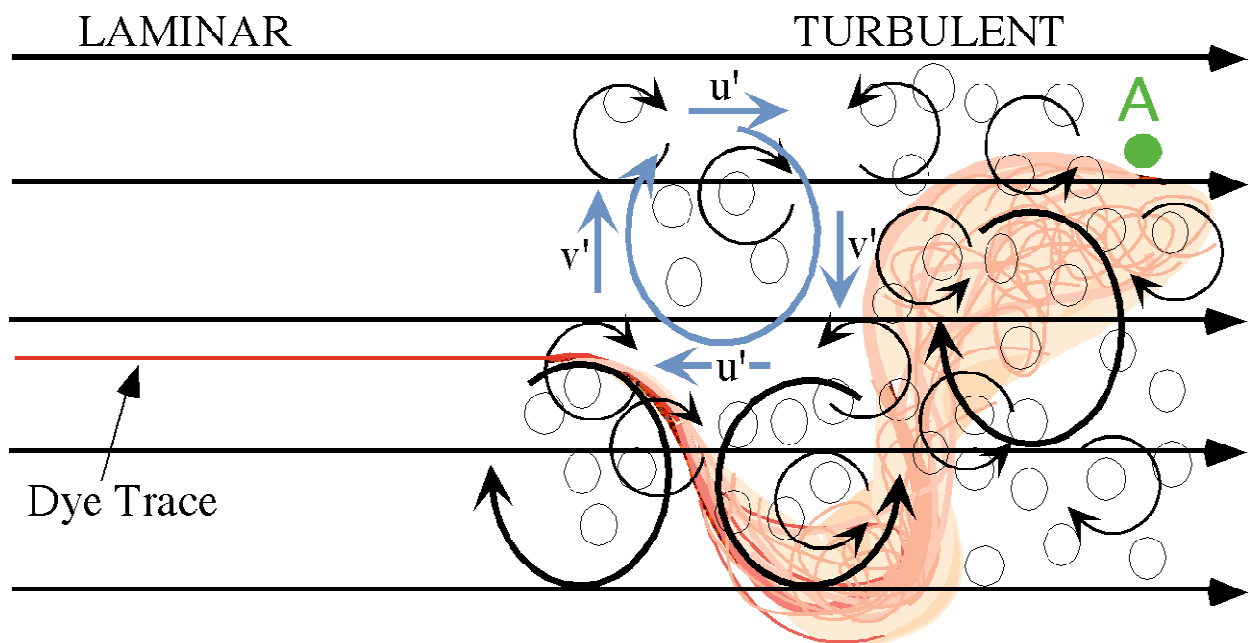


Figure 2. Example of turbulence on many scales (MIT Open Courseware).

Turbulence is often (and in this study) described by the turbulence intensity. This is given by:

$$TI = \frac{\sigma_{10min}}{U_{10min}}$$

Where  $\sigma_{10min}$  is the standard deviation of the wind speed during 10 minutes and  $U$  is the mean wind speed during 10 minutes. In other terms the turbulence intensity is the ratio of the wind speed changes to the mean wind speed. This ratio is given in percentage. For a standard atmosphere it is commonly known that the standard deviation is unchanged with height, but that the wind speed increases with height resulting in lower turbulence intensity at high altitude. Choosing a low height is therefore likely to give a higher turbulence.

Turbulence is very much dependent on the kind of terrain of the ground. Sea surface causes little turbulence whereas forest creates high turbulence. High turbulence requires a long distance to dissipate; therefore wind coming from a forested coast may stay turbulent far offshore.

There are two types of turbulence: Ambient turbulence and wake added turbulence.

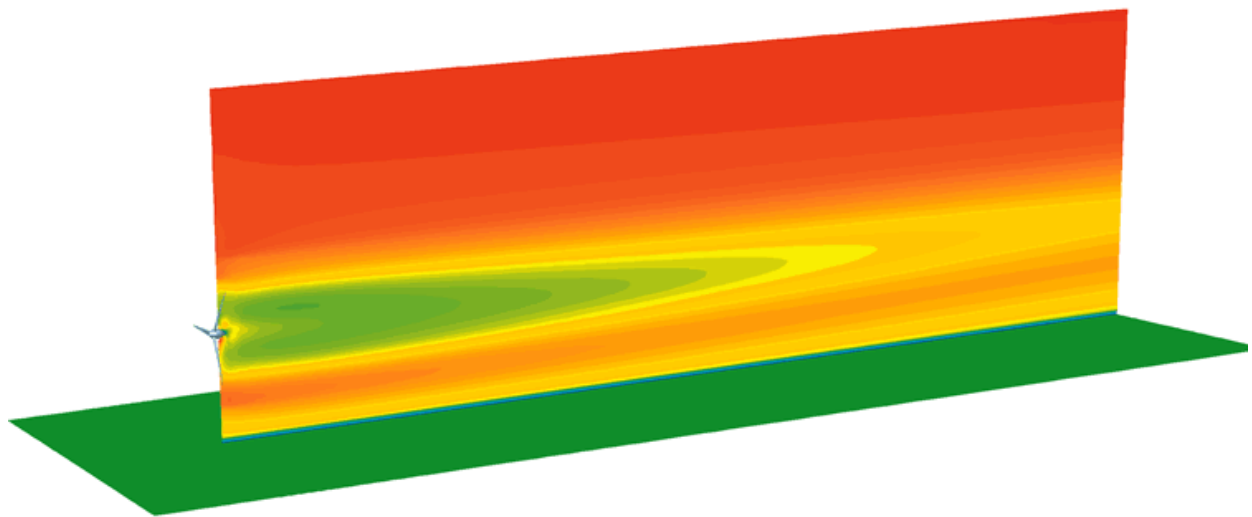


The first is the turbulence already there on the site. 4Energia has measured this turbulence offshore with a turbulence intensity of 5% at 96 m corresponding to 6% at 10 m height. On land this turbulence increases to typically 24%.

Natural turbulence has a very wide range of spectral size, from tiny wavelets to kilometre size gusts. Natural turbulence therefore feels very uneven and unpredictable.

### 3.2. The wake of wind turbines

The wake added turbulence is the turbulence caused by the wind turbines stirring the wind. When the turbine takes out energy from the wind it leaves behind a wake of reduced wind speed (Figure 3) and increased turbulence. This has a shape as a fan that gradually widens and dissipates. While the core of the turbulence remains at hub height the turbulence will not be so different near the ground. Downwind it is recognizable up to 2000 m, but the decrease is fastest in the beginning shortly behind the turbine. As such, the wind speed deficits and the wake turbulence is largest directly behind the turbine, and is decreasing along with the further distance downstream from the turbine.



**Figure 3. Modelling the wake behind a wind turbine with software (FLUENT) shows the low wind speed wake that gradually fills up behind the turbine. (Hahm and Kröning, ANSYS).**

The turbulence in the wake of the wind turbine has in the beginning a rotational component and a scale defined by the rotor diameter. Shortly downwind however the rotational part is not recognizable from the natural chaotic direction changes in the ambient wind, only the intensity is higher as illustrated later in Figure 10.

Turbulence from turbines has a fairly short spectral size and is quite predictable as they follow the circular motion of the rotor. High turbulence intensity from a wind turbine is therefore much less likely to have the violent spikes of natural turbulence.

The following figures illustrate the turbulence behind a single wind turbine, in this case a Vestas V90 with 80 m hub height. Please note for reference that turbulence above a forest has a turbulence intensity at low height of around 25% and at sea the ambient turbulence intensity is around 6%. Here is used 6% at 10 m height.

The figures show the fan of turbulence at different distances (200m – 2000m) and at different heights.

