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Industrial Electrical Engineering and Automation

WPP Design and Analysis

An assessment of wake effects and power fluctuations from large scale wind power plant clusters

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THESIS

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Abstract

For the last decades, the wind energy industry has been growing rapidly. More of the production is moving offshore, and in the Baltic Sea some key areas have been identified as particularly suitable for wind power plants. The European Commission have initiated the Baltic Integrid project to assess the potential of building meshed HVDC grids between the Baltic countries and use these areas for wind power plants and connection hubs. The plan for 2030 and beyond is that clusters of plants will be built closely around common connection points. The thesis includes a case study and design of a wind power plant cluster at Södra Midsjöbanken, with a total installed power of 5,2 GW. The results show that these plants are going to shade each other from the oncoming wind. Some areas will be more attractive than others, and depending on how the plants are optimized, they could make neighboring areas undesirable. To reach maximum benefit for society, there might be a need for regulations on how to optimize wind power plants in clusters. A turbine and cable layout is suggested for the cluster, and an economic assessment suggests that the LCOE will be 55,7 €/MWh, about two to three times lower than the average price today. Through the analyses in this thesis, it is shown that there is a correlation between larger turbines and lower wake losses. To increase production and reduce the price of wind energy, it is therefore important that we strive to develop and implement larger turbines. Large scale wind power plant clusters may produce overwhelming power fluctuations to the electric grid. A model developed for the thesis show that unpredicted wind fronts travel gradually through the area and can inject around over 5 GW of power in less than 14 minutes to the grid.

Acronyms

WPP	Wind power plant
HVDC	High voltage direct current
CF	Capacity factor
VSC	Voltage source converter
SMB	Södra Midsjöbanken
MW	Megawatt
MWh	Megawatt-hour
TSO	Transmission system operator
C_P	Power coefficient
LCOE	Levelized cost of energy
BoP	Balance of plant

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Preface

This thesis was built from a curiosity to learn more about the effects that large wind power plants can have on each other, specifically when they are built closely around a common connection point. During the simulations, I realized the positive effects that large turbines have on the overall cost effectiveness of a wind power plant, which slightly changed the direction of the thesis. After analyzing some projects under construction today, it seems that companies are going in very different directions. Some are choosing to build fewer and larger turbines, while others choose many and smaller instead. I hope with this thesis to provide some background and show that using big turbines is the right way to go. Many signs indicate that offshore wind energy could replace large parts of the nuclear and fossil fuel power. For the industry to really take off, we must show decision makers that the future is now. Going toward large scale construction is a key factor in this process. This thesis is a contribution to the Baltic Integrid project, initiated by the European Commission. I want to thank Jörgen Svensson and Andreas Möser for their endless support and devotion to my project. Without them I don't know how I could have done this. I also want to direct my sincerest thanks to Gunnar Lindstedt and the rest of the IEA department at LTH for technical support and great coffee break discussions.

David Eickhoff

1 Introduction

As more and more countries turn toward a renewable power production, the wind energy industry has been on the rise in the last decades. Subsidies from governments have pushed the technological development forward to a point where wind energy is among the most cost efficient ways to generate electricity (Manwell, McGowan, & Rogers, 2009). Prices are competing with those of nuclear- and hydropower, at least when the wind turbines are placed strategically in relation to both the wind resource and each other. Up until recently, onshore sites have been the most popular choice across the globe, with only a few countries focusing heavily on offshore placement, such as the Great Britain and Germany. However, the sites available on land have many disadvantages. In many countries, they are getting fewer and fewer. The best locations are occupied, or owned by people opposing construction of wind turbines on their property. Wind resource is obstructed by forests, hills and buildings which decrease the power production. This has led to companies turning their focus to offshore sites where the wind speed is higher and winds more consistent. This leads to higher production and less power fluctuations over a longer time span. But additional costs associated with the plants being far out at sea make the cost of offshore wind significantly larger than its onshore counterpart (IRENA, 2012).

Many offshore wind power plants (WPPs) are operating today, and many are in pipeline to be built. But as more offshore WPPs are constructed, the distance between them become shorter, and there is reason to believe that they affect each other negatively by shading from incoming wind. Technologies are also emerging to "cluster" plants around common transmission points in a way to reduce cable costs when the WPPs move further out to sea. This strategy assumes that plants are built relatively close to the transmission point, which would further increase the plants' impact on each other. How they interact is highly dependent on the circumstances and will vary between cases. Some facts are however true in most situations, for example that a plant covering another from the dominating wind direction likely will have a higher production. To optimise your WPP and extract as much energy as possible from the wind is obviously important for a single plant without interactions with others, but when building clusters, it is probably better to have all WPPs optimised together. How this can be done is one of the main topics of this thesis.

Furthermore, when building large plants, it is natural to consider using large turbines. Some research has indicated that bigger turbines will lead to lower losses in a WPP. The reason for this will be discussed in detail later in the thesis. Lower losses mean more revenue, and to reduce the total cost of energy it may be worth investing in larger turbines. Using fewer and larger turbines also has several other benefits, such as fewer cables and foundations.

Wind energy is often criticized because of the inconsistent and unpredictable power production. Intermittent power sources are difficult to implement in the grid balance since they cannot produce electricity on request, like a nuclear or hydro power plant can. An ideal scenario from the transmission system operator's (TSO's) point of view would be to have a static electricity demand and a reliable production source, such as nuclear energy. In reality, the demand changes second by second, and this needs to be compensated by increasing or decreasing production. This can be challenging enough, but when you add wind power to the energy mix it becomes even more complex. A sudden wind speed change can cause the balance of the grid to shift, requiring a counter reaction from another power source. This is a side effect of the renewable energy system we are changing to. How fast these variations occur in a designated area will be tested in a power fluctuation model.

1.1 Background

For centuries humans have used the energy in the wind to our benefit, but only recently has it become a major source of electricity. In the first half of the 20th century, when technological advancements in other areas, such as aerodynamics of airplane wings, was applied to turbines, a reawakening of the wind energy industry occured. The first electric wind turbines were expensive, and it took a while before wind power generation could compete with fossil fuel based production. In the 1960's governments started giving support for renewable energy research, which gave the wind power industry a huge push forward. Until 1990 only individual small scale projects were in operation (Manwell et al., 2009). Since then, when the technology matured to the point where companies could make a profit on the free market, the amount of installed wind power has increased dramatically.

In the 1990s, wind power became increasingly popular in Europe. A demand for renewable energy sprung up from the fear of global warming, and with Germany, Denmark and USA leading the race, more and more wind power was installed each year. In 1991 Dong Energy in Denmark built the first offshore wind farm, Vindeby, consisting of 11 turbines with a rated capacity of 0,45 MW each (4cOffshore, 2016). Around 20 years later, the same company began building the Anholt offshore wind power plant, with 111 turbines of 3,6 MW each (DONG, 2017b). Today, Vattenfall is currently constructing the WPP Horns Rev III on the west coast of Denmark, using 49 turbines with a power rating of 8 MW (Vattenfall, 2016b). The EU has set up goals in the Renewable Energy Directive, stating that 20 % of all energy consumption should come from renewable sources by 2020 (EU, 2017). The commission expects 40 % of this to come from wind power.

Since 2000, the wind energy sector has dramatically grown, both in Europe and the world which is illustrated in Figure 1. The subsidies from governments and the EU have also dropped significantly during this time, which is a sign that the technology is mature enough to stand on its own.

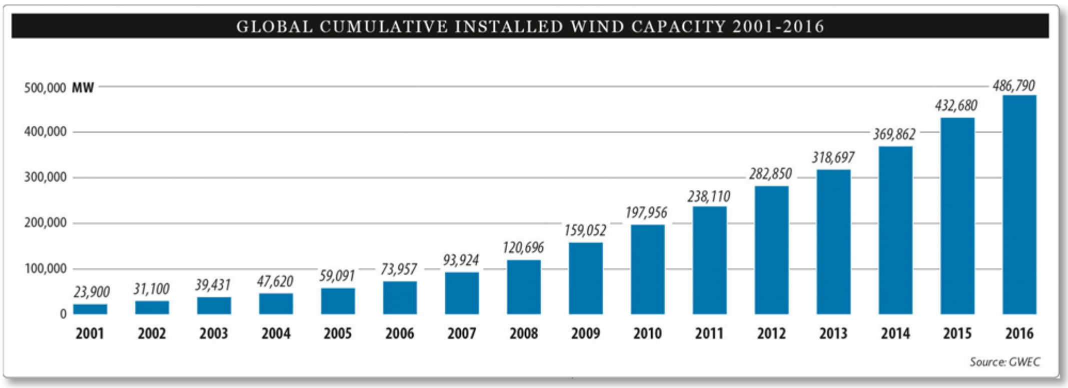

Figure 1: Time evolution of global wind power capacity. (GWEC, 2016b)

In November 2016, Vattenfall gave a remarkably low bid for building a WPP at the Danish side of Kriegers Flak (49,9 €/MWh) (Vattenfall, 2016c). A few months later, in April 2017, DONG Energy made a zero-subsidy bid to build two German WPPs (DONG, 2017a). This means that they will not receive any government support aside from the connection from the offshore station to the grid, which in Germany is supplied by the TSO. These bids indicate that the industry believes in the coming cost reductions, and that offshore wind is about to take a real leap forward.

According to WindEurope (2016a), the levelized cost of energy (LCOE) for onshore wind is in the range of 55-110 €/MWh today. Compare this to the slightly more expensive offshore wind which is in the range of 100-150 €/MWh. The prices for offshore wind is expected to drop to 79-85 €/MWh in 2025, but recent bids from Vattenfall and DONG Energy indicate that prices might drop even faster than that.

1.1.1 Offshore Wind in the Baltic Sea Region

Bloomberg New Energy Finance forecasts that Europe will have installed another 47,3 GW of new wind power until 2030, of which 3,3 GW will be in the Baltic sea. Currently there is around 1 GW of wind power installed in the Baltic Sea, compared with around 10 GW installed in the North Sea (Kruger & Hostert, 2016). In Figure 2, we see a forecast of installed wind power for countries around the Baltic Sea over the next decades. Germany and Denmark are the two biggest contributors. Poland currently have no wind power installed offshore, but are expected to build in the 2020s due to their motivation to reach the goals set up in the Renewable Energy Directive. Finland, which has virtually no offshore wind power today, is struggling with seasonal icy conditions and have a demonstration project of 40 MW about to come online in 2018 to test technologies for coping with the cold weather, but the economic climate for offshore wind power in Finland is not thriving. Sweden has an installed capacity of 201 MW as of 2016, and no new projects are under construction. The policies for renewable energy in Sweden are focused on cost effective, rather than diversified production, which has benefited some industries, but not all. Unfortunately, the offshore wind industry has lagged behind. In Estonia, the development is slow for offshore wind projects. They currently have no installed capacity, but there is one large project of 700 MW which has received state approval for planning. Lithuania, like Estonia does not have any operating offshore wind power plants, but have a 400 MW project under investigation. Instead they have focused on the onshore wind market until now. In 2016, Lithuania was the country in Europe with the highest ratio of installed wind power to annual power consumption (Windeurope, 2016b).

