Developing boundary conditions using the nesting technique on simple terrain
A study of wind and turbulence intensity profiles sensitivity

Photo taken on April 12, 2011 from boat, Lillgrund and Øresund Bridge; a nice, grey and windy day.

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Abstract

As wind industry is developing steadily offshore, the wind turbine spacing remains a key element for maximizing revenues and reducing loading from turbines wake interaction. In the case of relatively close to shore offshore wind farms, or large arrays onshore, the turbulence intensity coming from different sectors can have an effect on wake growth and decay. In an attempt to obtain wind features at site, some boundary conditions for micro-siting simulation are found, using a commercial RANS flow solver CFD software was used. The approach in this work could be described more practical than theoretical and could be more useful for developers than pure CFD specialists.

By simulating with three different roughness length for open sea, with the appropriate and contextual assumptions, for the offshore Lillgrund wind farm, vertical profiles and turbulence intensity were extracted from the WindSim software at the meteorological mast position and enabled measurement comparison. In a second attempt to compare the effect of the wind and turbulence profiles previously obtained, a sector of interest is simulated with the actuator disc model.

In general, the site conditions over the large-scale domain evaluated by the commercial software are satisfactory after adjusting the roughness length for the open sea. The turbulence intensity trend for various in flow angle is captured by the simulations and computed wind profiles are for the most part adequately. A comparison of spring and winter filtered measurements enable discussion upon some sectors disagreement. As for the small-scale actuator disc model using the developed site conditions, the result is over-estimated by the simulations, especially for the second row downstream.

**Keywords:** Lillgrund, turbulence intensity, WindSim, case study, actuator disc model, roughness length, boundary conditions;
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À Kalle et Charles, vous avez été là plus d’une fois pour moi, peut-être mille fois, merci à vous deux, du fond du coeur. Pour mes grand-mamans, de femmes très fortes, pour mes parents et toute la famille, pour ma douce et ceux que j’omet mais qui ont le plaisir de m’endurer dans les pires moments.

Det har varit en bra resa Sverige. Tack så mycket

And for two Turks, the cabròn-wey, the spaniard, one blond swede, two Canadians, a bunch of Iranians and more:

"See everything, overlook a great deal, correct a little."

- Pope John XXIII
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# Nomenclature and glossary

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Chapter 1

Introduction

Even in fairly simple terrain, turbulence intensity evaluation is still required to study and predict energy production from wind power plants. In large arrays of turbine, the initial turbulence intensity, or ambient turbulence, can influence the wake formation, interaction and decay inside the wind farm. This work wish to evaluate the simulation and the sensitivity of wind and turbulence profiles for micro-siting purposes, smaller scale numerical simulations. In other words, performing nesting simulation.

Earlier work and official reports such as Dahlberg [5] on the Lillgrund wind farm have shown interesting insight on how the turbines are affected by the wake. Yet, some unpublished numerical simulations realized on this farm do not totally match the actual phenomenon. These simulations, on a few kilometers scale, using the logarithmic wind profile and the turbulence calculated from the water surface roughness at the inlet, could be enough for a offshore windfarms situated at a great distance from shore. On the other hand, Lillgrund wind farm is situated relatively close to the shore. Hence, the hypothesis drawn from the two premises, modeling the terrain to better develop the boundary conditions for the small scale numerical analysis may be of importance.

As building close to the shores cuts on the current large offshore venture costs, it also deals with lower winds and increased turbulence coming from the land in its vicinity. Turbines installed on large lakes, though seldom the case, or more commonly at sea near coast are of interest in this study. Studying closely a similar area in a more practical way, wishes to help developing such sites.

Research objectives

As a first step, the large scale domain simulated numerically will evaluate how terrain induced turbulence intensity can be reproduced for an offshore, close to coast, windfarm. Comparison with actual measurements will enable a good evaluation of this exercise. The second milestone is to try with a different roughness classification of the open water near the offshore wind farm in order to steer, or in a certain way shift, the turbulence intensity at site for further calculations and comparisons. The third step is the realization of flow modeling using the actuator disc model for a certain part of the wind farm for a certain sector of interest with
the large domain obtained inlet conditions. Later, a comparison with the actual trend in production and without the inlet conditions will also be possible. It is aimed by this study to better reproduce the condition at site in order to assess wake interaction in such, close to shore, offshore windfarm.

### Background information

**Lillgrund wind farm**

Largest in Sweden to date, Vattenfall’s Lillgrund offshore windfarm has been producing since December 2007 and has shown good overall availability in the last years [17]. Yet, important wake interactions between turbines, as shown in a report by Dahlberg 2009 [5], are of interest. For instance, the second turbine downstream, when the wind comes from the less spaced row disposition, produces approximately 20 percent of the first one. Moreover, the missing turbines in the array due to shallow water is a unique characteristic. Furthermore, the turbines are closely spaced when compared to other wind farms with similar capacity turbines. Such features of interest and being able to simulate it motivates research on that windfarm.

Important information is disseminated on the Lillgrund project, enabling interesting discussions (more than normally privately owned wind farm where information are kept secret). Measurements from a mast installed three years prior to the construction of the wind farm were available but individual production data per turbine was not available at the time of writing and summarizing this thesis work.

**Commercial wind energy estimation software**

For the past two decades, most of the wind energy assessment were achieved rather with fast and linearly estimating software. The industry is now experienced using tools like EMD WindPro or GH Windfarmer with state-of-the-art WAsP calculations by formerly Risø. Nowadays, performances of personal computers offer the possibility to numerically solve time averaged flow equation within several minutes and hours depending on the volume discretization and the number of equations.

A growing number of users are now developing with software such as WindSim, WindFarm and MeteoDyn WT that allow users to solve sector by sector a certain volume using steady state Reynold Averaged Navier-Stokes equations (RANS) to subsequently calculate the wind energy production. Numerous research code are also developed and mostly used by scholars and other private partnerships. Some may also use Unsteady RANS (URANS) to capture the time-dependent flow characteristics with, of course, an increased simulation cost. Even more computational intensive Detached Eddy Simulation (DES) or Large Eddies Simulations (LES), slowly closing the gap with Direct Navier-Stokes (DNS), are now being elaborated and used mostly by scholars, may be be use in the future for develop-
ing wind energy generation.

The current study focus on using a commercial code solving RANS, more specifically the WindSim software, originally an air pollution dispersion simulation code that initiates PHOENICS CFD engine. For turbulence closure, a concept inherent to fluid dynamics, WindSim uses a two equations scheme, typically k-ε, for turbulence kinetic energy while other software, like Windfarm and MeteoDyn, use one-equation mixing length model originally also from the Boussinesq’s hypothesis, considered as eddy viscosity models like the two equations models by Davidson [3].

In numerical calculations, as reported by [15], [1], [13], the user plays a major role since initiating the software requires knowledge either specific to the software, to numerical calculation solving or to the fluid dynamics theory behind it. Even though the author could be considered as a newcomer in energy estimation software, supervision from more experienced users helped to achieve the goals presented in this paper.