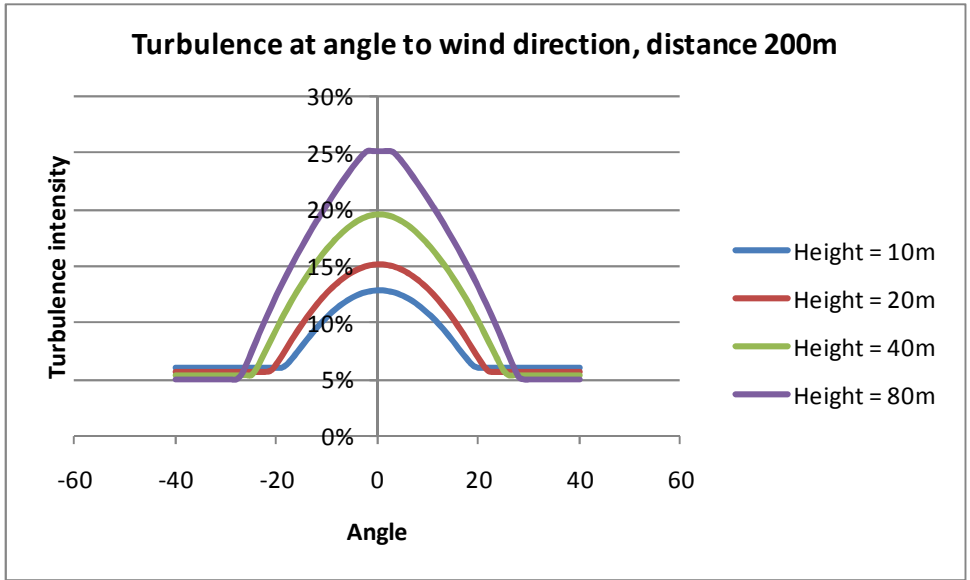


Figure 4. The turbulence fan 200 m behind the turbine.

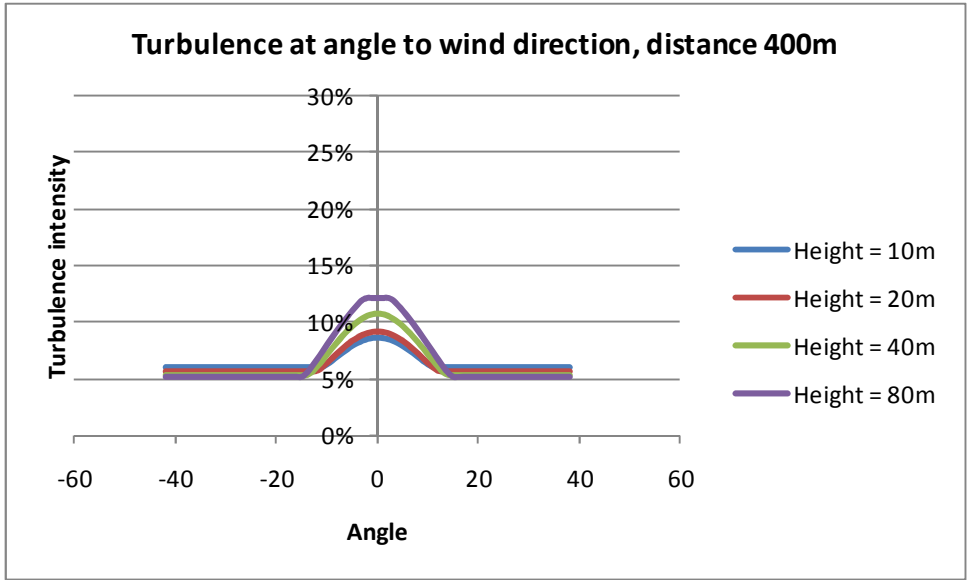


Figure 5. The turbulence fan 400 m behind the turbine.

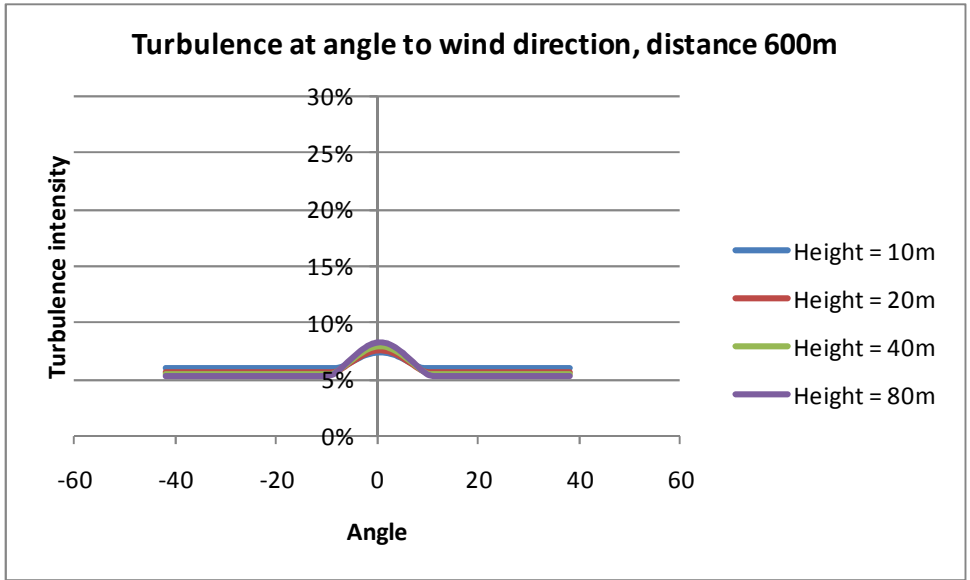


Figure 6. The turbulence fan 600 m behind the turbine.

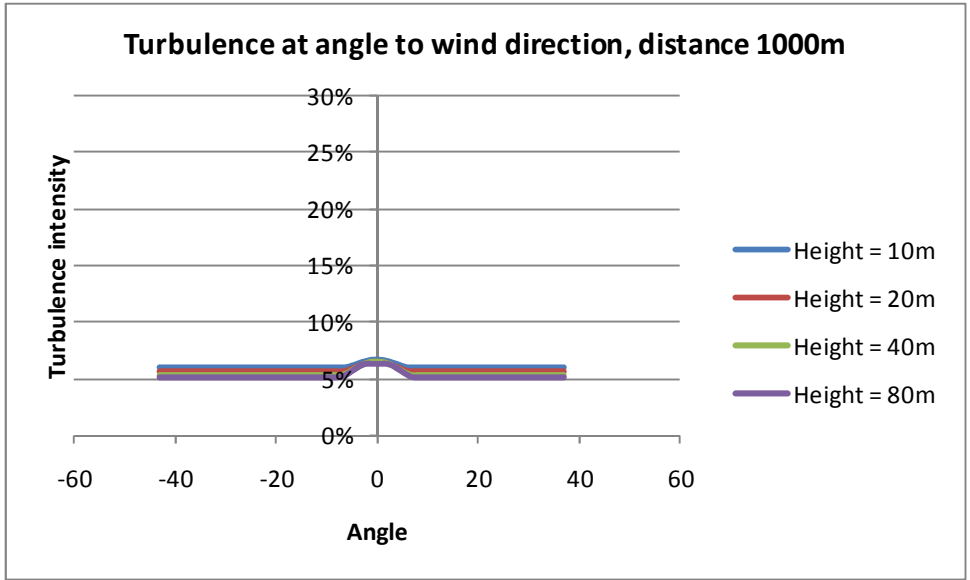
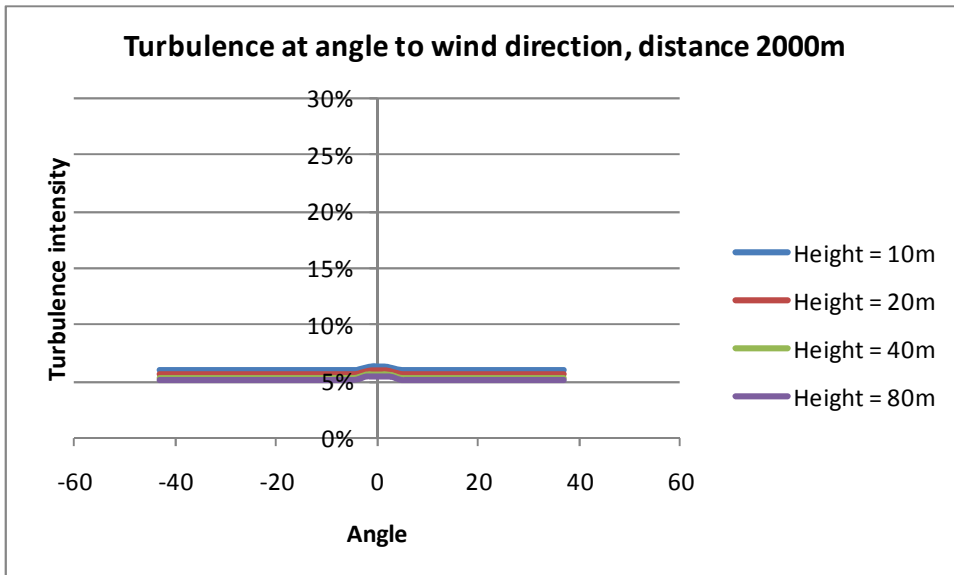


Figure 7. The turbulence fan 1000 m behind the turbine.