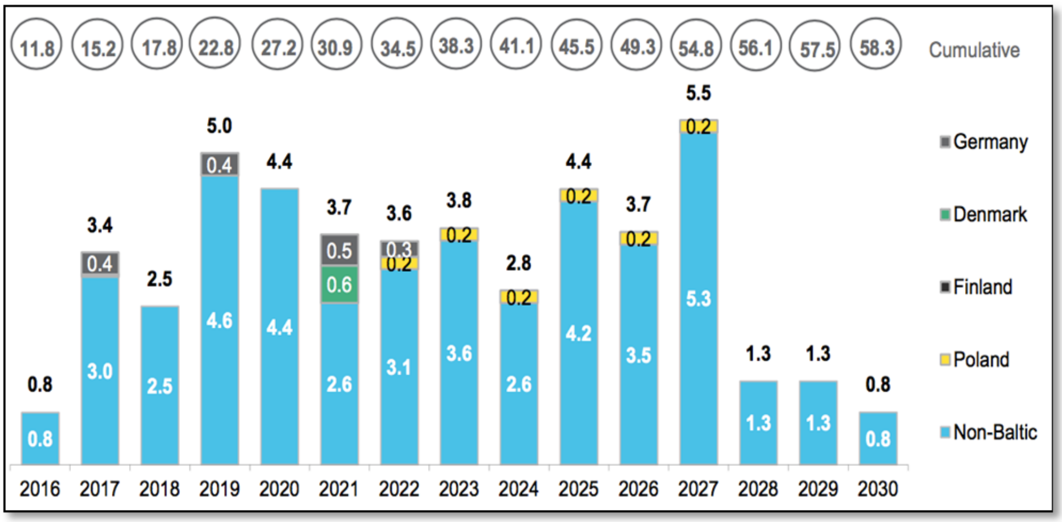

Figure 2: European offshore wind forecast 2016-2030. (Kruger & Hostert, 2016)

The European Union has initiated the project Baltic Integrid to investigate the potential of building offshore WPP clusters and, through them, link the electricity grids between countries around the Baltic Sea. The aim of the project is to "connect relevant stakeholders to optimize the transnational coordination of offshore wind energy infrastructure" (Baltic-Integrid, 2016). The project will equip participants with state of the art insight on framework conditions for development of a regional meshed grid. This means connecting the electric grids using high-voltage direct current (HVDC) transmission lines, and placing offshore wind power plants as hubs for transmitting power to more than one country. This strategy could lead to countries sharing electricity in a more efficient way to even out the supply and demand over large areas, and to increase political stability in Europe.

As a part of this project countries around the Baltic Sea have targeted some geographical areas with high wind speeds which seem very suitable for power production. Although wind resource is important, it is not the only factor being considered when deciding which areas are suitable. According to a report by the Global Wind Energy Council (GWEC) in 2015, wind resource has a relative weight of around 40 % in the decision making process (FOWIND, 2015). Other important aspects are water depth (30 % relative weighting), proximity to construction ports (10 % relative weighting), distance to existing grid (12.5 % relative weighting) and visual impact, proximity to pipelines, oil and gas platforms or shipping lanes (2.5 % relative weighting). Seabed type, extreme weather risks and seismic intensity are also considered. Different organisations and companies have their own ways of finding suitable areas. As an example, the Baltic Sea Region Energy Co-operation (BASREC) have in their 2012 report described a process to score areas based on factors including the ones described above, but also to weigh in other wind farms in operation nearby.

One of the areas currently being considered is Södra Midsjöbanken (SMB), located in the Baltic Sea about 90 km southeast of Öland in Sweden, see Figure 3. It is right by the border between Sweden and Poland.

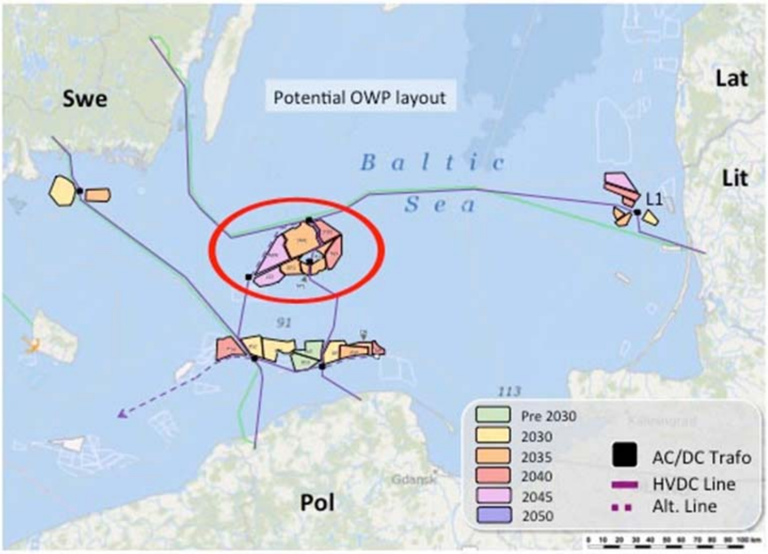

Figure 3: Map of the southeastern Baltic Sea. Södra Midsjöbanken is highlighted.

Södra Midsjöbanken has a water depth of around 30 m, which means it is relatively cheap to place the wind turbines' bottom structures, called foundations. The area is also far away from the coast, which makes it easier to get permission with regard to visual impact and other public interests in the coastal area (EON Wind Sweden, 2015). As a part of the Baltic Integrid project, LTH at Lund University has taken on the task to provide a suggestion for wind power plants in the area, which is one of the things this thesis will cover.

This area is too large for any one company to cover with turbines at one single point in time, and will most likely be divided into smaller sections, as illustrated in the figure above. Companies will then apply to construct WPPs, resulting in many neighboring WPP clusters. If the scenario is followed through, and many WPPs are built this close to each other, several problems arise.

Consider the scenario that the first company builds their plant in one of the areas at SMB. When a nearby plant is being built by another company at a later time, the wind profile for the first plant may change, potentially making it less profitable. Also consider the fact that the first company can without any legal restrictions optimize their plant to the point where it may no longer be profitable to build in the nearby subsections at all. Obviously, from the perspective of transforming into a renewable energy system, it would be best to make sure that all areas are eventually being built and optimized together. For this to occur, governments may need to create legal restrictions to regulate how companies are allowed to optimize their allocated areas.

If the entire area of Södra Midsjöbanken is occupied by WPPs, the total installed power could be around 5 GW, which is much larger than any operating plant today. This would put an enormous pressure on the electric grids in the event of a sudden wind speed increase. However, because of the sheer size of the plants, a rise in wind speed would not occur simultaneously in all turbines, and any sudden power fluctuations would be easier to handle. As a second part of this thesis, a model is built to simulate the total power output when the wind speed increases suddenly.

1.2 Aim of this report

Today, there are no regulations on how companies are allowed to optimise the plants in relation to nearby ones, but this might need to change in the future in order to maintain profitable wind resources in certain areas. This thesis will illuminate some problems of clustering wind power plants together by simulating wake effects in a case study for SMB. A turbine and cable layout will be suggested, as part of the Baltic Integrid project.

One aspect of reducing the cost for offshore wind is to build larger plants with larger wind turbines. The thesis includes an analysis covering the effects of scaling up a wind power plant.

Additionally, the final analysis of this thesis is a simulation of the power fluctuations of a WPP cluster. The idea is that when a wind speed increase occurs, it will take a while before each turbine increases production because of the large area that a wind front needs to travel through.

Because of Poland's very recent attention to offshore wind, and the low revenue opportunities in Sweden, it is not likely that any construction of the SMB area will begin until the late 2020s. This thesis will forecast the situation to 2030-40.

Scientific questions:

1. How do WPPs in a cluster affect each other negatively, and what can be done to minimize the effects?
2. Is it possible to reach a better optimization for a WPP cluster by reducing the turbine density for the first plants? (in the dominating wind direction)
3. How do the wake effects change when scaling up a wind turbine?
4. What happens to wake losses when scaling up a WPP in relation to the turbine rotor diameter?
5. What unexpected loads must the connected electricity grids be able to handle in the case that Södra Midsjöbanken is fully commissioned?

1.2.1 Boundaries

This thesis will cover aspects of a WPP above the turbine level. I.e. smaller details like electrical components inside the turbine or the blade design will not be addressed. Also, the outer boundary will be the HVDC rectifier, before the transmission line to shore. Anything after that, such as connection point in the electrical grid, will be out of the scope. Between the boundaries described above, the focus will be on system-wide perspectives, and just like I will not dive down into the subcomponents of a turbine, I will not go into details for the other components either (transformer station, rectifier etc.)
The outer scope of the thesis is illustrated in Figure 4 below.

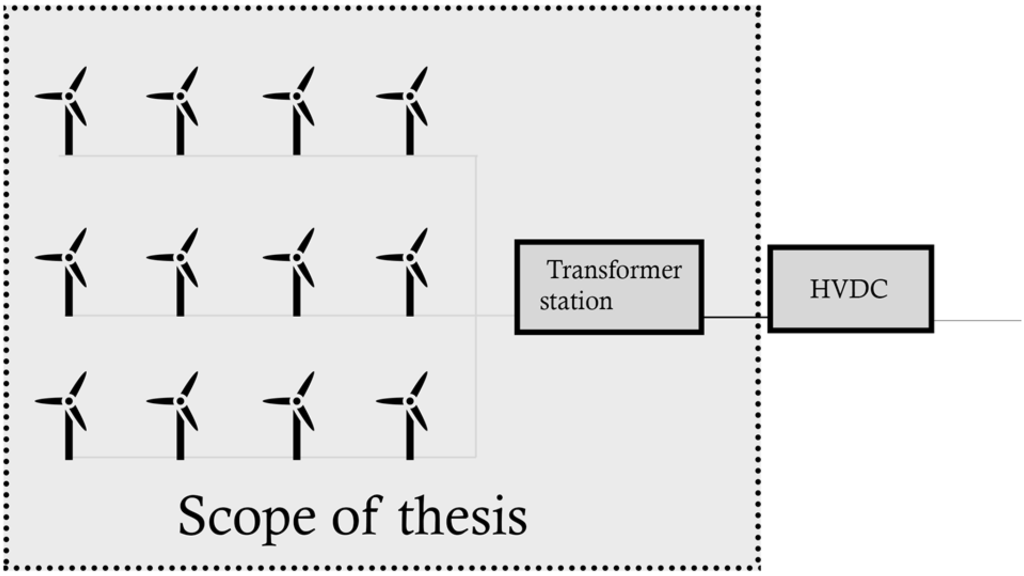

Figure 4: The scope of the thesis starts on turbine level and ends at the HVDC rectifier.