**Turbulence intensity at sites**

Turbulent flow fluctuations can induce different mechanical and vibrational loading and could reduce the expected life of turbines. As defined in IEC 61400-1, different classification for reference wind speed sorted from reference turbulence intensity at 15 m/s A to C ranging from 16 to 12 % are design criterion for turbine manufacturers and developers selection. In the case of the Lillgrund wind farm, the turbulence intensity at the site is rather minimal, wake induced turbulence intensity, on the other hand, inside the array of turbines, is an interesting topic of investigation. Since wakes are affected by the wind speed, the ambient turbulence at the site, the atmospheric stability and the rotor geometry, obtaining better estimation of the physics at the site can increase energy prediction accuracy and allow optimization of the site. Given that wake modelling accurately reproduce the flow in the windfarm.

**Report structure**

In the section following the introduction that incorporates the background subsection, the theory framework will quickly elaborate on some global wind concepts, atmospheric boundary layer, flow modeling, wind energy and the commercial CFD software. The methodology and the assumptions section follows. Results from both simulations type are presented and then analysed. Lastly, conclusions are presented and future work is suggested.
Chapter 2

Theory and concepts

2.1 Global wind

Wind physics, on a global scale, involves the Coriolis force due to the rotation of the earth, the friction force, the pressure gradient forces, gravitational forces, centrifugal and centripetal accelerations forces. All these, act together in a balanced manner to generate the winds in the earth’s atmosphere. Global winds and earth’s features responsible for continental phenomenon are beyond the scope of this work. Nevertheless, let enumerate the force balances that act perpendicular to the surface of the earth and parallel to the ground to introduce the meso-scale wind modelling.

Forces balances

The atmospheric forces balances can be observed within the troposphere and occurs when forces interact with each other both in direction and magnitude. Understanding these concepts help to appreciate the limitations of simplified numerical simulations and the complexity of modelling wind precisely in a large scale domain.

Hydrostatic balance

The balance in the vertical plane occurs when the vertical pressure gradient and the gravitational force are equal. Locally, the air parcel is dragged down by the gravity while it is directed upward due to decreasing pressure when increasing altitude. The hydrostatic balance is of interest specially in analysing the atmospheric boundary layer stability as will be discussed.

\[
PGF = GF \rightarrow \frac{F_p}{m} = \frac{F_g}{m} \rightarrow \frac{-1}{\rho} \frac{\delta P}{\delta z} = g
\]  

Geostrophic balance

This equality occurs when the horizontal pressure gradient forces counter the effect of the Coriolis force. It is the main wind driver in meteorological maps. In
the northern hemisphere, the rotation is clockwise around a high pressure zone
and counter-clockwise around low pressure, it is the Buys Ballot’s Law. Due to
the Coriolis force, the rotation sense is the opposite for the southern hemisphere
and the balance is not achieved at the equator where the Coriolis force is null.
In the commercial software for wind resources assessment, this equality can be
introduced, though in this work, the author decided to exclude it.

\[
PGF = CF \rightarrow \frac{F_p}{m} = \pm \frac{fV}{m} \rightarrow -\frac{1}{\rho} \frac{\delta p}{\delta s} = \pm fV
\]  

(2.2)

Gradient balance

Since geostrophic wind are seldom flowing in a straight line, an adjustment to
the previous balance is needed to take account of the centrifugal force. The force
is always oriented outward of the pressure gradient and this balance represent
really well the forces acting in the middle latitudes of the earth. In the case
of high pressure the balance magnify the wind speed creating supergeostrophic
wind while on the other hand it reduces the wind speed for subgeostrophic wind
around low pressure zones.

Guldberg-Mohn balance

When flowing near the surface of the earth, the wind is slowed by the friction force
and consequently weaken the Coriolis force. On a meso scale, this combination
of forces tilt the wind to cross isobars in a weak angle for smooth terrain or open
sea while crossing with a straighter angle, towards perpendicularity, for larger
friction areas such as forests.

Mesoscale modelling

A perfect prediction model would include all the physics, seasonal disturbance,
diurnal cycle and yearly variations. More importantly, the perfect model would
take also into account large-scale eddy formation. Closer to the site, a finer res-
olution would enable more precise reproduction of the smaller scale turbulence.
Yet, such model would require an immense amount of computational power and
increased complexity that would involve an extensive modelling, hence compro-
mise is needed on meso and micro-scale.

On a broad perspective, meso-scale models are useful to take into account the
meteorological patterns and global-winds, the drawback; the resolution is usually
coarser due to the larger domain and are matched against meteorological data.
Interestingly, though not the case for this study, these models can be included in
small-scale models as input to grasp the physics calculated in the larger model.
The small-scale model is computed, as the name suggest, on a smaller domain to
evaluate the local effect and to position the wind turbines.
2.2 Atmospheric Boundary Layer

The atmospheric boundary layer (ABL) is the region of the atmosphere often defined by continuous turbulent transport of air almost for the whole depth. As it will be covered later, assumptions are made to calculate this mixing transport near the earth surface where strong drag and energy dissipation take place. The boundary layer is changing in an hourly time scale and reach equilibrium typically at daytime and at night. Needless to say, a complex location to position a mechanical machine. Three stability concepts are also brought forward in the three following sub-section: stable, unstable and neutral.

Day time characteristics

At sunrise, the surface of the earth is slowly heated by sun rays thus forming the entrainment zone that eventually become the cloud layer. Later the stratification consist of the surface layer, within the first hundred metres or so, followed by the mixed layer and the entrainment zone. The fully developed daytime boundary layer is typically hundred of metres to few kilometres deep. Equilibrium is reached with cooled air from the clouds and rising warmer air creating mixing. As it is described in Burton [3], the unstable stratification of the boundary layer happens in important surface heating where warm air keep on rising without reaching thermal equilibrium and creating large convection stream, large-scale turbulent eddies. A greater vertical transport increase the depth of a stable ABL, the wind speed vary timidly with height, hence a lower wind shear.

Night time characteristics

At dawn, sun rays stop heating the earth’s surface and cool down. The surface layer reduce in height while a stable nocturnal boundary layer develop with sinking cooler air. The stable boundary layer is characterized by low-level, or nocturnal, jets that has the effect to create a speed-up just in the stable layer section fading out in the residual layer above. Wind shear in the first hundred meters of a stable boundary layer can be large. The last stratification is the capping inversion, later entrainment zone, that act as a buffer zone with the ABL and the free atmosphere.

Neutral characteristics and coastal areas considerations

In neutral atmospheric conditions, thermal equilibrium is reached with increasing height. This is commonly true when strong winds enable strong mixing with rough surface created turbulence. According to Burton [3] again, it would be the most important situation to consider especially when looking at turbine design loads. Calculations ran throughout the duration of this study are only enabled for neutral stability. Still, discussing the stability phenomenon is crucial in analysing the results and understanding the potential causes of error. For instance, unstable conditions can generates important low level gusts and stable ABL important wind shear can lead to important asymmetric loading on the total swept area.
2.3 Flow modelling

Roughness classification

The classification proposed by Wieranga and Davenport [19] presented in the next table list the land surface roughness into different roughness length. These height-independent parameters represent how the averaged wind energy over a plane is transformed into turbulence for the above boundary layer. This is a fairly simple approach for modelling an area since modelling all objects would require an extensive effort. Other approach like the roughness class, used by EMD software’s WindPro, correspond to the sorting from the table 2.1 but on a linear scale.