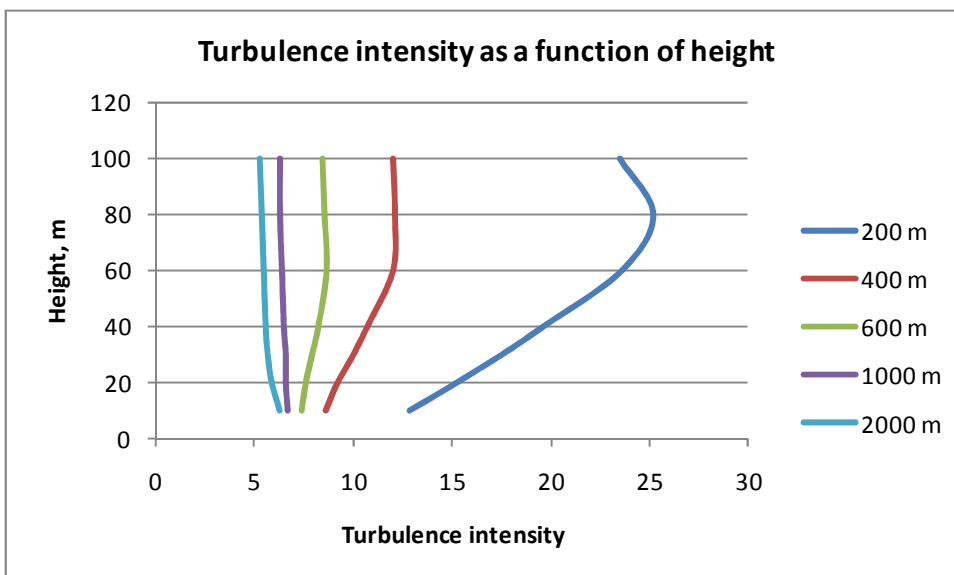
**Figure 8. The turbulence fan 2000 m behind the turbine.**

At 200 m distance from the turbine the turbulence at hub height (80 m) is similar to the turbulence above a forest, but only directly downwind from the wind turbine. At an angle of 30 degrees the turbulence has disappeared.

At 10m height the turbulence at 200m distance is reduced to 12,8%.

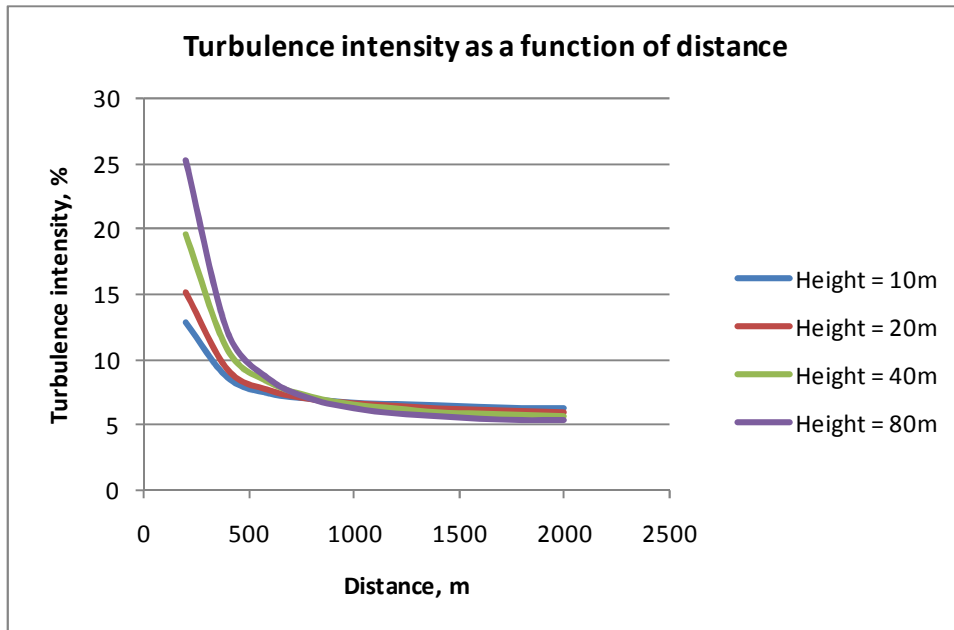
Downwind the turbulence dissipates until it is unrecognizable at 2000m.

If we look at maximum turbulence as a function of height and distance (Figure 9), then we can see a rapidly increasing turbulence with height at 200m, while at 1000 meters this is back to a decreasing turbulence with height.



**Figure 9. Turbulence as a function of height.**

Finally Figure 10 shows the decrease of turbulence with distance from a wind turbine. Here we can clearly see the rapid dissipation of the turbulence with distance. Little remains for some distance however after 1000 m the influence is negligible.



**Figure 10. Turbulence downwind from a wind turbine.**

In a wind farm there is a cumulative effect which will be examined later, but from above figure it is clear that with turbine spacing of no less than 700m very little turbulence carry over from one turbine to the next.

### 3.3. Calculation method.

The current study calculates the impact for sailors and paragliders. A typical reference height for both would be 10m or 20m. As shown above the turbulence close to the wind farm will increase with height, while turbulence at a distance will actually decrease with height.

A reference wind speed of 8 m/s at 10 m height is selected. This corresponds to the typical operational wind speed of the turbine and is a wind speed relevant for the recreational users. At low wind speed the turbulence has no detrimental effect and the turbines are indeed not even in operation at low wind speed. At higher wind speed the recreational activity is likely limited and the hazard will anyway not be from the turbines.

Ambient and wake added turbulence are calculated in two different ways.

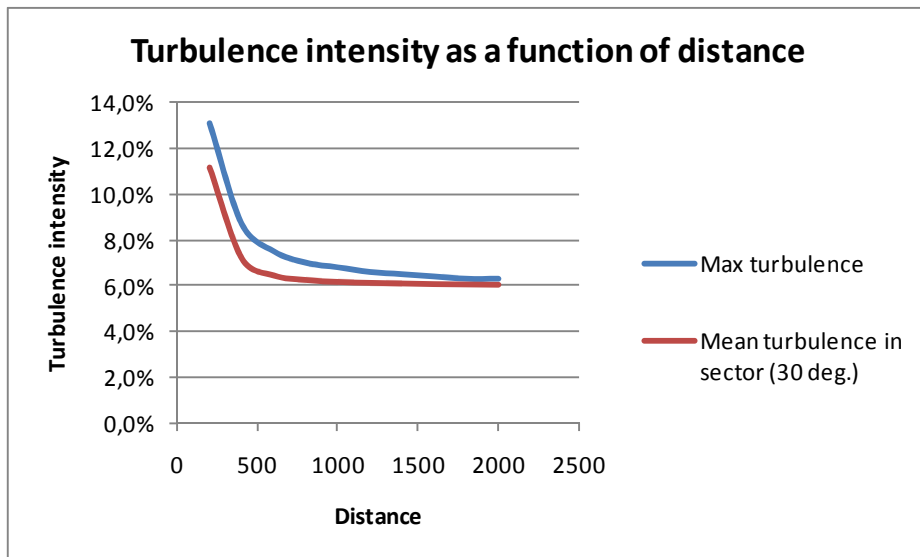
The ambient turbulence is calculated with the software WASP Engineering from Risø. This software is able to model the turbulence caused by the terrain (the ambient turbulence) then it is not suitable for calculating the wake added turbulence contribution from the turbines. Additionally, another limitation with this model is a boundary problem meaning that when the wind direction is from sea to land the software is failing to correctly calculate the turbulence offshore resulting in unrealistic values. For this reason in the case of on-shore wind the turbulence on land is abandoned.