The results in this thesis are based on the calculations made in WAsP and Fuga. The latter is intended for wake calculations and uses pre-calculated data tables to compute the fluid dynamics of air. There are many other ways of calculating wake effects, but this will be the only method used. Other results may be achieved using another calculation process.

1.3 Method – Overview

The method of this thesis is divided into three parts. This method chapter provides a brief overview of the work. Two smaller method chapters are found later in the thesis, in closer connection to the main simulation parts. To answer the proposed research questions, the work of this thesis was divided into 3 major parts. First a literature review of relevant research on which to base the wake effect calculations, turbine layout and power fluctuations chapters. Sources were found along the way from internet searching, books and using various literature databases. The focus was to understand the current situation of offshore wind power production, and to find valuable insights to where the trends are heading within the next decades. For some predictions, such as the turbine capacity forecast to 2030 in Table 1 (chapter 2.3.1), I collected data from several sources and made extrapolations. The forecasts for components could have been backed up with other methods than just literature, such as interviews with people in the business. This was not prioritised, to have more time for the calculations.

The two other main parts of the work are the turbine layout and the power fluctuation model. Both of these parts are based on wake loss calculations which were performed in WAsP 11 and Fuga (v 2.9.6.1), two softwares developed by the Danish Technical University (DTU). The turbine layout calculations were done by trying out various layout options and changing turbine densities to find a good balance between production and wake losses. The power fluctuation model was developed in Microsoft Excel to simulate the power production from the entire SMB area over time as a wind front passes through.

For many tasks, such as the turbine siting and designing the cable layout, the freeware QGIS (version 2.18) was used. Coordinates were exported from QGIS into WAsP and saved into workspace files for analysis in Fuga.

As described above, further details on the calculations in each part is covered in two smaller method chapters (3.3 and 4.3). The reason to divide the method chapter is so the reader will have a better chance of understanding after going through the theoretical chapter called WPP Overview.

1.4 Outline of the report

This thesis has the following disposition. A theoretical chapter called WPP Overview describes how electricity production can be calculated from the energy contained in the wind, and the losses in a a WPP. Some typical components of a WPP are described, with forecasts of what might happen in the future. This is followed by Chapter 3, with the aim to design a turbine layout for Södra Midsjöbanken. A method describes the details of the process. Some analytical tests were done to see how wake effects in a plant behave based on the size of the turbine used, and then a series of iterative tests led to a final suggested turbine layout.

Chapter 4 introduces the model built in Excel to simulate power fluctuations from SMB.

Chapter 5 gives indications for the economic aspect of the layouts for Södra Midsjöbanken. The key value LCOE is calculated, using assumed prices for all the components.

Chapter 6 is a discussion, where the results are analysed and debated. This is followed by a summary of the conclusions, and some ideas for future research topics in this field.

2 WPP Overview

For a reader new to the subject to fully understand the concepts discussed later in this report, I will explain some of the fundamental theories behind wind power production.

2.1 Energy in the wind

To evaluate if a site is profitable for a WPP, it is necessary to estimate the cost of installing and operating, but also how much energy the park is expected to yield over a year, or the course of its lifetime. This can be done by gathering local wind data and analyzing how often the wind speed is within the operating range. If the wind is too low, the turbine will not move, and if the wind is too high, the turbine will shut off automatically to avoid damaging the components.

Winds are large movements of air, caused by pressure differences in the atmosphere. Near the equator, the Coriolis effect can also be a cause to some extent. Influx of energy from the sun warms up the ground, oceans and air. Large air masses move from areas with high pressure to areas with low pressure, and these movements are what we call wind. If the sun did not constantly warm up different parts of the planet, the pressure differences in the atmosphere would eventually equal out and the winds would die. High up in the stratosphere, winds can be more consistent and very predictable, while there is a lot more variation near the earth's surface. The wind can go from practically nothing to a full storm in very little time, which is a challenge for the wind turbine industry.

The energy contained in the wind is in kinetic form. A wind turbine captures part of this kinetic energy and converts it to mechanical energy as the rotor spins. The mechanical energy drives a generator, which converts it to electric energy. In every step of energy-conversion, there are losses. We can begin to understand how WPPs are planned by looking at the following formula, describing the kinetic power in the wind.

$$P(U) = \frac{1}{2}\rho A U^3 \qquad (1)$$

Here, U is the wind speed, ρ is the air density and A is the rotor plane area. When the turbine is operating, the ratio of how much wind "passes through" the rotor is described by the power coefficient, C_p, expressed in the following way.

$$C_p = \frac{P}{\frac{1}{2}\rho A U^3} = \frac{Rotor\ power}{Power\ in\ the\ wind} \qquad (2)$$

This value is between 0 and 1, and the optimal capacity factor as described in 1926 by Betz (Manwell et al., 2009) is 0.5926. A C_p value of 0 means that all wind passes right through the rotor and nothing is converted to mechanical power, while a C_p value of 1 means that the rotor behaves like a wall, and nothing passes. However, if the rotor does not let any air pass, the wind stops, and our turbine would be useless. There needs to be a way for the wind to keep flowing, and we know that a $C_p$value of 0.5926 (or more accurately; $C_p = 16/27$) is optimal.

The losses in the generator are often included in the equation, and denoted η. The electrical power extracted by a turbine from the wind can then be expressed with the following formula. Note that these losses are only for one turbine. There are other losses associated with plants which will be covered later.

$$P_w(U) = \frac{1}{2}\rho A C_p \eta U^3 \qquad (3)$$

One of the most important aspects of this formula is the cubic relationship between wind speed and power. When deciding where to build a WPP it is crucial to know, or at least have a very good estimate of the average wind speed of the site. Wind energy is ultimately converted into money for the owners, and a site with just a few percent more wind than another can have large effects on the power production. WPPs today often cost in the billions of Euros range, which means that companies need to be very convinced about the location. Several years of wind data gathering is often carried out before knowing whether to continue planning for a specific site. This is often done by placing wind masts that measure wind speed and other atmospheric conditions, such as temperature and pressure (M. Brower et al., 2010). When the company has collected enough wind speed data, they can use a power production model, such as equation (3) to have an estimation of the total power output each year (most companies are using professional computer software to do these calculations). The total power output over the whole lifetime will then be compared with the cost of building and maintaining the plant to see if the project is going to generate revenue. A common way to express the cost of producing electricity is with the term Levelized Cost of Energy (COE_L or LCOE).

$$LCOE = \frac{NPV_C * CRF}{Annual\ energy\ production} \qquad (4)$$

Where NPV_C is the levelized net present value, and CRF is a recovery factor based on the discount rate and lifetime of the project. This is the method used for calculating LCOE in this thesis.

An example of a wind data profile is illustrated in Figure 5 below. This is also the wind data that later will be used in the simulations. In this figure one can see how the wind fluctuates up and down during one year. This is one of the most negative aspects of wind energy, it is unpredictable.

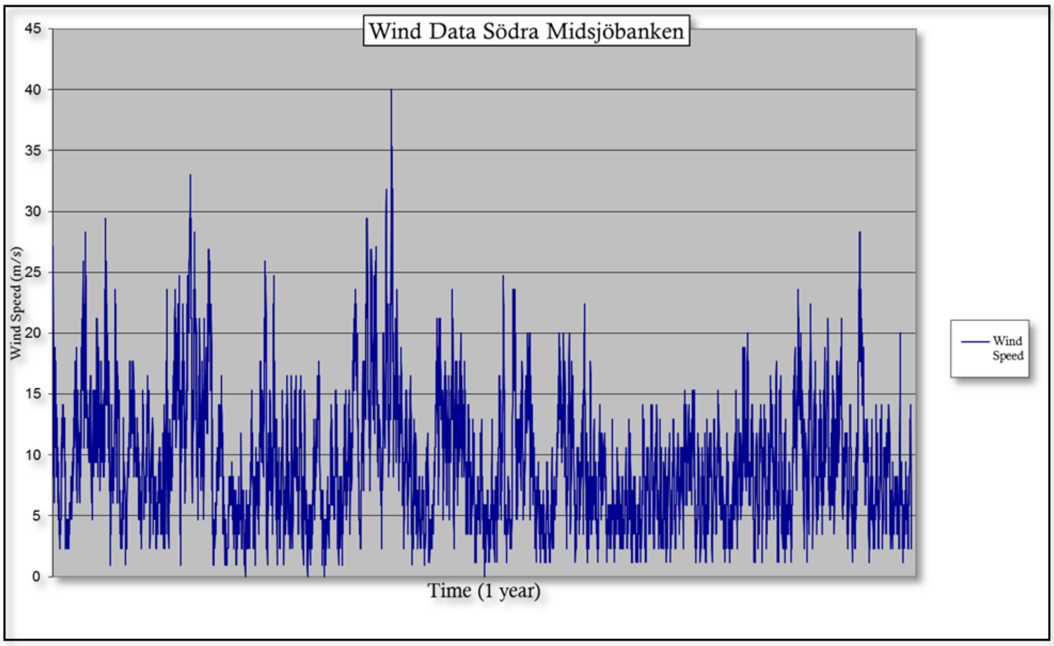

Figure 5: Wind speed data for Nysted 2004. Hourly values over one year.

Another important aspect to take into consideration is the wind angle. This is crucial when designing the layout of the park, since the turbines need to be aligned strategically in relation to the dominating wind direction to increase production. A typical way of presenting the yearly wind angles is by using a wind-rose diagram, see Figure 6 below. This wind rose diagram is based on the same wind data as Figure 5.

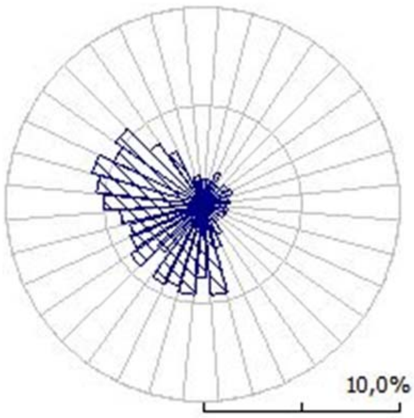

Figure 6: Wind rose diagram used in the simulations of this thesis.

Wind directions are commonly described in degrees. In this thesis, the angle zero is north, and 180 degrees is south. In this particular wind rose diagram, a large portion of the time the wind will arrive from west-northwest (270-315 degrees) while the wind rarely comes from eastern directions.

In the case of the Baltic Integrid project, a final construction at SMB would mean that several hundred, maybe thousands, of wind turbines will be competing to catch the oncoming wind. The turbines in the westernmost part of the area will receive the wind before the turbines in the east. This means that some energy is gone by the time the wind reaches the eastern parts.