<table>
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<tr>
<td>0.0002</td>
<td>Sea: open sea, lake and desert</td>
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<tr>
<td>0.005</td>
<td>Smooth: Land with negligible vegetation and free of obstacles</td>
</tr>
<tr>
<td>0.03</td>
<td>Open: Low vegetation, isolated obstacles</td>
</tr>
<tr>
<td>0.10</td>
<td>Roughly open: Low crops or plants, relatively low and few obstacles</td>
</tr>
<tr>
<td>0.25</td>
<td>Rough: scattered obstacles, relatively high crops area</td>
</tr>
<tr>
<td>0.5</td>
<td>Very rough: large obstacle separated with spaces, young forest, low buildings</td>
</tr>
<tr>
<td>1.0</td>
<td>Skimming: similar-size and similarly-spaced large obstacles</td>
</tr>
<tr>
<td>&gt; 2</td>
<td>Chaotic: Numerous low and high obstacles randomly spaced</td>
</tr>
</tbody>
</table>

Table 2.1: Roughness length list and associated landscape classification for surface roughness modelling, reference Weiranga and Davenport [19]

Logarithmic wind profile

Typically, in the ABL, the velocity is given as height function of the wind speed according to equation (2.3) and is characterized with lower values at lower heights and asymptotic value, probably near the geostrophic wind, at greater heights. This shape fits the concept that the mixing is higher at earth surface and stabilize slowly with height in the first part of the atmosphere.

\[
 u(z) = \frac{u^*}{\kappa} \left[ \ln \left( \frac{z - d}{z_0} \right) + \Psi \right] \tag{2.3}
\]

The friction velocity \(u^*\) represent the surface friction velocity, the rate of vertical transfer by turbulence of surface plane momentum per mass of air, the square root of shear stress at the surface divided by the density of air. The variable \(\kappa\) is the von Karman constant.

When ignoring the stability function \(\Psi\), for neutral boundary layer, and also removing the zero plane displacement \(d\), typically used for evenly spaced objects.
of a certain height, like forest, it is possible to obtain from the last equation the next, handy equation (2.4).

\[
\frac{U_1}{U_2} = \frac{\ln \left( \frac{z_1}{z_0} \right)}{\ln \left( \frac{z_2}{z_0} \right)}
\]  

(2.4)

**RANS flow model**

Being interested in statistically averaged flow, partly due to the nature of the measurements obtained, Reynold’s decomposition helps to compute the flow more precisely than the linear approximation. We can then define the flow as such in the next equation (2.5) that summerize the wind speed over time plotted at figure 2.1.

\[
u(t) = \langle u \rangle + u'(t)
\]  

(2.5)

**Figure 2.1:** Fictional wind speed plotted in function of time where the averaged wind speed is \( \langle u \rangle \) and \( u' \) the fluctuating member

It is assumed, by averaging the flow, that rapid turbulent fluctuation time interval is enough to obtain a reliable and significant approximation but short enough to grasp the slower evolution of the considered flow. The interested reader can dig further into Reynold Averaged Navier-Stokes equations while only an overview is provided here. Still the driving RANS equations are presented for steady-state incompressible flow with equations (2.6). The capitalized variables are averaged values of the component while the small notation designate the fluctuations to lighten and ease the equations.

The following two equations, Reynold-averaged continuity and momentum equations for steady, incompressible flow, are the core of the simulations;

\[
\frac{\partial U_i}{\partial x_i} = 0, \quad U_j \frac{\partial U_i}{\partial x_j} = -\frac{1}{\rho} \frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j} \left( \nu \left( \frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i} \right) - \overline{u_iu_j} \right)
\]  

(2.6)

Where, for the second equation, the left hand side represent the convection term and right hand side the negative pressure gradient followed by viscosity term. The last term, the Reynold stress tensor in the parenthesis, is the component necessitating a set of equation to be solved. The next equation set up the ground for solving turbulence holding the two parameters \( \nu_T \) for turbulent viscosity and
2.3. Flow modelling

\[ \bar{u}_i u_j = \nu_T \left( \frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i} \right) + \frac{2}{3} \delta_{ij} \kappa \] (2.7)

**Turbulence closure**

Earlier work by Gravdahl 1998 [7] offers a comparison of the WindSim called standard and modified set of variable for the turbulence closure scheme. The interested reader can look upon a review of the CFD modelling for wind energy purposes by Sumner et Al. 2010 [16] providing an extensive review of the different models and simulation scales. For the homogeneous neutral surface layer over either analytical shapes or real topography, the k-\( \varepsilon \) two equations closure equations can be written as such with equations (2.8) to (2.9):

\[ \nu_T = c_\mu \frac{k^2}{\varepsilon} \] (2.8)

\[ \frac{\partial}{\partial x_i} (U_i k) = \frac{\partial}{\partial x_i} \left( \frac{\nu_T \partial k}{\sigma_k \partial x_i} \right) + P_k - \varepsilon \] (2.9)

\[ \frac{\partial}{\partial x_i} (U_i \varepsilon) = \frac{\partial}{\partial x_i} \left( \frac{\nu_T \partial \varepsilon}{\sigma_\varepsilon \partial x_i} \right) + P_k c_1 \frac{\varepsilon}{k} - c_2 \frac{\varepsilon^2}{k} \] (2.10)

\[ P_k = \nu_T \left( \frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i} \right) \frac{\partial U_i}{\partial x_j} \] (2.11)

Where the turbulent viscosity \( \nu_T \) is function of the turbulent kinetic energy and the dissipation rate. These two last parameters are solved with the next two equations where the production term \( P_k \) is lastly presented at equation (2.11). This set of equations is solved using constant from (2.2) that have been extracted from observations, either compared with measurements from wind tunnel or real topography.

<table>
<thead>
<tr>
<th>Models</th>
<th>( c_\mu )</th>
<th>( c_1 ) or ( c_{\varepsilon 1} )</th>
<th>( c_2 ) or ( c_{\varepsilon 2} )</th>
<th>( \sigma_k )</th>
<th>( \sigma_\varepsilon )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard k-( \varepsilon )</td>
<td>0.09</td>
<td>1.44</td>
<td>1.92</td>
<td>1</td>
<td>1.3</td>
</tr>
<tr>
<td>Modified k-( \varepsilon )</td>
<td>0.033</td>
<td>1.46</td>
<td>1.83</td>
<td>1</td>
<td>2.38</td>
</tr>
<tr>
<td>RNG k-( \varepsilon )</td>
<td>0.085</td>
<td>1.42 - ( C_{1R} )</td>
<td>1.68</td>
<td>0.7179</td>
<td>0.7179</td>
</tr>
</tbody>
</table>

Table 2.2: Turbulence constant for different two-equation models according to Kim and Patel [8]

\[ C_{1R} = \eta \left( \frac{1 - \eta}{4.38 \left( 1 + 0.015 \eta^3 \right)} \right) \] (2.12)

The last equation (2.12) is part of the RNG model as shown in table 2.2. In this model, as reported by [8], \( k \) and \( \varepsilon \) in the parameter \( \eta \) from the following
2.4 Wind Energy

As we go further into theory, it is important to note how wind energy is extracted with the electromechanical machines. Although, the turbine as whole is interesting let us focus on an overview of the concepts associated with wind energy extraction, omitting the mechanical or electrical losses, the availability and such.