A grid is devised along the coast of Hiiumaa with a spacing of 500 m and the ambient turbulence is calculated for 12 wind directions based on a reference wind speed of 8 m/s at 10 m height offshore. Input for the calculation is height contours and roughness of the terrain.

Further offshore the ambient turbulence is considered basically uniform except for the decrease of wind speed near the coast that leads to higher turbulence intensity.

The turbulence from the wind turbines is calculated with the software WindPRO from EMD. The turbulence model used is the Dutch TNO model (ECN, 1998), which studies have shown to be quite accurate.

While the WindPRO software can calculate the turbulence intensity in dense enough direction steps to catch the maximum turbulence (10 degrees), WAsP Engineering only calculates in 30 degree sectors and the turbulence intensity is a mean of those 30 degrees. As shown in the Figure 4 to Figure 8 then the turbulence in the wake behind turbines is very focused and the mean turbulence may therefore be somewhat less than the max turbulence. A comparison of mean and max turbulence is presented in Figure 11.



**Figure 11. Turbulence intensity as a function of distance from a Vestas V90-3.0 wind turbine. Comparison between mean and max turbulence over a 30 degree sector.**

In the following the average and max turbulence intensity per sector is used for the presentations.

A grid is devised to map the extent of the wake added turbulence offshore. Near the wind farm segments a grid spacing of 500 m is used, while for the large areas in between a less dense net with a spacing of 1500 m is used (Figure 12)

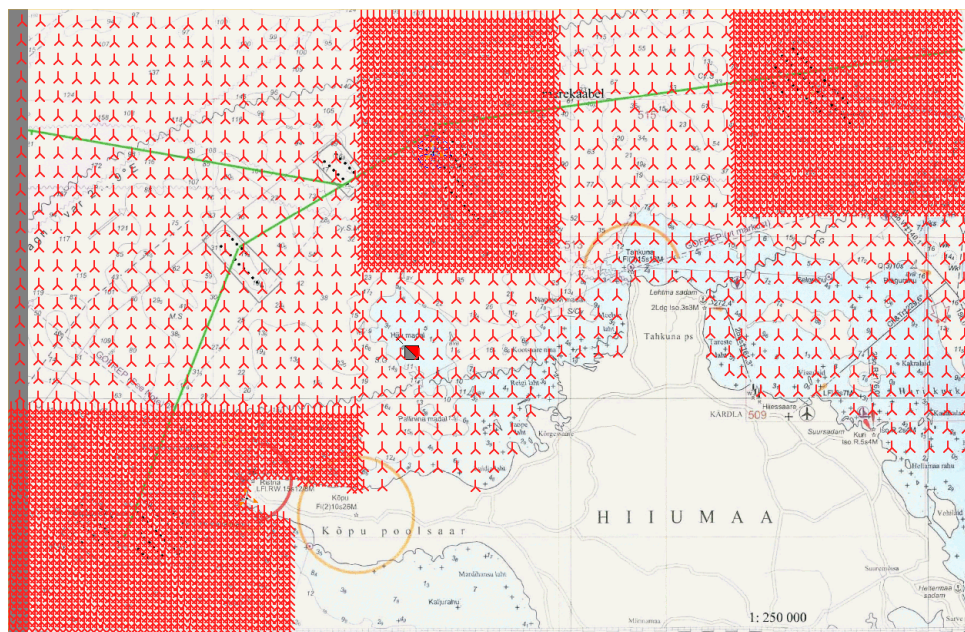


Figure 12. Definition of grid for calculation of wake turbulence.

#### 4. Presentation of results

The calculated turbulence intensity grid from WASP Engineering and the wake turbulence with fixed ambient turbulence grid were combined in WindPRO to create mappings the total turbulence levels in the area. The boundary condition problem described above however meant that the boundary between the two maps became rather sharp. Also it was not possible – due to model limitations - to make meaningful turbulence maps on Hiiumaa itself when the wind is coming from the sea.

The first map shows the mean turbulence intensity for sector 4 (southeast). The turbulence changes from 6% offshore to 24% onshore, a change that is of a magnitude that the influence from the wind turbines entirely disappears. Therefore in the following maps all turbulence above 15% is simply shown as red colour.

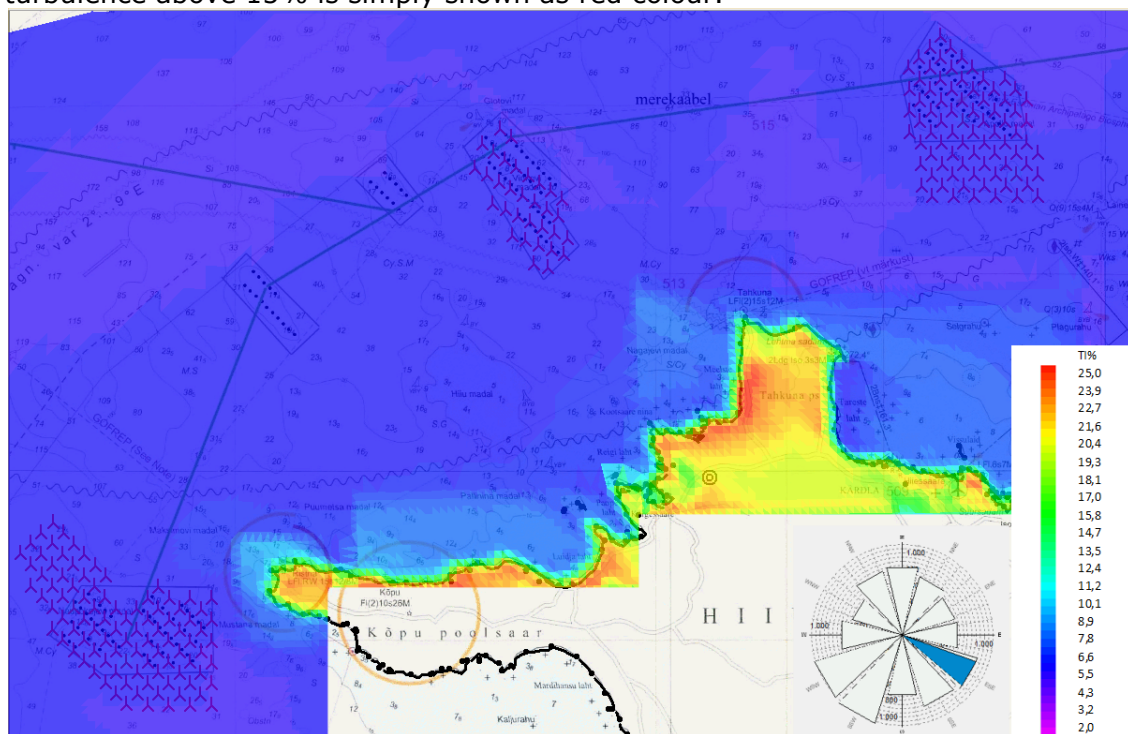
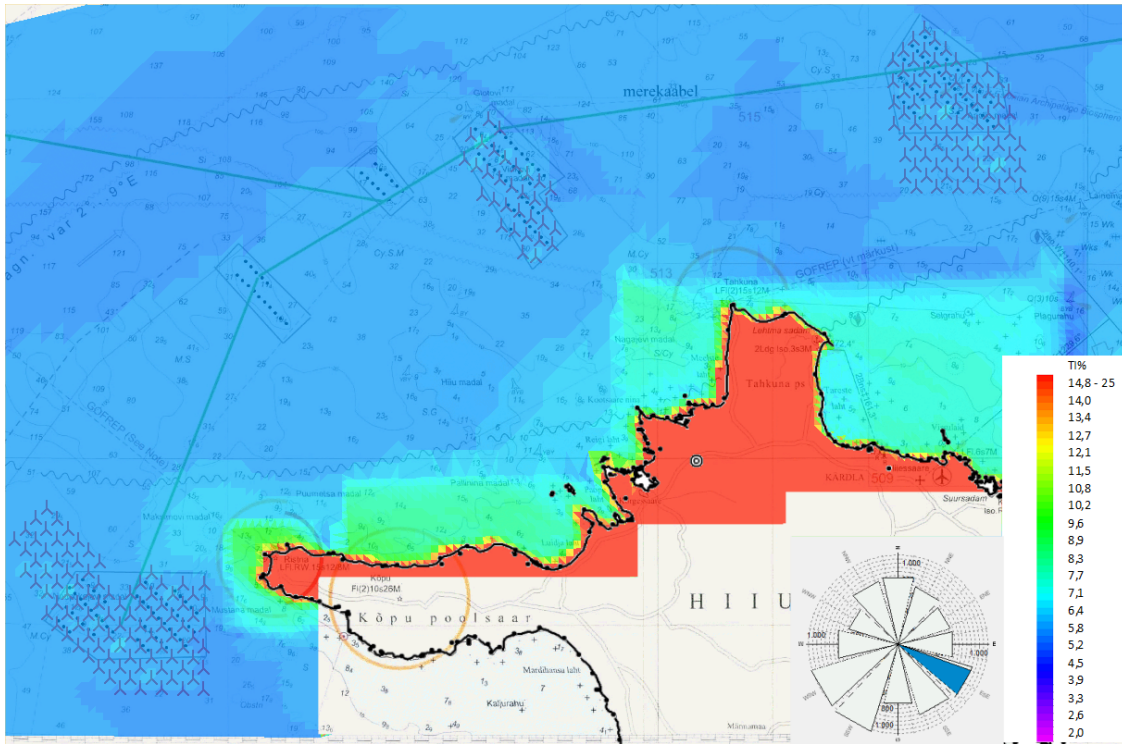