2.2 Losses in a WPP

From the kinetic energy in the wind to the consumer, there are many places where energy can go lost along the way. According to Gardner et al. (2008), there are six different categories of losses from a WPP.

- Wake effects
- Availability
- Electrical efficiency
- Turbine performance
- Environmental losses
- Curtailment

Wake Effect

As wind generators convert kinetic energy from the wind into electricity, the remaining wind behind the turbine has a lower speed. This affects turbines located downstream from the first row in a WPP. Internal wake effects are the losses from within the WPP, whereas external wake effects are losses occurring because of nearby plants. In the next chapter, I will go into more detail about this, since it is one of the core ideas of the thesis.

Availability

The technical equipment in a WPP and its transmission system may break, or for other reasons need maintenance. This is not avoidable and will ultimately affect the production of the WPP. The availability can be divided into; turbine availability, grid availability and balance of plant (BoP) availability. Turbine availability is the expected fraction of time when the turbine will deliver power over its lifetime, i.e. when it is not down for scheduled or unexpected maintenance. Grid availability is the fraction of time during which the WPP is able to deliver power to the electric grid, both regarding grid downtime and when the grid is outside of the grid connection agreement. BoP availability considers maintenance and repair of equipment other than the turbines within the plant, such as transformers, internal electrical infrastructure and substations.

Electrical efficiency

These are all the electrical losses between the turbine and the grid connection., mainly in the cables and transformers. Sometimes the non-operational cost of running a WPP is included here, such as electrical consumption by equipment in the substation or turbines themselves.

Turbine performance

When calculating power production in the planning phase of a WPP, a power curve is used, supplied by the turbine manufacturer. These power curves are usually drawn for a very simple terrain site, and in reality it is common that nearby obstacles or other factors will alter the power curve. In some cases, according to Gardner et al. (2008), the supplied power curve does not accurately represent the real power curve even for a simple terrain wind site, and an adjustment should be applied. The turbine performance category also includes the so called high wind hysteresis losses, which is a term for the losses experienced when a turbine automatically adjusts the power output when the wind speeds are getting around cut-out speed, in order to avoid a situation where the turbine repeatedly stops and starts. For offshore locations, the surface is acting in a unique way in the sense that it's roughness changes with wind speed, which can also be a cause of error when calculating the production.

Environmental losses

These are losses occuring from conditions such as ice, dirt, insects, physical degradation of the blades or shutdown because of high equipment temperatures.

Curtailment

Every once in a while, certain conditions make it necessary or beneficial to turn down production. This could be due to turbine loading from unusual wake effects. One or more wind turbines may experience heavy loads under certain wind conditions and need to be turned off. It could also be curtailment of production because of grid frequency control, or for other reasons related to the grid connection agreement. Under certain conditions, it may also be necessary to shut down production because of environmental concerns such as noise emissions, shadow flicker or bird protection.

As an example of losses from the real world, below are some data for the losses experienced by WPP Rödsand II, in Denmark (Svensson (2013).

- *Internal wake effects* *-12.4 %*
- *External wake effects* *-1.6 %*
- *Availability of turbines* *-3.0 %*
- *Availability of grid* *-0.0 %*
- *Internal electrical losses* *-1.5 %*
- *External electrical losses* *-0.0 %*
- *Environmental losses* *-1.0 %*

Note that the external electrical losses are zero. This is because in Denmark, the TSO is responsible for the connection to shore. In other words, the WPP company sells their electricity when it leaves the transformer station, so they do not include any external losses in their budget. Beside these obvious losses described above, a wind power plant will not be able to run at rated power all the time, like a nuclear power plant for example. This is simply because the wind speed varies during the year, and is not always high. Because of this it is not comparable with a 1 GW wind power plant and a 1 GW nuclear power plant. There is a very important concept of wind energy generation called the capacity factor (CF) which is defined as follows.

$$CF = \frac{Full\ load\ hours\ per\ year}{Total\ hours\ per\ year} \quad (5)$$

Or in other words; how much energy a WPP is producing each year, compared with the energy it *could* have produced if it was operating at rated power 100 % of the time. Typical values for CF today are between 20-40 %.

Losses are a natural part of the wind power generation, and some are more avoidable than others. Modern and high quality equipment can save a lot of energy, while other losses are harder to avoid. Minimising wake losses is a typical example of an engineering task. Turbines must be placed so that their wakes have as little impact as possible on other turbines, which can be a real challenge. Since wake losses often decrease a WPPs production by 10-20 %, there are economic incentives to improve the layouts.

2.3 Wind power plant components

In this chapter I will discuss the major components included in a modern WPP, both today and what we may expect in the future. There is not one single way to build a wind power plant, and variations in design, size, location, conditions, etc. will all affect the choices. Today, the price of offshore wind energy is in the range of 100-150 €/MWh, which still is quite high compared with other energy sources, such as hard coal (50-80 €/MWh), nuclear (80-120 €/MWh) or onshore wind (50-110 €/MWh) (Sacha Alberici, Gardiner, Klaassen, & Wouters, 2014). The study by Ernst & Young (2016) forecasts that offshore wind energy costs will decrease to 90 €/MWh by 2030, which would make it more competitive on the market.

The strategy to drive down the price includes building larger turbines to capture more energy, encourage greater competition, keeping the volumes up and improving supply chain challenges (GWEC, 2016a). In a report by BVG-Associates (2016), a series of cost reducing actions likely to happen in the next decade are presented. This includes things like innovations in WPP development, turbine technology, construction and operation. The small improvements in each sector will add up to make offshore wind more cost competitive. Dong energy show with their two German plants and zero-subsidy bids that offshore wind profit is not anymore tied to government support.

2.3.1 Turbines

Today

The most important aspect of a wind power plant is obviously the turbine. The machine responsible for converting wind energy into electricity. There are mainly two types of wind turbines, distinguished by the axis of rotation. Vertical axis wind turbines (VAWT), and horizontal axis wind turbines (HAWT), where the latter is far more common. Since the dawn of modern wind power generation, turbines have made a long journey in design and scale. Today, much of the research carried out to improve turbines is in the aerodynamics of the blades. There are also some experimental parts of the turbine industry, where research is focused on finding alternative designs for the energy generation technology, but as of today, three bladed horizontal axis turbines largely dominate the market. There have been prototypes using fewer or more number of blades, and the conclusion has led to a few key points. Increasing the number of blades tend to increase power extraction slightly while increasing noise, and making the turbine more expensive.

Three blades are a good trade-off between power extraction and cost, and are also more comfortable to look at than one, two or four-bladed turbines. Another effect to consider is the natural resonance of the structure, where a turbine with an even number of blades can give stability problems (DWIA, 2003).

Two key features of a wind turbine are the rotor diameter and the rated power. Generally, these two parameters scale with each other, but a larger rotor does not necessarily mean a higher power output. Since the first modern wind turbine, the average rotor has increased in size every year. Figure 7 below show the evolution of rotor diameters since 1985 with an estimated forecast into the future (IRENA, 2016).

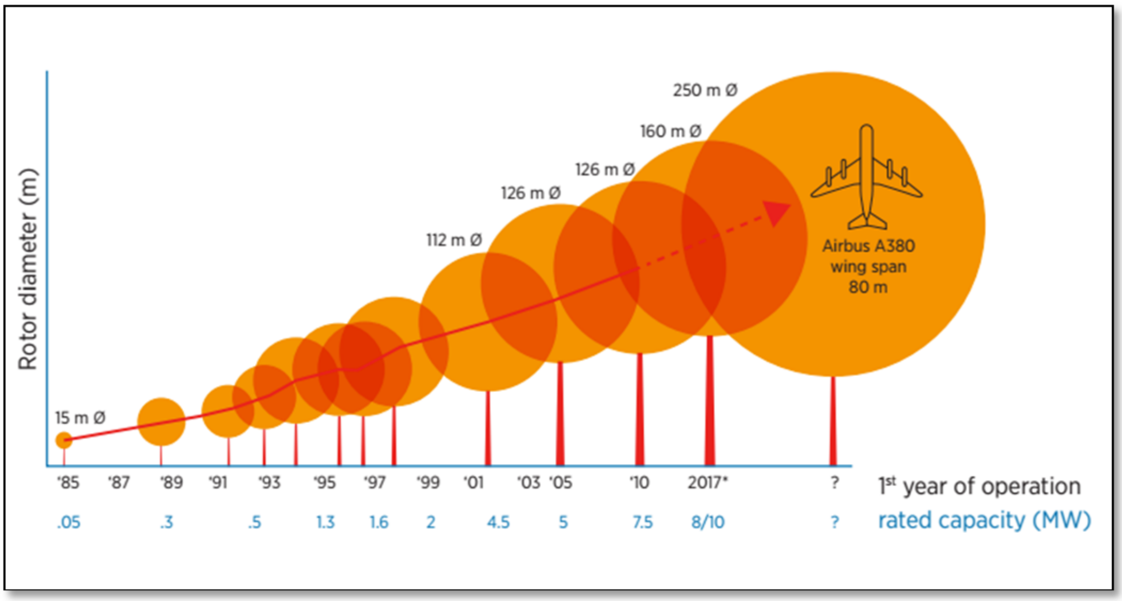

Figure 7: Growth in rotor diameters of wind turbines in 1985-2016 (IRENA, 2016).

Bigger rotors can catch more wind and turn larger generators. A trend in land based turbines in the recent years is to release so called low-wind models with increased rotor diameter while keeping the rated power down. When the rotor diameter increases, so does the area where the wind is caught, which means lower wind speeds are required to reach full production. This increases the range of operation, and improves the CF, meaning that the turbine can operate at nominal power during more hours per year. When the best wind resource locations are occupied, and the second best are being constructed, some companies have chosen this strategy to balance for the lower wind speed. However, a turbine with a higher rated power could yield more *energy* during a year, so it is a trade off between catching a lot of wind versus making better use of the high wind days. This strategy of increasing the CF also leads to less intermittency, and a more unvaried power production, which is good for the electric grid. It does however make the turbines more expensive per installed MW, and a larger mass at the top will make the tower less stable.

The rated power of wind turbines has also increased steadily in the last decades, which can be seen in Figure 8. The illustration estimates a 10 MW turbine in 2018, which may be a reasonable prediction when considering the previous trends. In 2012, the average wind turbine to be installed offshore was 4 MW (Frede Blaabjerg, Fellow, & Ma, 2013). In 2016, this value increased to 4.8 MW and the largest wind turbines on the market today have a rated power output of around 8 MW. In January 2017, Vestas broke a record for wind energy generated within 24 hours with an 8 MW turbine uprated to 9 MW, producing 216 000 kWh.