Energy in wind and momentum theory

The following equation \[(2.15)\] gives the energy available in the wind. Since the total extraction of the wind is impossible, the power coefficient is introduce \(C_P\) that account for the energy that can be extracted for a given machine, where, in that case the area multiplied by the velocity and the air density give the mass air flow through the diameter formed by the rotation of the rotor.

\[
E_k = \frac{1}{2}mv^2
\]

\[
P_{\text{wind}} = \frac{1}{2}C_P\rho AU^3
\]

The energy extraction principles are represented using a stream-tube concept

\[\text{Figure 2.2: stream-tube representation for axisymmetric flow}\]

where the mass air flow rate is constant upstream and downstream the modelled
porous disc between position 2 and 3 in figure 2.2 representing the turbine such as in the equation (2.17). Let us note as well $A$ equal to $A_2$ and $A_3$.

$$\rho A_\infty U_\infty = \rho A U_2 = \rho A U_3 = \rho A U_4$$

(2.17)

Velocity upstream $U_\infty$, at the turbine directly before $U_2$ or directly after $U_3$ and downstream $U_4$ slows down axially according to the axial flow induction factor $a$, also known as axial interference factor, entered in the next equation (2.18).

$$U_2 = U_\infty (1 - a)$$

(2.18)

Given the nature of the stream-tube concept, the force that change momentum at the beginning and end of the volume is entirely due to the pressure difference across the actuator disc. The stream tube figure 2.2 shows the pressure difference with the bold line where the pressure builds up before the disc and drop through the porous plane to slowly recover downstream. Hence, the following equation from the momentum theory:

$$(p_3 - p_2)A = (U_\infty + U_4)\rho AU_\infty (1 - a)$$

(2.19)

Using Bernoulli’s equation, assuming incompressible flow ($\rho_\infty = \rho_2$) and constant height, it is possible to obtain for both upstream and downstream flow the following:

$$\frac{1}{2} \rho U_\infty^2 + p_\infty = \frac{1}{2} \rho U_2^2 + p_2$$

(2.20)

$$\frac{1}{2} \rho U_3^2 + p_3 = \frac{1}{2} \rho U_4^2 + p_4$$

(2.21)

Then by subtracting the last two equations, when assuming that pressure at both end of the tubes are equal ($p_\infty = p_4$) and equal velocity before and after the disc are equal ($U_2 = U_3$), we obtain the following:

$$p_2 - p_3 = \frac{1}{2} \rho (U_\infty^2 - U_2^2)$$

(2.22)

So that such result included in equation ### gives;

$$(U_\infty + U_4)AU_\infty (1 - a) = \frac{1}{2} (U_\infty^2 - U_4^2)A_{23}$$

(2.23)

**Power & thrust coefficient**

Developing from the last result, the force on the air can be written then from equations ### and (2.18):

$$P = FU_2 = 2\rho AU_\infty^3 a(1 - a)^2$$

(2.24)

We then define the power coefficient as such where the last equation is at the numerator divided by the total power in the wind from the earlier equation (2.24):

$$C_P = \frac{P}{\frac{1}{2} \rho U_\infty^3 A}$$

(2.25)
To finally obtain the following expression in function of the axial interference variable;

\[ C_P = 4a(1 - a)^2 \]  \hspace{1cm} (2.26)

The force of the air being;

\[ T = (P_2 - P_3)A_{23} = 2\rho A_{23}U_{\infty}^2 a(1 - a)^2 C_T = \frac{T}{\frac{1}{2}\rho U_{\infty}^2 A_{23}} \]  \hspace{1cm} (2.27)

The force on the actuator disc can now be as a function of the axial interference as such;

\[ C_T = 4a(1 - a) \]  \hspace{1cm} (2.28)

These equations are applicable for \( a \) varying from 0 to 0.5. Exceeding this range would mean the velocity dropped to zero after the rotor plane, the turbine would have blocked all the wind.

### 2.5 Commercial CFD

#### WindSim simulation domain

As mentioned earlier, the WindSim software by Vector A/S is an interface for the PHOENICS CFD engine. The interface requires first a certain terrain file to render, or discrete, the mesh. Various parameters can be set at that stage, affecting either the number, the aspect ratio and the refinement spacing of the cells.

Once the simulation domain is set, boundary conditions are established on the volume. At the top boundary, the pressure can be fixed or a frictionless wall can be assumed. Best practices suggest the usage of “fixed-pressure” for complex terrain and “no-friction wall” for simple terrain. The boundary layer height and speed are manually set, the domain is then simulated sector by sector for the number of iterations manually entered. Unfortunately, restarting the calculations, when convergence is not achieved for instance, with WindSim software was found to be sometime give errors. Users should preferably use the PHOENICS console to monitor the calculation convergence and overestimate the number of iterations.

Other parameters such as the turbulence closure model, changing the coefficient values shown at the table 2.2, and the air density are entered while the Coriolis force, temperature gradient more advanced parameters can also be configured. The coupled solver or the segregated one, for alternative use, then runs the calculations on the domain. The methodology section covers also some information related to the software behaviour.

#### Model initialization

Most of the models, in RANS simulations, are initiated at the boundary of the domain with the following three equations \([2.29]\) to \([2.31]\) where most of the
constant can be found at 2.2 in a previous section.

\[
  u(z) = \frac{u_*}{\kappa} \ln \left( \frac{z}{z_0} \right) \tag{2.29}
\]

\[
  k = \frac{u_*^2}{\sqrt{\nu}} \tag{2.30}
\]

\[
  \varepsilon = \frac{u_*^2}{kd} \tag{2.31}
\]

In the code, volume inlet variables are calculated directly from the user entered terrain while other values such as boundary layer height and speed. The area of interest being far from the wall, errors induced by these assumptions are reduced significantly. In the case of nested simulations, the inlet conditions for a smaller domain are extracted from the larger domain already simulated values. This is the essence of the last simulation of the current work.

**ABL simulations**

As pointed in the Bolund Blind Comparison results from Bechmann et al. [1] conclusions, some argues that RANS codes will be the workhorses for the coming years. The experiment regrouped many RANS solvers and the top ten results, based on error percentage compared to measurements, consisted of different RANS solvers where only one used one equation turbulence closure scheme while the majority used two equations.

Another conclusion drawn from the experiment was the importance of the user in the results outcome. From this conclusion, a certain necessity for standardization into modelling techniques will eventually be necessary. Though, initiatives like the Bolund experiment are a good step into benchmarking and achieve repeatable results for the industry.