Figure 13. Mean turbulence intensity calculated for sector 4 (southeast). The full range of turbulence intensity means that the influence from the turbines is not visible in this view.

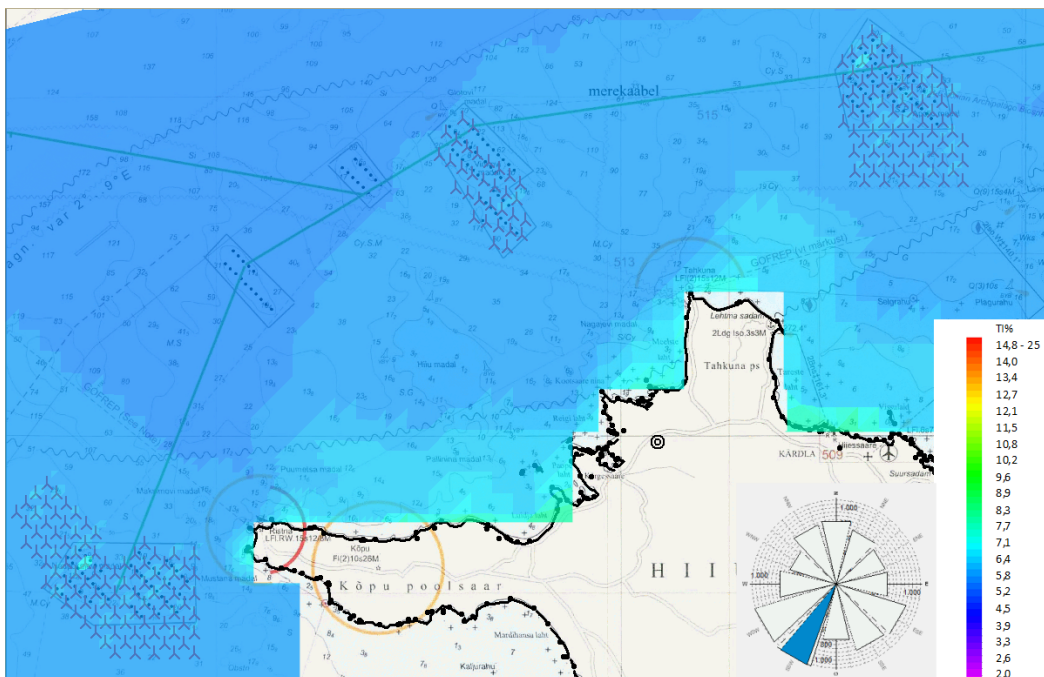




**Figure 14.** Same map as in previous figure, but with a cap in turbulence at 15%. The influence of the turbines is now barely visible. The map gives the mean 30 degree turbulence.

At 10 m above ground the turbulence on land totally exceeds the wake turbulence. The turbulence is also carried to sea so that the coastal regions are influenced by much more turbulent conditions in the ambient wind from land than they get from the turbines.

The interesting situation however is when the wind comes from the sea towards land. The following figures show sector 7 and 8 (southwest and west) both as mean turbulence and peak (maximum) turbulence. In this view we have not added any contribution from the island itself.



**Figure 15.** Mean (30 degree) turbulence when the wind is from sector 7.

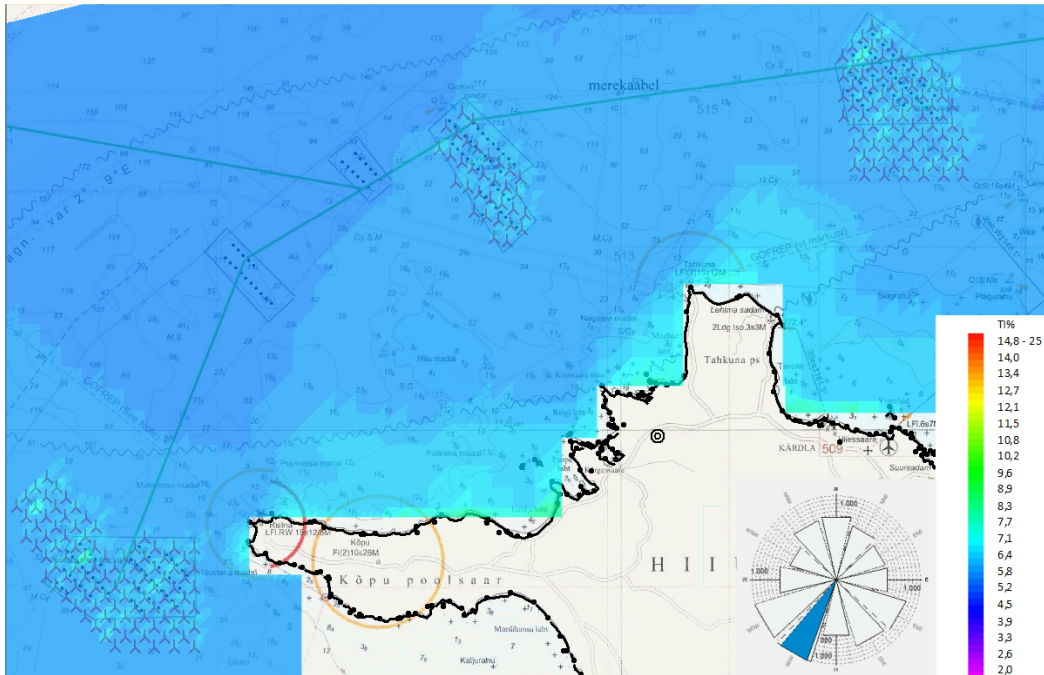


Figure 16. Peak (maximum) turbulence when the wind is from sector 7.