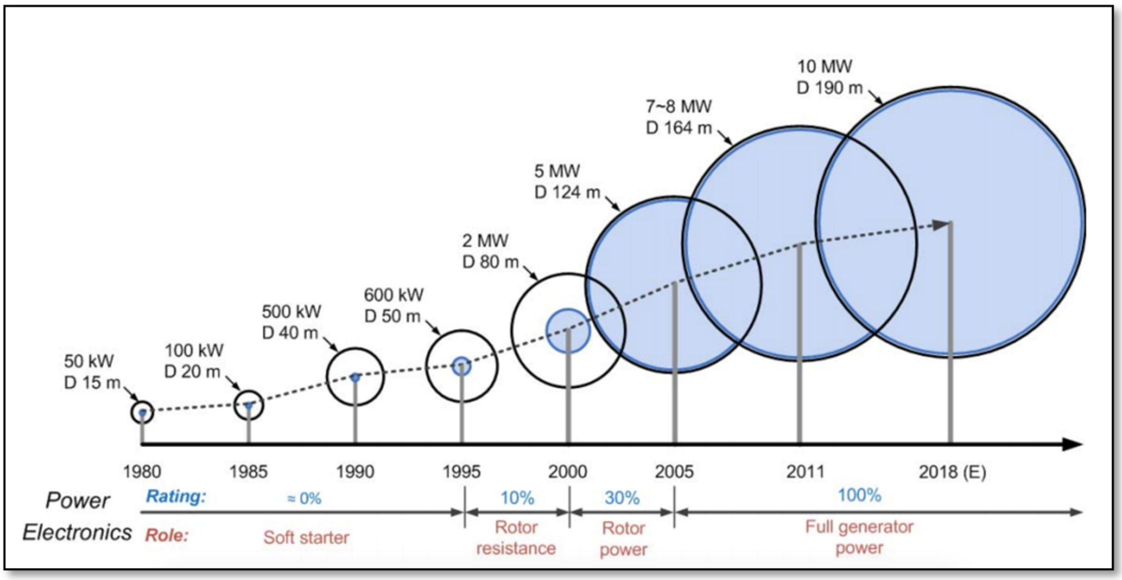

Figure 8: Evolution of wind turbine rated power. (Frede Blaabjerg et al., 2013)

The capacity factors of turbines today vary widely depending on many factors, such as wind resource, obstacles, nearby turbines or WPPs, etc. A general trend is that higher average wind speeds give higher capacity factors, illustrated in Figure 9. Since average wind speeds generally are higher offshore than onshore, the capacity factor is higher for offshore turbines.

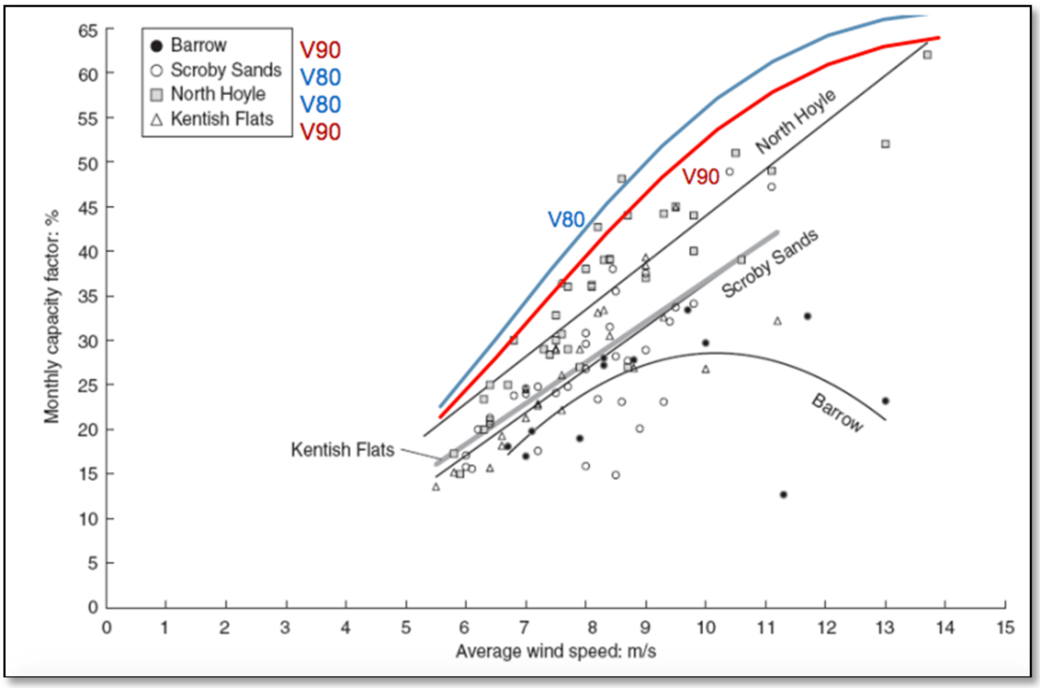

Figure 9: Capacity factors for four different locations at different wind speeds.(Tavner, 2011)

In the future

Since 2009, the association for wind energy in Europe (Windeurope, 2016b) have released statistics over the average installed wind turbine sizes offshore.

Based on these values, a trendline shows that the average offshore turbine size could be 7,7 MW by 2030, if the trend continues like the last 7 years (see Table 1 and Figure 10). 7,7 MW may seem small, since we already today have 8 MW turbines on the market, but the data also includes near shore turbines which are generally smaller due to less wind and more visual disturbance. It is reasonable to think that by 2030 the average turbine size installed in *far-offshore* locations is higher, somewhere closer to 12 MW. It is also probable that the average turbine curve is not going to be perfectly linear, but slightly exponential due to the expansive pursuit to build further offshore in the North and Baltic sea. This development increases the share of far-offshore sites in relation to near-coastal, many of which are already occupied.

Table 1: Average installed wind turbine size offshore. (Windeurope, 2016b)

	Year	Average Turbine Power in MW
Real world data	2009	2,9
	2010	3,2
	2011	3,6
	2012	4
	2013	4
	2014	3,7
	2015	4,2
	2016	4,8
Extrapolated	2017	4,796
	2018	5,017
	2019	5,239
	2020	5,460
	2021	5,682
	2022	5,903
	2023	6,125
	2024	6,346
	2025	6,567
	2026	6,789
	2027	7,010
	2028	7,232
	2029	7,453
	2030	7,675

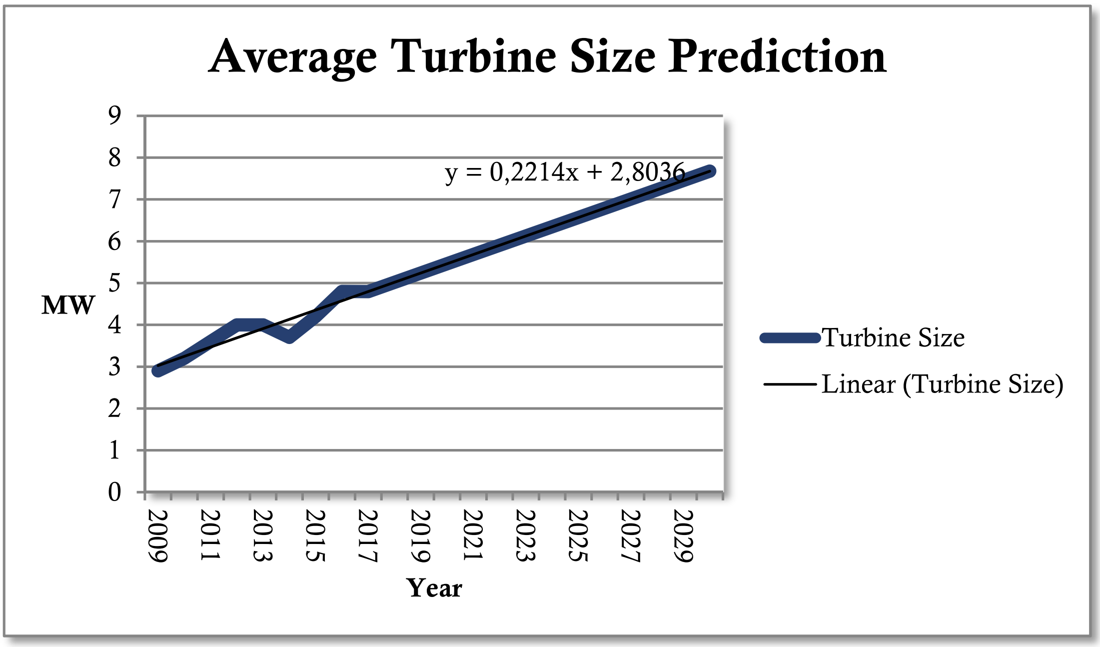

Figure 10: Average turbine size prediction based on data from 2009-16. Extrapolated after 2016. (Windeurope, 2016b)

The International Energy Agency and the Energy Research Institute have in their report (Zhongying et al., 2011) outlined a likely trend in the average wind turbines installed in China between 2010-2050. Figure 11 below illustrates this trend.

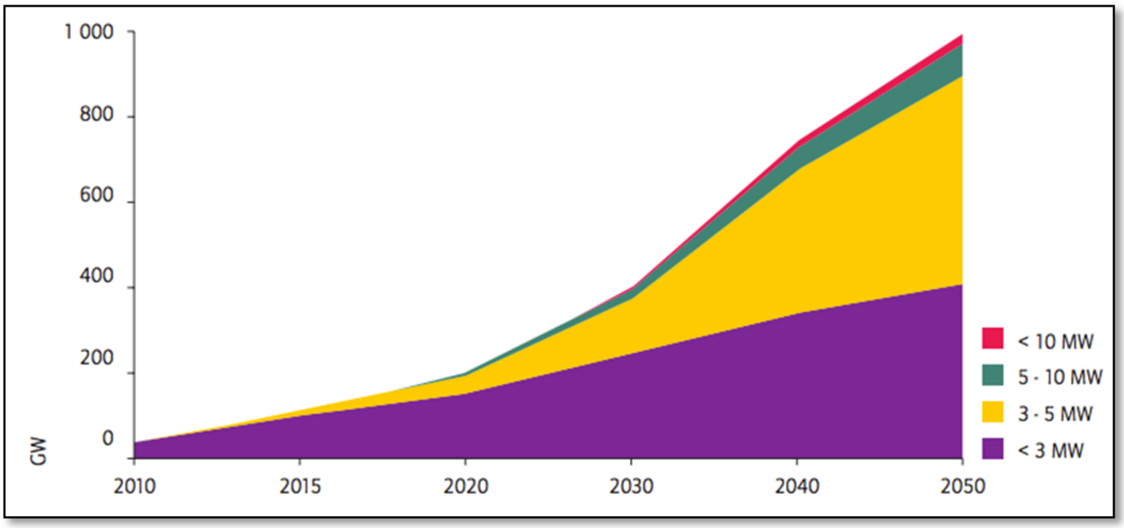

Figure 11: MW-Scale turbine system demand 2010-50. (Zhongying et al., 2011)

Their forecast states that turbines with a rated power below 3 MW are going to increase steadily all the way to 2050. Between 2015-20, turbines with a rated power of 3-5 MW are taking a larger share of the market, and turbines rated at 5-10 MW start coming out. Between 2020-30, the 3-5 MW turbines grow in popularity. At 2030 there is a sudden increase in both 3-5 MW and 5-10 MW turbines, which is explained by the end of life of many currently installed < 3 MW turbines being replaced by bigger versions.