Finally, as mentioned earlier, computational capacities of computers are increasing and enable more calculation. However, the results are still not as instantaneous as linear solving programs. For example, over 30 simulations of 10-12 hours were conducted for this work using a high-end personal computer, such work require monitoring and still not straight forward as other method for wind energy assessment.

**ACD model simulations**

As described by Crasto [4] the pressure drop is defined with equation (2.32) and applied upon the evenly distributed porous cells to represent the rotor. This operation on the mesh is conducted by separating into a certain number of sections the rotor area and assigning solid cells for the tower. Note the result from equation (2.27) in a previous section.

\[
  p_i = \frac{T}{A} = C_T \frac{1}{2} \rho u_\infty^2 \tag{2.32}
\]
Forces are applied over each cells of the discrete disc by a distribution defined by the user. In a paper, Gravdahl et Al. [6] describe the three different pressure field distribution; uniform, polynomial, and parabolic.

### 2.6 Wind data

A complete report on the meteorological conditions at the site was produce by Bergström [2] in 2009 for Vattenfall. In that report, a description of the meteorological mast used and a validation study of the data is achieved. Reader that want to learn more on the data used for the comparison work can consult that report to find more information.

Focus is given on two values, the wind speed and the turbulence intensity at three different height of 25, 40 and 65 metres. The last height correspond to the specified hub height. The velocity at site comes from 10 minutes averaged measurements and the turbulence from the statistical standard deviation of this value. The turbulence intensity is then calculated with the ratio between the standard deviation and the mean wind speed as stated with equation (2.33).

\[
TI(\%) = \frac{\sigma_u}{\langle u \rangle}
\]  

(2.33)

WindSim software calculate the turbulent kinetic energy and calculate turbulence intensity with the following equation (2.34). Values used in the context of this work are calculated directly in the WindSim software that assume the standard deviation being the square root of four third of the turbulent kinetic energy.

\[
\sigma_u = \sqrt{\frac{4}{3} TKE} \rightarrow TI(\%) = \sqrt{\frac{4}{3} TKE} \langle u \rangle
\]

(2.34)
Chapter 3
Methodology

Four distinct parts were achieved in this work. Terrain assessment and preparation for the large-scale simulations was conducted. Monitoring, analysis and tuning of the large-scale simulations was achieved, indeed two terrain modifications were simulated iteratively in order to tune the site. Data handling for both the large-scale and small-scale was accomplished by extracting the vertical profiles at site and computed with filter routines. Finally, the actuator disc micro-siting analysis was conducted.

3.1 Terrain assessment

In order to assess 60 kilometres per 60 kilometres study area around Lillgrund, a thorough and repeatable definition of the area was achieved with high resolution maps. Different data sets were available in the two different countries but the best available source was chosen for each. For Sweden, maps were accessed on Digitala Kartbiblioteket [10], height contours were acquired from the same source with several shape format files that were merged. Height contours were associated with the correct height and some corrections were individually needed. As for Denmark data, topography was extracted from DataForWind [12] online. Accessible online roughness classification being fairly detailed, approximately 200 metres resolution, from DataForWind [12] was used for Denmark side. Roughness length classification was manually achieved in WindPro software for Sweden.

Roughness classification

Roughness classification plays an important role when compared with the terrain elevation in this work since the Lillgrund windfarm vicinity is fairly flat. Unless classified otherwise the roughness for Sweden is roughness length of 0.1 metre. Cities were assigned values between roughness length of 0.4 to 1.6 metres depending on the building height and density. Generally a roughness class of 3 for really small town, 3.5 for suburbs and 4 for the inner city of Malmö and Copenhagen. The first open water roughness length was 0.0005 and was choose because of classification from [12]. As will be seen in the result, lower roughness length was then used to match the measurements turbulence intensity. In the case where
such data is available scaling of the roughness for one or two sectors should be among the first methodological step, especially for such simple terrain. Moreover, the Öresund bridge was modelled using a roughness length of 0.8 in an arbitrary fashion. The area covered by the bridge was tripled to ensure that at least one node of the mesh could be calculated with the roughness of the bridge. At figure [3.1] this last assumption is probably at the origin of the glitch observed in the roughness map generated by the WindSim software. Increasing the number of points in the model file could also correct the irregularity.

Large-scale simulations

The studied area limits were decided upon, partly the cities location but, mostly the maximal practical computation capabilities of the computer. A square domain of 60 kilometres edges length, where the meteorological tower is situated in the centre, covers both the cities of Copenhagen in Denmark and Malmö in Sweden. Nesting technique refers to the larger model where the final smaller studying areas are located. In this case, to effectively capture the effect of both cities in the simulation on the flow, a 60 kilometres edges square volume is studied while twenty to forty kilometres is more usual. Studies published on WindSim website for user reference, Steinbach 2007 [14] and Wallbank 2008 [18], show results of large scale domains simulations.

Terrain Module

The first module of WindSim software is enabled with WAsP format extension generated with WindPro software containing both topography and roughness. The area boundaries are then cropped by WindSim to fit the simulations parameters. In this study, the measurement mast is positioned in the middle of the square domain. Roughness is read from file and no refinement is used. The height above terrain is set to 1500 metres since convergence could not be reached otherwise, terrain variations are not great enough to compute the height above terrain from calculations. The number of cell in $z$ direction is 30 and the total number of cells is set to three million. After terrain module calculation, the number of cell required to solve the volume is 2505630 cells with a distance between nodes of 207 metres in $x$ and $y$ direction.

Wind fields module

In most directions, the convergence is obtained within 600 iterations for an average of 10 hours per sector. More than 30 simulations were ran in a few weeks. In low roughness directions, open sea sectors 180° and 270° for example, “Fixed pressure” parameter was chosen and otherwise the “no-friction wall” boundary condition at top was enabled. No potential temperature function were used. Turbulence model from the ReNormalization Group (RNG k-$\epsilon$) with the coupled solver was chosen. A wind speed of 14 metre per second was calculated using equation [2.4] to obtain an approximated value of 10 metre per second at site.
3.2 Data handling

Chapter 3. Methodology

Figure 3.1: Log of roughness height logarithmic scale, generated in WindSim from terrain module

An atmospheric boundary layer height of 1000 metres was arbitrarily used. Figure 3.1 shows some sectors that have been looked upon closer specially because of the full wake angles of the wind farm and the rougher sectors, Malmö and Copenhagen.

Objects & results module

Climatology was created for each measurement mast height and then inserted into object module for correlation in the later module. Due to correlation limitations, the data was not used but the vertical profiles were extracted from the climatology position at met mast location 55°30’00.00” northing and 12°45’36.00” easting. Several variables can be extracted in that module where values are given at each node for a certain requested height. This last data can then be used but require a certain amount of work to handled the thousand of extracted entries.