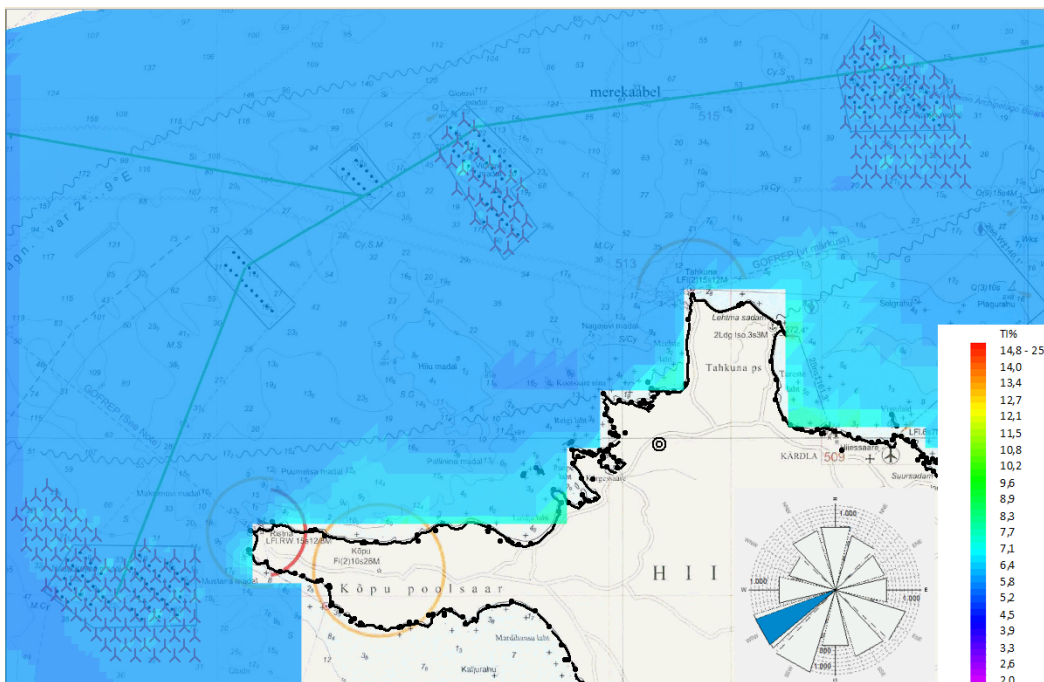
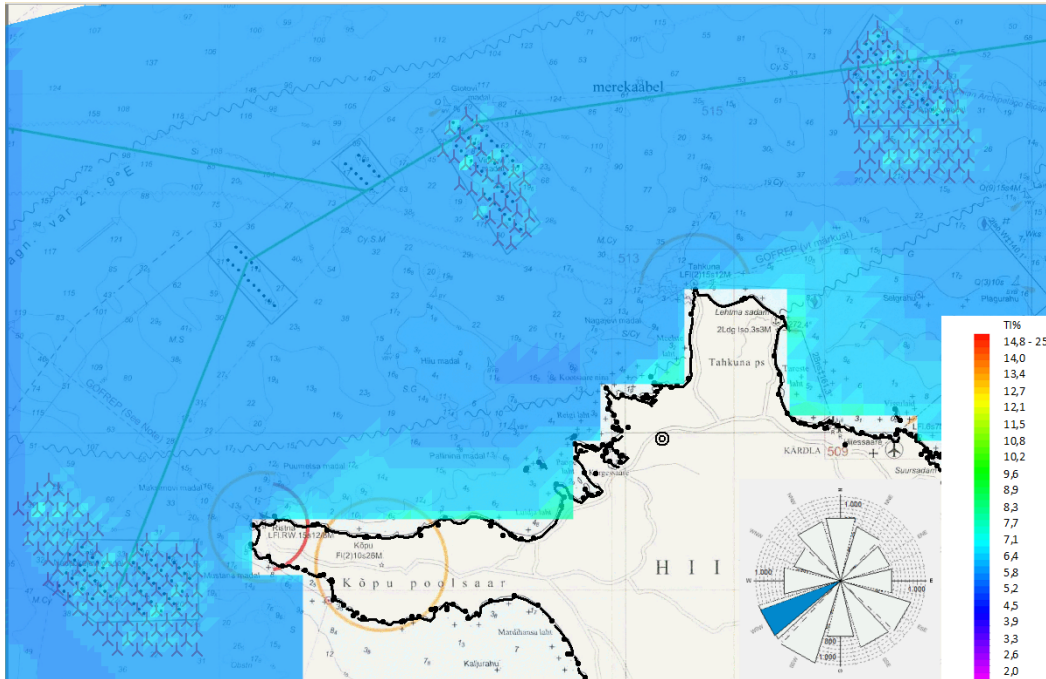


Figure 17. Mean (30 degree) turbulence when the wind is from sector 8.

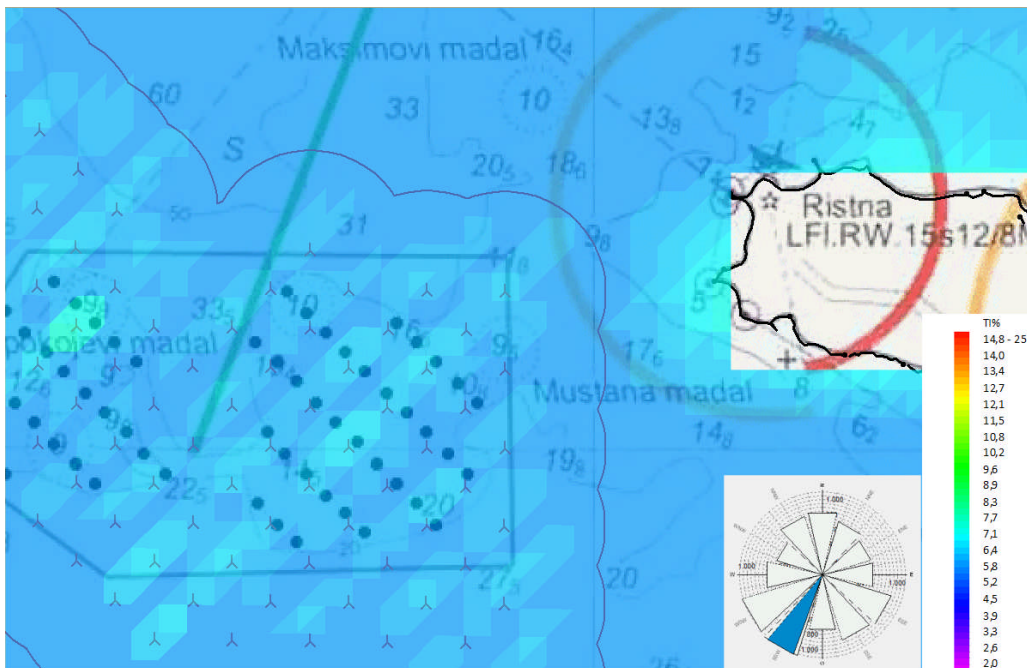




**Figure 18. Peak (maximum) turbulence when the wind is from sector 8.**

In the displays of the maximum turbulence within the sector the wake turbulence become visible and close to the turbines themselves the scale is comparable with turbulence near the shore when wind is from the land, but this turbulence is quickly reduced to a level slightly higher than the background turbulence.

The next figure is a close up on the Ristna peninsula when wind is from sector 7.



**Figure 19. Close up on the Ristna peninsula. The turbulence is the maximum turbulence. The line around the wind farm is 1800 m.**

Here it is possible to see the extend of the peak of turbulence. There is an increase in turbulence out to 1800 m though this is a very minor increase.

## 5. Interpretation of results

The plots show that in general the influence of the turbulence from the wind turbines is very limited compared to the influence from the coast. The extent of influence from the turbines is also limited. At 500 m distance the influence is low and at 1000 m distance the influence is entirely unrecognizable.

In the grid the highest turbulence found 10,5%. This must be compared to 24% on land and turbulence on the same magnitude over coastal water when the wind is from land as inside the wind farm.

## 6. Wind speed reduction

In addition to studying the turbulence in the wakes of the wind farm EMD has also looked into the loss of wind speed due to the wakes of the turbines.

For this purpose two representative, but also specifically interesting locations have been selected (Figure 20). One is on the boundary of the western wind farm segment facing the Ristna peninsula. This one is called "Inside wind farm". The other is exactly on the coast of Ristna peninsula at the closest point to the wind farm. This one is called "Ristna". Users of the coast are expected to use the body of water in-between these two locations.