This forecast includes both on- and offshore wind turbines in China, which explains the high number of small turbines. The market in china may differ from the here, but it can serve as an indication for the future even in Europe. The turbines larger than 10 MW may start to roll out by the 2020s, and by 2030, this segment of turbines will have a market share of around 10 %. Onshore turbines and near-coastal offshore turbines will contribute to the major part of smaller sized (< 5 MW) turbines installed, and far-offshore installations are still dominated by the largest models of turbines. This forecast supports the prediction that by 2030, the average offshore wind turbine for far-offshore sites may be around 12 MW. It is also a possibility that 2-bladed turbines are going to take a larger market share offshore due to their cost efficiency.

Apart from horizontal axis wind turbines, some research is ongoing about vertical axis technology. The European Union is funding a project called Inflow, aiming to investigate the competitiveness between VAWT and HAWT in floating offshore plants (InFlow, 2014).

The thought of utilizing stronger and more consistent winds higher up in the atmosphere is also growing within the wind power research industry. Some companies are looking into using airfoil kites connected to turbines and control systems on the ground to generate electricity. Obviously there are many problems with this approach. Kites with lines reaching high up in the atmosphere affect birds and air traffic, and if the winds die, the kites need to avoid crashing.

2.3.2 Foundations

Today

The foundation is the base on which the turbine stands. Offshore turbines and their structures need to withstand harsh weather conditions. Waves and winds can make the them experience significant loads, which puts high stress on the materials. There are two main types of wind turbine foundations, floating and bottom fixed. As of today, the market is dominated by bottom fixed turbines since the floating structures are still in a development phase.

The most common bottom fixed foundation is the monopile, while other types include tripod, gravity-base, high-rise pile cap, tri-pile, jacket and suction bucket (see Figure 12). The Baltic Sea has an average depth of around 55m (BSBD, 2016) with many large areas below 30 m, particularly suitable for bottom fixed foundations.

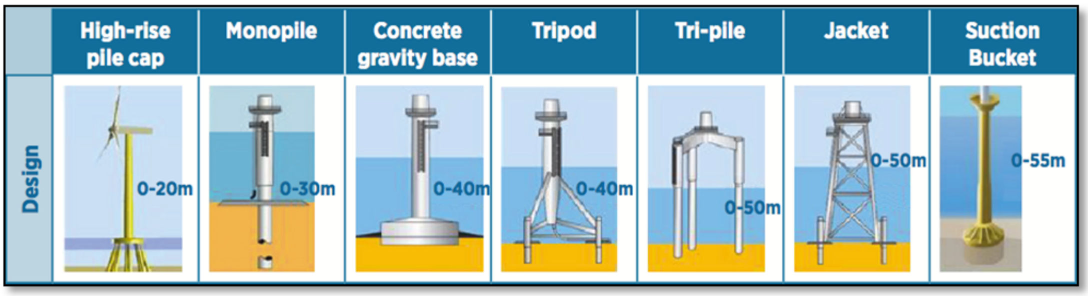

Figure 12: Different bottom fixed foundation types. (IRENA, 2016)

A summary of the pros and cons of different bottom fixed foundation types can be found in Table 2.

Table 2: Pros and cons of different foundation technologies. (IRENA, 2016)

	Monopile	**Tripod**	**Gravity-base**	**High-rise pile cap**	**Tri-pile**	**Jacket**	**Suction Bucket**
Pros	Simple design	More stable than monopile	Cheap. No drilling	Cap protects against maritime collisions	Can be installed with traditional jack up barge	Stable. Light. Good alternative for deep waters	Less steel. No drilling
Cons	Deep locations requires large diameter Drilling stressful to environment	More complex installation Expensive	Currently only used in shallow waters	Limited water depth. Complex manufacturing	Expensive due to complex structure and weight	Quite expensive	Requires soft bottom

Floating foundations are being researched in several parts of the world where the water is too deep for bottom fixed structures, but no large plants yet use this technology.

In the future

Bottom fixed foundations are today much cheaper than floating in shallow waters (< 50 m), which has led to most WPPs being constructed at a depth below 50 m. If floating foundations one day became economically competitive, this would unlock a huge potential of high-wind locations. One study shows that floating foundations could reach cost parity with bottom-fixed already during the 2020s (CarbonTrust, 2015). It is not impossible to see a scenario where floating foundations will be the go-to technology even in shallow waters like the Baltic Sea. If the floating foundations prove stable and cost effective it might be a clever option when using very large turbines, since the tower, nacelle, rotor and foundations can be assembled at the coast and towed out by boat. Also, bigger foundations and turbines mean that it is less likely for the structures to oscillate in frequency with the waves, which is one of the main concerns for floating platforms.

2.3.3 Grid infrastructure

Today

The first turbines were directly connected to the grid with so called "fixed speed" generators. This means that the rotor is moving with a constant speed to create AC current with the same frequency as the grid. A fixed speed wind turbine connected straight to the grid is a simple and robust solution, but a constant rotor speed means that the turbine is not working optimally. To do this, the wind turbine needs to control the rotation speed of the blades. Changing the rotor speed without releasing the generator from the grid frequency can result in damage, so this is normally done by converting the current from AC to DC and then back to AC again within or near the turbine. In this way it is possible to control the frequency of the rotor. Turbine generators typically have an output of < 1000 V, which is stepped up in each turbine to 33 kV. The first offshore WPPs used the same voltage as the plant in the transmission lines to shore, but 33 kV power cables quickly became the limiting factor in power transmission, and the solution was to step up the voltage at the end of the collection grid.

Losses in AC systems are partly related to joule heating. Essentially, as current travels through a medium with a resistance, some power will convert to heat. The active power in an AC system is proportional to the resistance and voltage. Losses are $P_{loss} = 3RI^2$ where R is the line resistance and I is the current; the same current that with the line-line voltage U gives the transferred active power $P = \sqrt{3}UI$. P_{loss} is in the order of a percent of P.

Losses are $3RI^2$, where R is the resistance and I is the current, which can also be expressed by $P = \sqrt{3}UI$ where P is the active power and U the voltage. To reduce losses in transmission, companies started building plants with an offshore transformer for stepping up the voltage before transmission to shore. An early example of this type of system is the WPP Horns Rev 1, outside the west coast of Denmark. This was one of the first large scale WPPs to use a transformer station system. The 160 MW plant has 80 turbines rated at 2 MW, and the transmission to shore is through a 150 kV HVAC cable, 19,2 cm in diameter. At the time of construction, this was the thickest submarine cable ever made (Vattenfall, 2017).

But AC cables produce more losses than joule heating. Reactive power occur when the voltage and current are not in phase. Above a certain distance (50 – 200 km) the losses can be so large that it is not viable to use conventional AC power lines anymore. This is where we are at today, as plants move farther from the coast. To avoid these losses, there are several alternative technologies emerging. One of the most promising one is high voltage direct current with voltage source converter (VSC HVDC). This technology is an appropriate choice for transmitting electricity long distances. Some plants built in the North Sea in the last few years already use HVDC technology to transmit power to shore (Tennet, 2017). The equipment is still quite expensive and new to the market, but will likely drop in price in the coming years.

Another technology for transmitting electricity long distances without large losses is low frequency AC. DONG Energy are implementing this technology in their WPP Hornsea Project One, with a distance to shore of 120 km (ABB, 2016). The main benefit of LFAC over HVDC is that the expensive offshore converter station for converting AC to DC is not needed. However, a study by Ruddy, Meere, and O'Donnell (2015) suggests that the cost reduction by avoiding the converter is partially eliminated by the more expensive AC cables. A wind farm operating at LFAC would utilize the same AC cables as HFAC but at a frequency of 16,7 Hz to reduce losses. In another article (Ruddy, Meere, & O'Donnell, 2016) the authors suggest that LFAC works best when the distance is between 80-180 km, and that a challenge today is the design of the low frequency offshore transformer station. Another study suggests that LFAC is a viable alternative for certain distance gaps between HVAC and HVDC, where the power transfer is not too high (Xiang, Merlin, & Green, 2016).

In the future

The strategy of clustering WPPs together around a single transmission line, or several lines going to different countries, i.e. a "meshed grid", have both advantages and disadvantages. Investment costs can be cut by having to lay fewer cables, but in order to make sense of a meshed grid, HVDC technology must be used, which instead could make the final cost higher. This is due to expensive components, like breakers, which are necessary to create a safe and reliable network. The HVDC industry is expanding rapidly at the moment, and technical advancements could significantly reduce the costs in coming years. Cole, Martinot, Rapoport, Papaefthymiou, and Gori (2014) suggests that even if a meshed grid may increase the initial cost, other benefits can outweigh the negative aspects. A significant amount of CO_2 emissions could be avoided partly due to the efficient use of a meshed grid to reduce wind curtailment, in the case that wind power substitutes fossil fuel plants. Socio-economic benefits can also be expected when WPPs can sell electricity to several markets. They can then sell to the highest price, benefiting both the grid with a shortage in production, as well as the electricity producer. The higher production reliability of a meshed grid will also lead to a value both for the system operator and the plant owner. If a WPP loses the grid connection to one grid, it can still operate and sell to another grid. This can lower, or eliminate, the grid availability losses. The conclusion is that meshed grids are profitable in almost all cases, which is an insight companies and governments are likely to embrace in the coming years.

HVDC transmission has the benefit of being able to supply power to more than one electric grid at the same time, even if the grids are operating at different frequencies. This is particularly interesting when considering "sharing" WPPs between countries.

For the case study of Södra Midsjöbanken and the simulations of this thesis, the assumption was made that HVDC will be the preferred technology. It is also assumed that a meshed grid will be implemented as it will be of interest for both Sweden and Poland. By 2030, it is safe to assume that the equipment costs will be lower as well.

For a long time, 33 kV has been the most common voltage level for collection grids, but 66 kV grids are emerging to cope with higher power transfer. With growing turbines, the 33 kV cables will have problems handling all the power in longer arrays. It is possible to use 33 kV systems, using more cables (as illustrated in Figure 13), but a more reasonable approach may be to use the 66 kV grids.