3.2 Data handling

Measurements

The three years of measurements prior to the installation of the turbines available for this study give a good insight on the turbulence intensity from all sectors. Data set from after the erection of the turbines was also available but a majority of the sectors are in the shadow of the wind turbines due to the proximity of the measurement mast to the farm, hence unsuitable to use.
Comparison values
Filtering of the data was achieved using Matlab and basic spreadsheet software operations. Data handling is done in a certain arbitrary way, for instance for a certain turbulence intensity percentage the value is obtained with corresponding simulated wind speed using a certain angle sensitivity and speed sensitivity. These values were chosen as plus or minus 5 degrees and plus-minus 0.5 metre per second. In the case of the seasonal comparison figures, 1 metre per second was used in order to obtain a larger sample of the time series. As will be observed, the 0.5 metre per second sensitivity, 1 metre per second, gives values pretty close to the desired value while using larger 2 metre per second bin shift significantly the values on one side when looking at the seasonal effect. Which is expected since the mean wind speed is lower than the simulated values. Spring correspond to months of March to May and winter correspond to December to February. Filtering was simplified with the calendar months numbers not on the exact first to the last day of the season.

3.3 ACD model simulation

After simulating several sectors for three different roughness length in order to match the measured turbulence intensity. A last set of simulation were initiated in order to appreciate the difference between using boundary conditions from a large scale model and the boundary conditions initiated only with the small scale local grid. Several attempts were required to find a proper sized mesh that would initiate with the available computer. Indeed, the software fail to begin the calculations for a certain number of nodes that seem to be different for the actuator disc refined simulations and the previously executed large-scale simulations. Four rows, in the 118 degrees direction, were chosen in order to reduce significantly the number of turbines and being able to produce meaningful results. Using four rows enable the comparison of the two inner rows since the two outer are not affected by the flow of the other removed rows. For practical reasons, letter rows are in the 220 degrees directions while number rows follow the 118 degrees direction.

Figure 3.2 shows the chosen layout in the 118 degrees sector, a direction of interest due to the hole in the array as presented in Vattenfall report on power performance and wake effects of Lillgrund [5]. Appendix 6 shows a graph from the same public and corporate report[5], a similar graph was produced with and without the nesting simulation and is shown in the result section.

Model spacing
In the terrain module, the mesh is created using an object file, consisting of turbine positions and specifications, over the specified volume and refined using a certain spacing over the rotor diameter. The spacing used for the experiment is a division of 10 even though it is suggested to use 16 in the WindSim software documentation. Earlier work from colleagues shown that a spacing of 10 or 12 did
Figure 3.2: Reduced Lilgrund rows for ACD simulations, rows labelling match report by Dahlberg [5], virtual climatology is positioned at the right of the figure for simulation purposes

not differ much in results. Furthermore, some discussions with a software developer also confirm usage of a spacing of 10 to be acceptable. Some more extensive work could be accomplished in order to validate this value but convergence was achieved with these values and results seemed satisfactory after some 400 to 600 iterations using the coupled solver. The number of cells in $x$, $y$ and $z$ directions were respectively 264, 244 and 29 for a total of 1868064 cells.

Power calculation

Because of the nature of the extracted vertical profiles at each turbine, power between the two simulations, with nesting and without, could not be directly compared, yet the relative power can be compared. The lower wind speed, yet comparable, for the nested boundary conditions simulation make it harder to compare the two scenarios. Furthermore, wind fields simulation extracted wind speeds correspond to the values of $U_2$ and $U_3$ not the free stream velocity in front of the turbines. Consequently, power production for the Siemens 2.3 MW turbines was calculated using the data from the $C_T$ and power curve and by multiplying the rotor plane wind speed from the extracted vertical profile. Then, the relative power against the first turbine of row 5 are calculated for both simulation.

Two methods are presented by Gravdalh et Al. [6] and the software literature, the adjusted $C_T$ curve to rotor plane velocity and the integral pressure methods.

In the frame of this work, only the adjusted $C_T$ curve to the rotor plane velocity, instead of the free stream velocity noted $u_\infty$, is used since it is aimed to look more at the effect of the nesting not to benchmark the actuator disc model. The curves at figures [D.1] and [D.2] in appendix [D] are obtained by plotting the values of the rotor plane velocity calculated by using equation (3.1) from the Betz’s theory.

$$C_T = 4a(1 - a) \rightarrow a = \left[\frac{1}{2} + \frac{1}{2}\sqrt{1 - C_T}, \frac{1}{2} - \frac{1}{2}\sqrt{1 - C_T}\right] \quad (3.1)$$

Where $a$ cannot exceed an half, as mentioned earlier, thus physically voiding the first root. Then, with the values of $a$, the power curve and the thrust coefficient in function of the rotor plane velocity can be plotted.
Chapter 4

Limitations

4.1 Wind measurement limitations

Available measurement data are a really good comparison basis but a fourth and higher wind speed measurement would have helped to assess the upper part of the rotor even better. Furthermore, seasonal comparisons consist of, at the best, three series totalizing nine months which is not a large sample when looking at different sectors that are not necessarily in the main wind direction. Data set from after the erection would have been interesting to analyse for the sectors that are not in the shadow of the wind farm but this data was disregarded. Finally, more sensors to verify the stability would have been of a great help to segregate the near-neutral boundary layer measurements and compare them with the simulations.

4.2 Large domain simulation

Discussed earlier in the background section, some affirm that CFD calculations need deep understanding of fluid dynamics coupled with information technologies knowledge. The different steps taken and explained in methodology try to mitigate this limitation. Among, the software related limitations, set boundary conditions are of importance even though the studied domain is fairly large. Two parameters have been disregarded when debuting the simulations, both Coriolis parameters and temperature equations, in both cases it is advised to use with care and simulating with either one of the parameters can cause convergence problems. In the case of the temperature gradient parameters, even though different methods can be used to compare the results, lack of information from the meteorological mast is not enabling true comparison for different ABL stability. Another aspect to consider is the final in flow angle that has been disregarded due to a variation of less than one degree from the simulated sectors angle. Most of the values are obtained using a five degrees sensitivity, hence comparing with these values induce slight error when compared to the one of the angle range.
Air density

For all the simulations, the air density $\rho$ was assumed to be $1.225 \text{ kg/m}^3$ while Bergström report [2] suggest an higher density of $1.25 \text{ kg/m}^3$ for the current site over the year. Simulation of the large domain were run for two sectors with the last value without any noticeable effect on the result. On the other hand, this value would probably have a difference for the ACD model simulations outcome and could be realized as a future work. Both with and without nesting simulations were run with $\rho$ of $1.225 \text{ kg/m}^3$, still enabling comparison.

4.3 Software limitations

Among the software limits, the fact that nesting simulations are not correlated prior to the introduction into the nested domain was unfortunate for the actuator disc simulations. Indeed, trial and error was necessary to try to obtain a similar wind speed at the virtual climatology inserted. Wind fields module simulations are to be correlated in other modules but in the current version of WindSim only extracted wind profile from uncorrelated wind field results are available. Calculated values at node location can then be reconstructed by using the extracted results files for different height. However, after a certain amount of time spent on extracting the values and trying to correlate them, the author decided not to go forward due to lack of time.

Simulations ran with WindSim, in the current version of the software, are somehow limited to angles with a multiple of 10. Hence, for the ACD model, the production value had to be calculated manually instead of software calculated. The assumption of a constant velocity over the rotor in the power calculation could be a source of error since the software use a more consistent approach to calculate at each node.