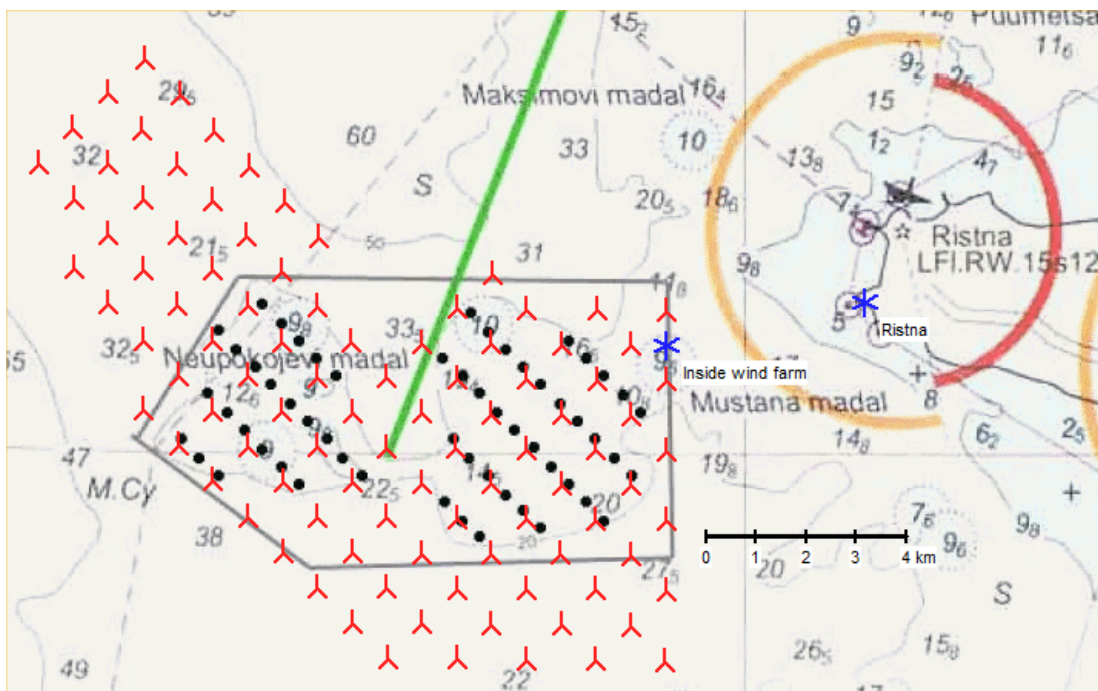


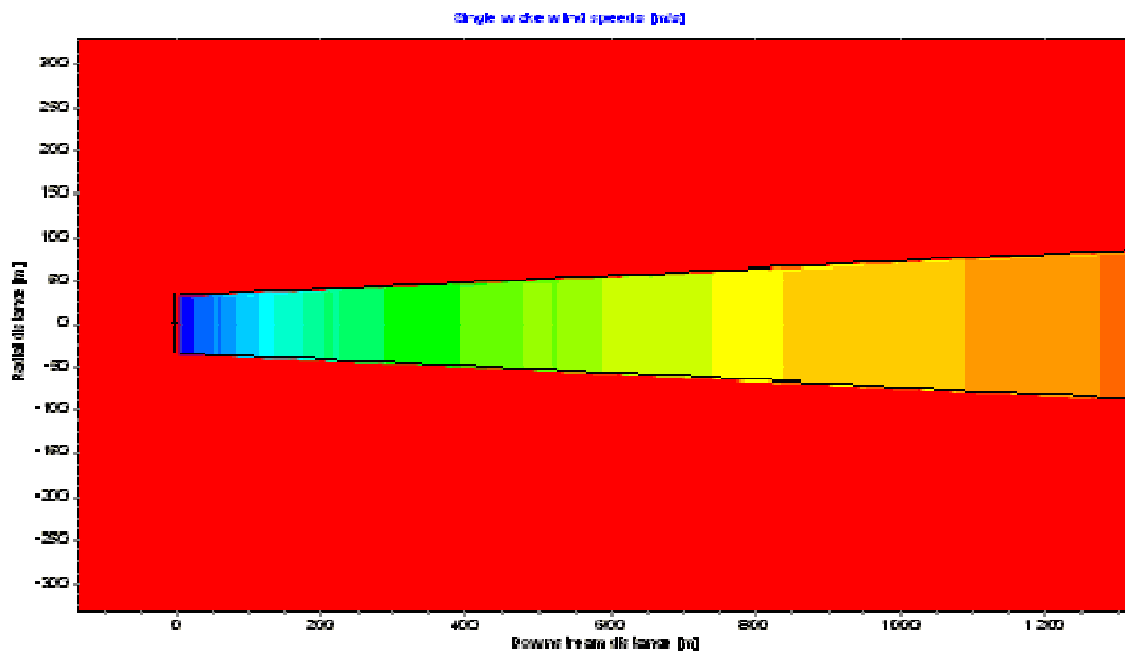
Figure 20. The locations of the wind speed loss analysis.

Again the layout is based on the Vestas V90, 80 m hub height, which is the densest layouts of the suggested options.

### 6.1. Calculation method.

The wakes are calculated with WindPRO using the N.O. Jensen wake model. This model assumes a simplified, uniform dispersion of the wakes as shown in Figure 21. While this is a simpler model than used for the turbulence calculation it has proved well suited for calculating the wake impact on other wind turbines. It is therefore also assumed to be able to give a reasonably correct result in this situation.





**Figure 21. Diagram of the wake wind speed calculation. The color scale inside the wake represents reduced wind speed, while the red color is undisturbed wind speed.**

Compared to a standard wake calculation a very low widening of the wake is used (Wake decay constant of 0,0225). This is because the wind flow offshore has a low turbulence, which makes it slow at refilling the wake again downwind of the turbines. In other words the wakes carry longer offshore than onshore and this has been taken into account. The typical wake decay constant that is used for on-shore turbines is 0.075.

## 6.2. Calculation results

The relative loss of wind speed is almost the same with height, so the relative reduction is the same no matter if we look at 10, 20 or 30 m height. Of course the wind speed increase with height and so does the absolute loss.

In Figure 22 and Figure 23 are shown radar diagrams of the relative loss inside the wind farm and at Ristna. The relative loss is shown for three different wind speeds at 20 m height. In this case the loss at these three wind speeds are almost the same since the drag of the turbines at this wind speed range is almost the same. With higher wind speed than these, the wind speed loss will decrease as the turbines use less of the wind and at lower wind speed the turbines will stop and of course not cause any loss of wind speed.

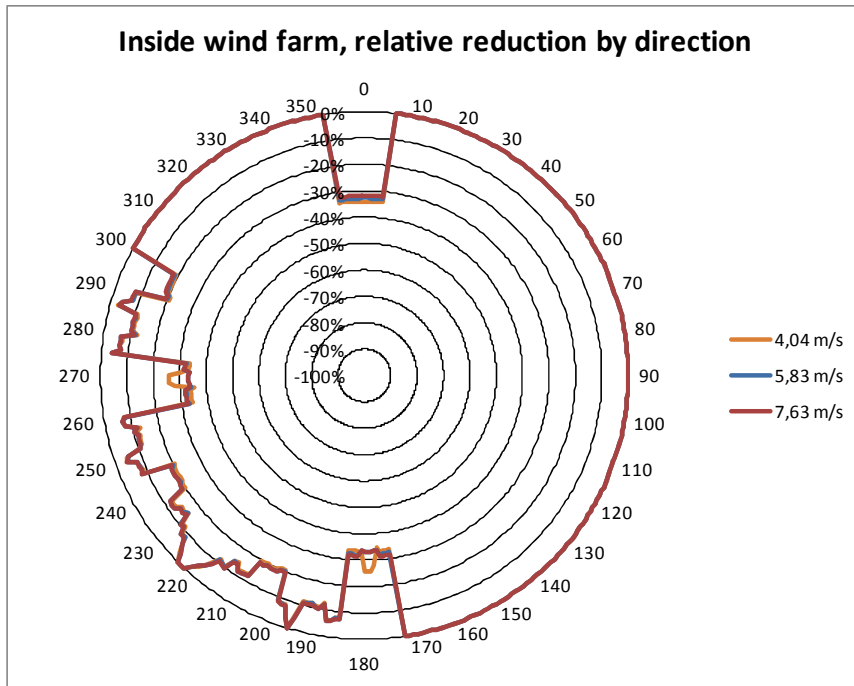


Figure 22. The direction wise relative reduction of wind speed at "Inside wind farm" at 20 m height.