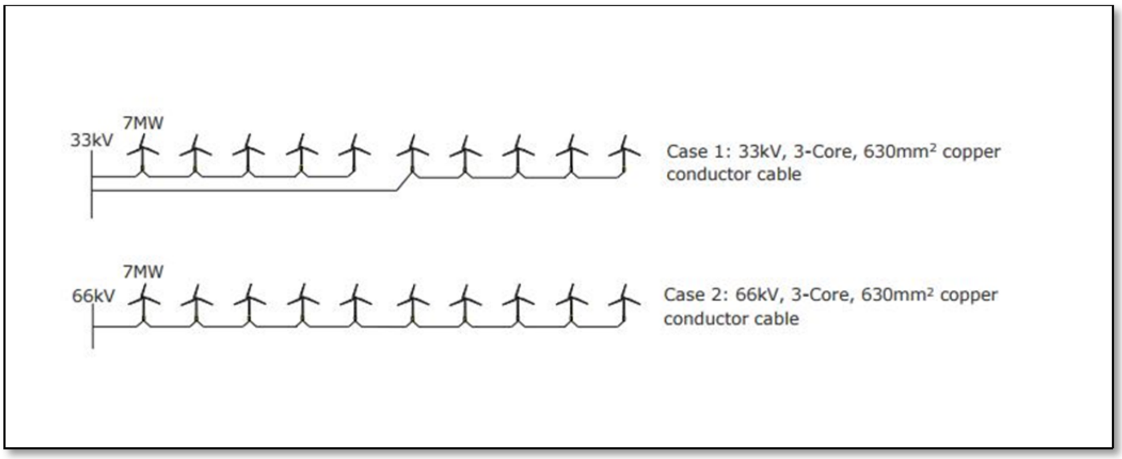

Figure 13: Example on 33 kV versus 66 kV internal grids. (Schlemmer & Greedy, 2015)

2.3.4 Substation

Today

The substation is another main component in a wind power plant (see Figure 14). Because the internal grid usually work at a voltage level of 33 kV, these cables have a limited power transfer capability and there is usually an offshore platform called a transformer station (or substation) at the site. In here, the 33 kV array cables are collected and the voltage is transformed up to a higher level (commonly today 132 kV). Some substations transform the voltage to 150 kV, 225 kV, or even more. As WPPs grow, the need for stronger transformers increase as well. Inside a transformer station is usually two transformers, handling half of the current each. This is to ensure that if one breaks, the other half will still operate. In Figure 15 one can see a single phase diagram for two such transformers on a single foundation.

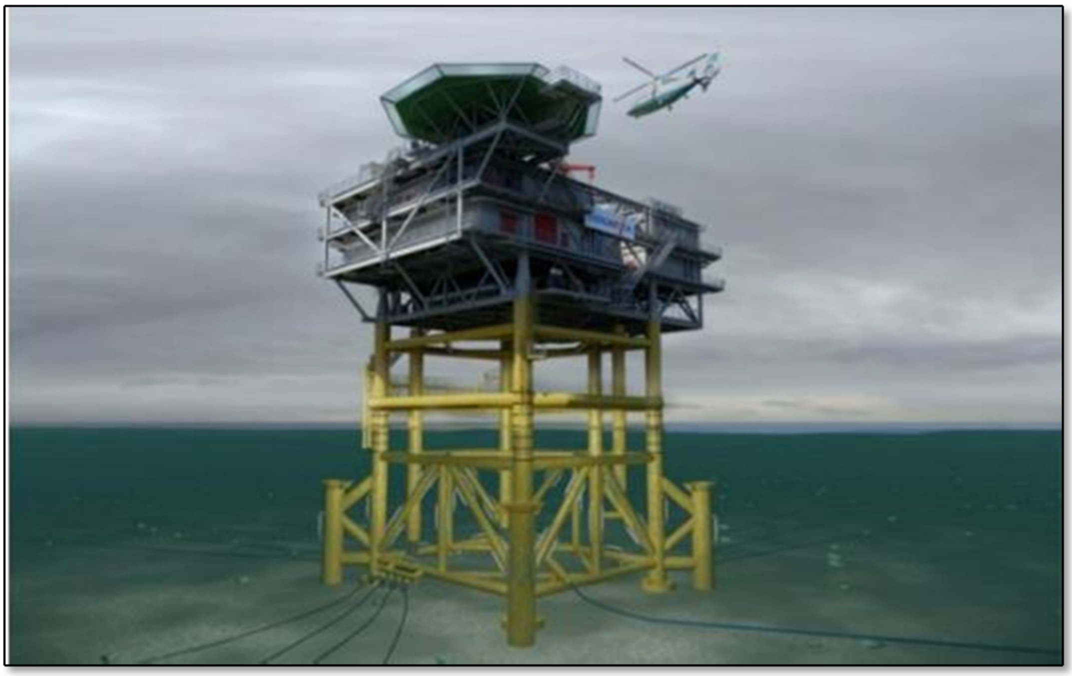

Figure 14: A transformer station installed on a jacket foundation. (MariLim, 2015)

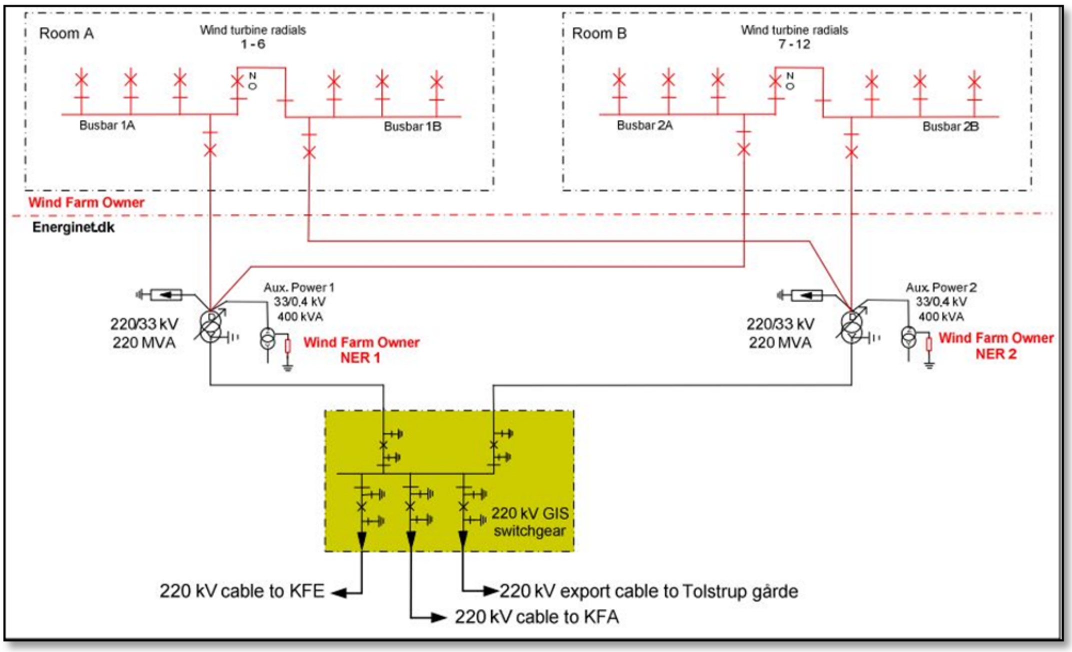

Figure 15: Single line diagram showing two transformers on a foundation. (Vattenfall, 2016a)

In the future

As WPPs grow larger, the need for bigger substations increase as well. To handle more power transmission, the voltage needs to be transformed to higher levels. Many of the large WPPs and clusters of plants will likely have several substations, each handling a portion of the turbines. In the cases where HVDC is used, the transformer station can be built in close connection to the rectifier, meaning that the high voltage cables don't need to be very long. In the suggested layout for SMB, the 66 kV internal grid will be transformed to 300 kV in several substations before reaching the HVDC hub.

3. WPP design and micrositing

Chapter 3 will try to answer a few of the main questions for this thesis; how clustered WPPs affect each other and if the effects can be mitigated by turbine density variations in the dominating wind direction. How the scaling of plants respond to the traditional way of spacing turbines based on their rotor diameter, as well as how wake effects relate to the size of turbines. To do this, tests were performed in the software WAsP, using the extension Fuga for wake modeling. After the results, a suggestion for a basic layout will be presented for the Baltic Integrid project, as a starting point for future work.

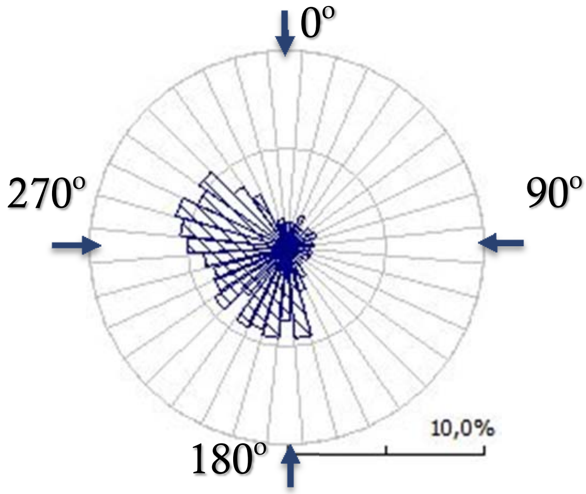

Figure 16: Wind rose for the adjusted Nysted wind data. (Showing how often the wind came from each direction)

The wind data used in the simulations (see Figure 16) were for one year (2004) at Nysted WPP, adjusted to a higher average wind speed to suit the conditions at SMB. The data contains hourly values of wind speed and direction. Data from Nysted was used because of the lack of local data from SMB. Data is available from wind masts at Bornholm, which is closer to SMB, but measurements on land can differ from offshore. E.ON has a wind measuring mast at SMB, but wind data can be quite valuable for a company and is usually not available to the public. The distance from Nysted to SMB is about 250 km, and the assumption is that wind speed is generally a little higher at SMB, but the wind directions are the same. The average wind speed is assumed to be 9,1 m/s at 70 m. E.ON later provided a real value for the average wind speed in the area, 9,4 m/s. This value is used in the final calculation.

For the simulations, based on the assumptions made in chapter 2.3.1, a hypothetical 12 MW turbine with rotor diameter 200 m and hub height 135 m was used. Because power and thrust curves do not exist, they were taken from a Vestas V112-3.0 MW turbine, scaled up to 12 MW (see Figure 17). The cut-in, rated and cut-out speeds are 3, 13 and 25 m/s respectively (see Table 3: Properties of the assumed turbine type.

Table 3: Properties of the assumed turbine type.