ACD model limitations

As pointed out, two methods are used by the commercial code developers to evaluate the power. Previous studies, such as [21] on Horns Rev wind farm, using the actuator disc model show discrepancies with measurements when using both calculating methods. A third correction according to IEC standard 61400 for a different wind shear is also suggested. Further work is required to look into this thrust coefficient curve correction.
Chapter 5

Results

As shown in methodology section, focus is set upon six sectors, whose wind profiles are plotted, the windfarm full rows angle and the cities, also nicknamed the rougher sectors. Moreover, turbulence intensity for all simulated sectors are plotted for each height, to appreciate the simulations results. After simulating same sectors with three different roughness length for the open water, the simulations disagree, for the most part, with the measurements. Starting with the wind profiles at figures 5.2 and 5.3, the wind shear slope simulated from smoother surfaces sectors are generally steeper than the measurements. On the other hand, at figure 5.3, both simulated sectors 60° and 330°, Malmö and Copenhagen, with rougher surface length, seems to agree more the measured wind profile. Even though the time series are shorter, spring and winter wind profiles were plotted to initiate some discussions in the next section.

As for turbulence intensity from all inflow directions at figure 5.4, the measured turbulence intensities are plotted against the values calculated for the simulated wind speed of the roughness length $z_0 = 0.0005$ simulations to facilitate the comparisons. An acceptable comparison given the relatively low variability turbulence intensity in function of the wind speed as shown in appendix A and also the low variation of the simulated wind speeds. The simulations, over all, assessed the rougher sectors. Even though the calculations over-estimate the turbulence intensity, the trend, with two maximums from the big cities directions defined by the measurements, is captured. Winter and spring measurements are also plotted and shown at figure 5.5 but care should be taken when drawing conclusions from it because of the reduction of the time series.

Finally, a last comparison is achieved when running the actuator disc model simulations for the 118° sector on the reduced Lillgrund layout with the boundary conditions developed with the roughness length $z_0 = 0.0001$ metres and only using a matching hub height wind speed logarithmic profile. The comparison, in figure 5.1, is set into the same format as the Lillgrund reported power assessment wake analysis [5]. The production seem to be over-predicted for all the rows downstream when compared to the all under-rated power values. The trend, shifted up by around 15 percent of the maximal relative power, is similar to the real production under rated power when normalized with the first row. The largest discrepancy is at the second row downstream where the power is almost three
Figure 5.1: Normalized against turbine 05A power values, for both actuator disc case times higher in the simulations. As for the developed wind fields, the rendered 2D velocity and turbulence intensity at hub height over the domain, a visual comparison of the two simulations, with and without nesting, can be consulted in appendix 4.
Chapter 5. Results

Figure 5.2: non-correlated and simulated wind profiles $z(u)$, in metres and metres per second, for 3 sectors of interest where the straight lines blue represent the calculation for open sea $z_0 = 0.0005$, green line $z_0 = 0.0003$, red line $z_0 = 0.0001$, dashed aqua line are measurements corresponding to the hub height wind speed $z = 65 \text{ m}$ for the open sea $z_0 = 0.0001$ simulation, black dashed for winter filtered data and green for spring
Chapter 5. Results

Higher roughness sectors simulated wind profiles against measurements

Figure 5.3: non-correlated and simulated wind profiles $z(u)$, in metres and metres per second, for 3 sectors of interest where the straight lines blue represent the calculation for open sea $z_0 = 0.0005$, green line $z_0 = 0.0003$, red line $z_0 = 0.0001$, dashed aqua line are measurements corresponding to the hub height wind speed $z = 65$ m for the open sea $z_0 = 0.0001$ simulation, black dashed for winter filtered data and green for spring.
Chapter 5. Results

Simulated turbulence intensity per sector angle compared with measurements

Figure 5.4: uncorrelated and simulated turbulence intensity in percentage per in-flow angle in degrees for three different modelled open sea roughness length for straight lines and where the dashed aqua line with square forms are measured values for wind speed corresponding to the simulated hub height wind speed for the $z_0 = 0.0005$ simulations.
Simulated turbulence intensity per sector angle compared with seasonal measurements

Figure 5.5: non-correlated and simulated turbulence intensity in percentage per in-flow angle in degrees for two different modelled open sea roughness length in straight lines and where the dashed lines are measured turbulence intensity values for spring and winter, for wind speed corresponding to the simulated hub height wind speed for the $z_0 = 0.0005$ simulations
Chapter 6

Analysis

6.1 Large-scale modelling analysis

Turbulence prediction

Typical turbulence intensity in offshore setting, as pointed by Petersen et al. [11], is 8% and the roughness change from land to shore on the flow can extend far offshore. Among the original hypothesis of this work, was to assume higher turbulence because of relatively shallow water of the Baltic Sea and the proximity to the coast of the Lillgrund wind farm. Hence, the advantage of evaluating the conditions at site from large scale model and not only developing conditions from the sea surface. By analysing closer the turbulence intensity per sector, spring values show interestingly low turbulence intensity values. Though, the original assumption seems correct when looking at all sectors.

A closer agreement was found using a roughness length of 0.0001 metre for open sea. As shown in appendix C a graph from [11] shows the Charnock relation often used for roughness classification for sea surfaces. For simplification sake, roughness was uniformly distributed and set constant for all the water surface. In a paper on the roughness classification of sea surface, Lange et al. [9] observed that constant roughness length seems sufficient for the purpose of wind resource assessment and that Charnock relation showed similar prediction error. The constant roughness classification seems to disagree the most for inflow angles from south, roughly 120 to 220°, fetch less affected by coastal phenomenon. This observation is more noticeable when plotting spring and winter turbulence intensity measurements because this region shows the most disagreement. Though, this observation may also be due to the stability, as will be discussed in next paragraphs. From the same Charnock relation graph, the near-coastal surface and open sea surfaces curves shows different roughness values. Indeed, water depth plays a role in the wave height and roughness length would be higher close to land due to shallow water.

Sectors with higher roughness classification in general, shows better agreement than sectors with a longer fetch to the coast. The roughness classification seems to reproduce well the city sectors of Malmö and Copenhagen. The Öresund bridge sector 40° could be considered well predicted but a certain difference is noted in
the wind profile, therefore more work would be required to conclude on bridge modelling by assuming a surface roughness. Over all, the trend follow the measurements sector variation and technique like modelling the city and the bridge as a geometry could possibly improve the reliability of the results. Another factor pointed by Petersen et al.\[11\] for low to moderate wind speed involves the statistical nature of the measurements and point that the variances are sensitive to the time averaging. Particularly for stable conditions the kinetic energy appear at low frequencies and the variability can “be completely dominated by large-scale slow variations in wind speed and direction overlaid with very little turbulence.”