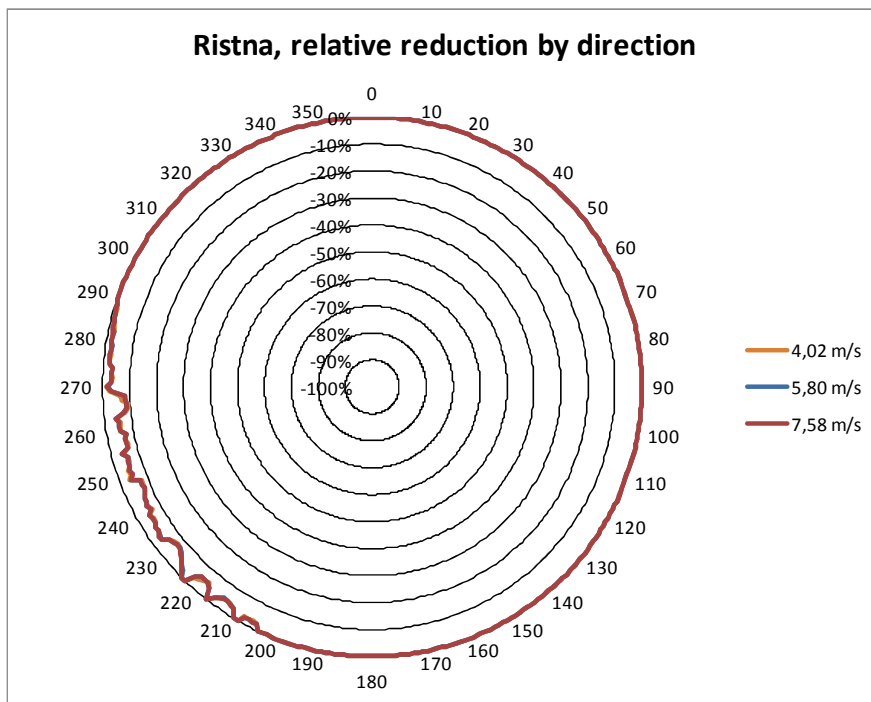


Figure 23. The direction wise relative reduction of wind speed at "Ristna" at 20 m height.

The major wind speed loss at "Inside wind farm" is from the three closest turbines. These are about 700 m away and in those 3 directions the loss is about 30%.

At Ristna these losses are greatly reduced. In the direction of the closest turbine they reach around 10% and considerably less in the other directions.

## 7. Conclusion



EMD has calculated the expected impact of turbulence on the coast of Hiiumaa.

The results are calculated for a typical layout of the wind farm, where results are obtained from the expected maximum number of turbines. The turbulence is calculated for 8 m/s at 10 m height on the offshore locations as this is considered a realistic regime for the operation of the turbines on this location and for sailors, paragliders, kitesurfers etc.

The presentation of the results is made in the form of maps showing the extent and magnitude of the turbulence from the turbines, and compares it to the turbulence on the coast itself.

The average turbulence intensity offshore has at Hiiumaa been measured to be 6%. The maximum turbulence contribution from a single turbine at 10 m height (and 8 m/s) is 12,8% calculated at a location directly 200 m behind a single turbine. The highest value found in any of the grid cells (calculated with a 500 m grid spacing) from the entire wind farm is 10,5%. That no higher turbulence is calculated for the entire wind farm is due to the narrowness of the high turbulence field and the spacing of 500 m between each calculation point. The very high turbulence situations are very rare. Any recognisable influence has not been found beyond 1800 m from the turbines.

By comparison the turbulence intensity on inland locations extent to 24% and the turbulence intensity when the wind direction is from land is regularly calculated to over 7% on a location located 10 km from the coast and 9,5% for locations at about 1,5 km from the coast.

Beyond a few hundred meters from the turbines the turbulence impact from the wind turbines is therefore negligible compared to turbulence from land.

The reduction of wind speeds has been examined as well. The wind speed loss extend further than the turbulence impact. At the perimeter of the wind farm (700 m from closest turbine) the wind speed loss is up to 30% in the direction of the turbines. 4 km away on the Ristna peninsula the wind speed is reduced up to 11% in the direction of the closest wind turbine.

## **7. References**

The WAsP Engineering manual.

European Wind Turbine Standards II, ECN-C—98-096, December 1998

Illustrations:

MIT Open Courseware: <http://dspace.mit.edu/bitstream/handle/1721.1/37147/1-061Fall-2002/OcwWeb/Civil-and-Environmental-Engineering/1-061Transport-Processes-in-the-EnvironmentFall2002/LectureNotes/detail/7-lec.htm>

Hahm and Kröning, ANSYS:

<http://www.fluent.com/about/news/newsletters/02v11i1/a1.htm>

CAEbridge: <http://caebridge.com/wind-turbine-design>

Recharge news (DONG Energy):

<http://www.rechargenews.com/energy/wind/article211238.ece>

WindPRO Reference Manual on Wakes and Turbulence

[http://help.emd.dk/knowledgebase/content/Wake\\_Model.pdf](http://help.emd.dk/knowledgebase/content/Wake_Model.pdf)



# APPENDIX A

**VESTAS V90 3000 90.0 !O!**

File C:\WindPRO Data\Siemens data\Vestas\VESTAS V90 3000 90.0 !O!.wtg

Company VESTAS  
 Type/Version V90  
 Rated power 3.000,0 kW  
 Secondary generator 0,0 kW  
 Rotor diameter 90,0 m  
 Tower Tubular  
 Grid connection 50 Hz

Origin country DK  
 Blade type VESTAS V44  
 Generator type One generator  
 Rpm, rated power 0,0 rpm  
 Rpm, initial 0,0 rpm  
 Hub height(s) 80,0; 65,0; 75,0; 90,0; 105,0 m  
 Maximum blade width 0,00 m  
 Blade width for 90% radius 0,00 m  
 Valid Yes  
 Creator USER  
 Created 09-12-2009 10:35  
 Edited 09-12-2009 10:35

**Power curve: V90-3MW (1.225) Mode 0**

Source Gen. Spec.

Source date	Creator	Created	Edited	Default	Stop windSpeed	Air density	Tip angle	Power control	CT curve type
26-03-2004 00:00	USER	26-03-2004 11:35	07-03-2006 14:04	Yes	[m/s] 25,0	[kg/m3] 1,225	[°] 0,0	Pitch	User defined

PC: Gen. Spec. 950011.R8

Ct: 950020.R1 Only for Air density 1.225

**Power curve**

Wind speed [m/s]	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
Power [kW]	77,00	190,00	353,00	581,00	886,00	1.273,00	1.710,00	2.145,00	2.544,00	2.837,00	2.965,00	2.995,00	3.000,00	3.000,00	3.000,00
Ce	0,309	0,390	0,419	0,435	0,444	0,448	0,439	0,414	0,378	0,331	0,277	0,228	0,188	0,157	0,132

Wind speed [m/s]	19,00	20,00	21,00	22,00	23,00	24,00	25,00
Power [kW]	3.000,00	3.000,00	3.000,00	3.000,00	3.000,00	3.000,00	3.000,00
Ce	0,112	0,096	0,083	0,072	0,063	0,056	0,049

**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	17,00	18,00	19,00	20,00	21,00	22,00	23,00	24,00	25,00
Ct	0,00	0,86	0,84	0,83	0,83	0,83	0,81	0,74	0,66	0,57	0,47	0,38	0,30	0,24	0,20	0,17	0,14	0,12	0,10	0,09	0,08	0,07	0,06

**HP curve comparison**

Vmean [m/s]	5	6	7	8	9	10
HP value [MWh]	3.019	5.077	7.277	9.571	11.471	13.103
V90-3MW (1.225) Mode 0 [MWh]	3.277	5.338	7.554	9.708	11.660	13.324
<b>Check value [%]</b>	<b>-8</b>	<b>-5</b>	<b>-4</b>	<b>-1</b>	<b>-2</b>	<b>-2</b>

The table shows comparison between annual energy production calculated on basis of simplified "HP-curves" which assume that all WTGs performs quite similar - only specific power loading (kW/m<sup>2</sup>) and single/dual speed or stall/pitch decides the calculated values. Productions are without wake losses. For further details, ask at the Danish Energy Agency for project report J.nr. 51171/00-0016 or see WindPRO manual chapter 3.5.2.

The method is refined in EMD report "20 Detailed Case Studies comparing Project Design Calculations and actual Energy Productions for Wind Energy Projects worldwide", jan 2003.

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.

### VESTAS V90 3000 90.0 !O!

File C:\WindPRO Data\Siemens data\Vestas\VESTAS V90 3000 90.0 !O!.wtg