**Wind profiles**

Water surfaces are not being affected, as the land surface, by sun-rays in an hourly manner and commenting on the diurnal cycle is less relevant. Partly because daylight in northern Europe is shorter in fall and higher in summer. However, seasonal temperature difference seems to have an influence on the stability given the observed measurements. Winter values with lower temperature difference at sea surface and air would be more unstable to near-neutral state. Moreover, spring values would be stable from warmer circulating air above cold water sea surface. These observations seem reasonable given the steeper wind speed profiles for winter and higher vertical wind shear in the spring. Petersen et al.\[11\] points out that cold water of the Baltic sea often creates low-level jets generating higher wind that the geostrophic wind assumption.

When looking more closely at sector 40°, the calculated wind profile seems to disagree differently since the measurement slopes seem steeper. A result going against the other trends which could be explained by the model simplification for the bridge but also from the sea corridor north. Another factor of error for the sector of 40° is the proximity of the land, important roughness change, that may be induce variations from a too wide angle sensitivity for measurements comparisons. The same error could arise with the 298° degrees sector being at the edge of open sea surface and rougher land.

Moreover, the assumption of a 1000 metres high atmospheric boundary layer may be erroneous in stable stratification and could have an influence of the wind profile shape. Finally, in a similar manner as for the turbulence intensity, the different roughness classification and assuming constant uniform length over all sea surface may induce error.

As pointed out by Lange \[9\], the wind estimation in offshore, or as the thesis title describe it, in simple terrain, is more complex than it actually appears because of the reason stated above.
6.2 Small-scale ACD simulation

Looking simply at the apparent difference between using boundary conditions as input for the ACD model simulation some comment can be noted. Production seems to be affected by the ambient turbulence and a higher level of turbulence from the nested simulation seems beneficial to the relative power production when looking at the obtained result in figure 5.1. From that starting point, it would probably be interesting to compare the production of winter and spring to look if the trends are modified accordingly.

Figures B.2 and B.3 presented in appendix B can also provide interesting analysis. Starting with the turbulence intensity plots, the ambient level is lower for the simulations without nesting when initializing the simulations only with the sea roughness length and an approximated wind speed at the boundary layer height. In the domain, the simulations calculate a greater maximal turbulence intensity in the case of the simulation with nesting. Even more interesting, a greater difference with the ambient and generated turbulence across the simulated domain is observed. When analysing the speed wind fields results, the difference from the free stream and minimum wind speed is greater for the simulation without nesting and could also suggest lower production as the figure 5.1 suggests.

Finally, when compared to the plot of actual production by Dahlberg [5] in from figure C.2 appendix C as mentioned in the result section, the trend is overall grasped by the simulation though over-estimated for all rows downstream. One hypothesis for this result is using a simulation speed of 11 metre per second, close to the rated power wind speed, when the change in power production is non-linear. This hypothesis would explain why all the estimated production downstream of the first row would be shifted up. Using a value closer to the mean wind speed in that direction would probably be closer to the linear slope and represent more the results shown in [5]. Further work is necessary to see how the wind deficit is predicted with the WindSim actuator disc model for the sector 118° of the Lillgrund windfarm.
Chapter 7

Conclusion

Large scale modelling in this study was achieved using a commercial software calculating RANS equations with the RNG k-\(varepsilon\) turbulence closure over sixty kilometre domain for a coastal offshore windfarm in the Baltic Sea. Acceptable considerations to compare measurements were put forward in the methodology section and extracted turbulence intensity and wind profiles could be compared visually for six different sectors. Better agreement was found when looking at winter season filtered measurements and would suggest that ABL conditions were closer to near-neutral stratification. Stronger disagreement was perceived for spring values, especially for sectors coming from the sea from south. Overall, for all sectors turbulence intensity, the trend was well predicted by the software when using a constant and uniform roughness length of 0.0001 metre for open sea.

A last micro-siting simulation was conducted with the ACD refinement model in WindSim with boundary conditions from the large scale domain and without. A reduced number of rows were simulated in order to obtain a computable number of cell while trying to obtain meaningful calculations. Relative power results show higher production for the turbines downstream when compared with published actual under rated for a free stream velocity close to the rated power wind speed. The trend, even though results are shifted up, is grasped and the hole shows good recovery. Unfortunately, the second row downstream does not seem to be predicted properly by the software.

7.1 Future work

As this work covers many aspect at the same time, numerous future step would be beneficial to further understand this wind farm production. Starting with the ACD model simulations, other sectors of interests should be simulated like sector 220°.

Site conditions, turbulence and wind profiles, could also be simulated with a better roughness classification for areas near shore and open sea as suggested in the Charnock’s relation graph at figure 19. Though, as shown in the result, the stability assumption of near-neutral state may be inadequate for this site, hence a more detailed ABL stability study would benefit further study on this windfarm,
especially to look at production from different seasons.
Two validations would be beneficial for the sake of verification. Firstly, simulating for few sectors a smaller but finer grid than the large-scale 60 km (ie. 30 km) and insuring that the result are not grid dependant. Secondly, even though unpublished results suggest that the spacing of 10 cells for the rotors diameter is sufficient, a grid dependency study could also be realized on for this specific case. For instance, reducing the number of row to only one of interest and aligning the grid to 0 or 90° may help to reduce the number of cells.
Bibliography


Appendix A

Measurements

Figure A.1: Plotted turbulence intensities for all sectors for different wind speed bins, plus minus 0.5 m/s, at Lillgrund windfarm based on three year measurements
Appendix A. Measurements

Measured turbulence intensity per wind speed bin per sector

Figure A.2: Plotted turbulence intensities for sectors of interest at hub height in function of wind speed
Appendix B

Results

Figure B.1: Simulated wind speed for each height
Appendix B. Results

Actuator disk simulation show-off, turbulence intensity

![Figure B.2: Plotted simulated turbulence intensity in percentage across the domain for the nesting actuator disc refinement model (left) and without nesting (right)](image1)

Actuator disk simulation show-off, wind speed scalar XY

![Figure B.3: Plotted simulated wind speed in metre per second across the domain for the nesting actuator disc refinement model (left) and without nesting (right)](image2)
Terrain extension and ACD model refinement

Figure B.4: WindSim generated terrain extension based on user defined topography (left) and refined actuator disc simulations horizontal grid (right)
Appendix C

Figures from other authors

Charnock’s relation for sea roughness length

Figure C.1: Plotted roughness length for 2 experiments (Triangle and circle) and plotted for two sea setting (dashed and line) according to the Charnock’s relation in function of the wind speed from Petersen 1997 [11]
Closely spaced turbines row angle production data

![Relative power levels for the turbines in row 1, 3 and 5 when the wind is blowing along the closely spaced rows direction. (Figure 30 from report [5])](image)

**Figure C.2:** Relative power levels for the turbines in row 1, 3 and 5 when the wind is blowing along the closely spaced rows direction (Figure 30 from report [5]).

Measured turbulence intensity per wind speed bin per sector

![Lillgrund layout and row position from last figure C.2 from report [5].](image)

**Figure C.3:** Lillgrund layout and row position from last figure C.2 from report [5] (figure 26 in the report).
Appendix D

Rotor plane adjustment

Turbine power curve function of the rotor plane velocity

Figure D.1: Modified power curve for rotor plane velocity

Turbine thrust coefficient function of the rotor plane velocity

Figure D.2: Modified thrust coefficient curve for rotor plane velocity