Rated P	Rotor D	Cut-in U	Rated U	Cut-out U
12 MW	200 m	3 m/s	13 m/s	25 m/s

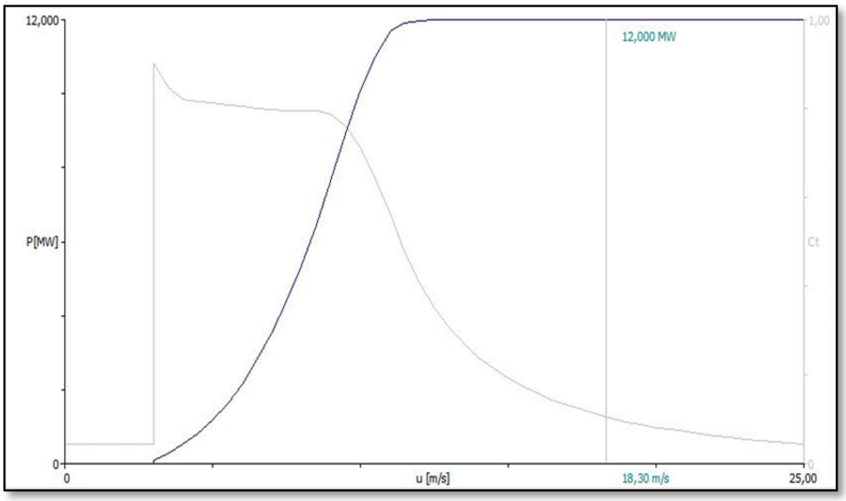

Figure 17: Power curve for hypothetical 12 MW turbine used in the simulations. The grey curve is the thrust curve for the turbine.

3.1 WPP scaling analysis

When designing a WPP, one important parameter to analyse is the distance between turbines. If they are built too close to each other, the wake effects will be too large, but if the distance is too big, the costs will increase, and so does the area for which a permit is needed. Wake effects lower than 5-10 % indicate that the turbines are quite dispersed, and the area could probably be smaller but still give a good yield. In literature on the subject you often find a rule of thumb to use around 5-9 rotor diameters distance in the dominating wind direction, and 3-5 rotor diameters in the perpendicular direction (see Figure 18). These values are used as a guideline to keep the efficiency high and area low.

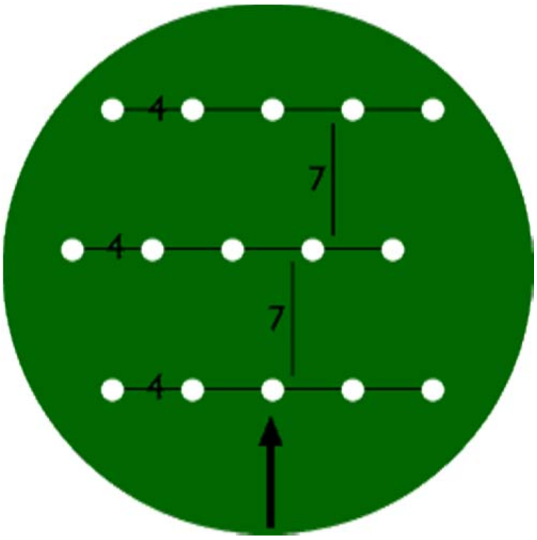

Figure 18: Illustration of the turbine spacing according to dominating wind direction. (Krohn, 2000)

However, when the industry starts using larger and larger turbines, these guidelines will continuously become more and more inaccurate. There is not a linear correlation between wake distance and rotor diameter. When sizing up a plant, you do not change the atmospheric conditions, i.e the refueling of the wake. This, in combination with the fact that larger turbines catch more energy lead to some interesting effects.

A study by Rivas, Clausen, Hansen, and Jensen (2009) suggests that WPPs with many small turbines will have higher losses than plants built with fewer large ones. The turbine density versus plant efficiency was compared for two scenarios. In one case, 106 turbines of 3 MW each were installed (318 MW total), and in the other case there were 64 turbines of 5 MW (320 MW total). The graph in Figure 19 shows the results, which point towards a higher overall efficiency when building with larger turbines.

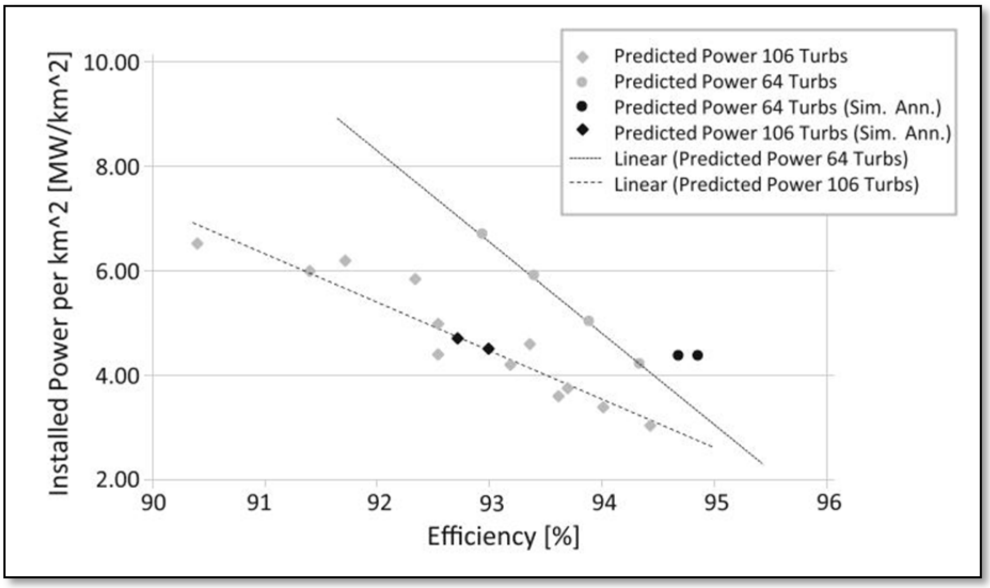

Figure 19: Study by Rivas et al. (2009) on the impact that turbine size and density have on the efficiency.

The reason for this is debated. Samorani (2010) explained it with the idea that when installing multiple turbines, it is expected that most of them are affected by at least one wake coming from another turbine. Installing fewer turbines means we get fewer wakes, and the chance is higher that we can reduce the number of turbine interactions. The writer does point out that his ideas are not supported by scientific research and suggests further studies on the subject.

Another reason for this behavior is that larger turbines have bigger rotors and reach higher into the sky. The total plant-area on a map may be the same, and fewer turbines fit in the same space, but the volume of air caught by each turbine is increased.

As a part of this thesis, a series of simulations were done to further verify the following hypothesis:

Plants with smaller turbines require larger turbine distances (in rotor diameters) to reach the same plant-efficiency as one using large turbines.

The question which I was trying to answer was the following:

If a total of 1000 MW is to be installed in an area of 100 km^2, how does the turbine size affect the wake losses?

To analyze this, a proposed area of $10 * 10\ km$ was evenly filled with 1000 MW (or as close as possible) of installed power, and the wake losses were simulated, using several turbine types.

As a separate approach to support this theory, some tests were performed to evaluate how wake effects change when scaling up the size of a WPP with regards to rotor diameter of the turbines. This test was done on the Nysted layout, which came pre-installed with Fuga. Details for the process will be covered in chapter 3.4.1.

3.2 WPP location

The final goal of Chapter 3 is to come up with a first layout suggestion for the Baltic Integrid project. To do this, a lot of time was spent on the simulations/calculations in WAsP and Fuga. The aim was to analyse different layout possibilities and see trends in how plants interact with each other. If and when these plants are eventually constructed, there will most likely be many companies involved, planning their WPPs separately in these areas. Because of the proximity between the sites, some plants are likely to shade others from the prevailing wind direction. If a single company would build all the WPPs, they would optimize the whole SMB so every plant got a reasonable power production. In reality, the free market may allow for companies to “build away” the competition. The prospected area of SMB is about 1240 km^2 in total. The area for each subdivision can be seen in Figure 20.

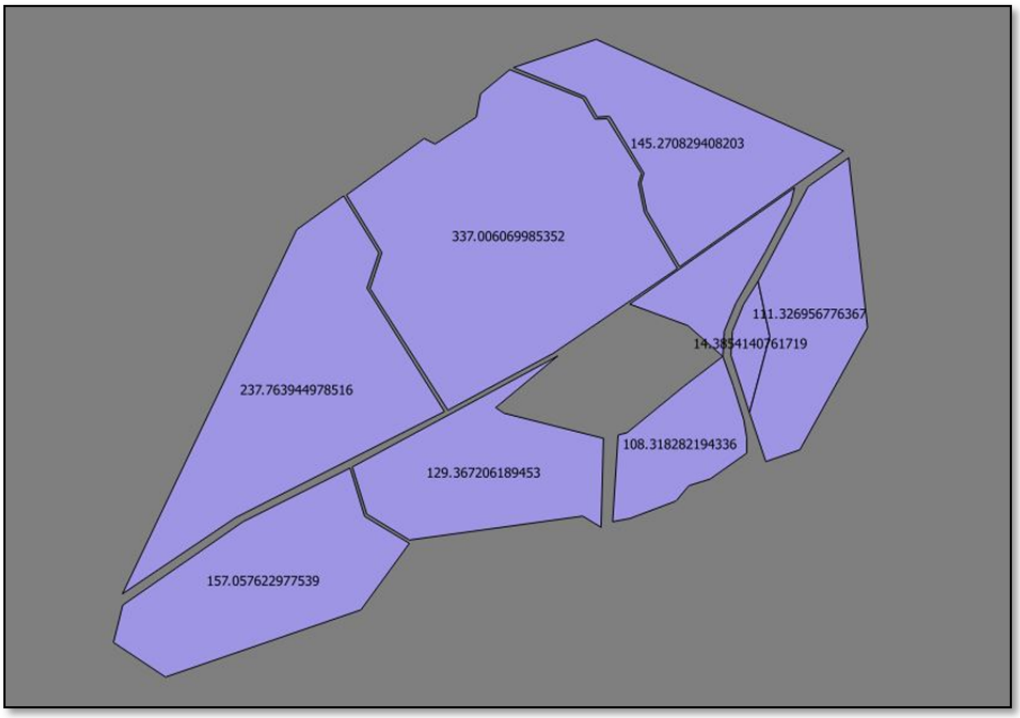

Figure 20: Map showing the identified locations of Södra Midsjöbanken where the Baltic Integrid project propose wind power to be constructed, including areas in km^2.

The work to find a good layout was done by changing the turbine densities (installed MW per km^2) of the different areas to see how the production in all plants was affected. By doing this, the suggested layout will include the external wake effects and give an idea of how one can optimize the entire area, rather than just one sub-region. The design, presented in chapter 3.5.2, is not intended as a final product, but may serve as an initial starting point for further work. Optimizing a single WPP is a complex process, and optimizing several plants, next to each other, is even harder. The time at disposal in a thesis would not be enough to optimize an area of this size to perfection. To understand more about this I will focus the next chapter on the theory of wake effects.

3.3 Wake effects

With only a basic knowledge of wind power generation, it is easy to realise that when a wind turbine is located downwind from another, it will experience less wind and generate lower power output. This phenomenon creates what is called the wake effect, as illustrated in Figure 21.

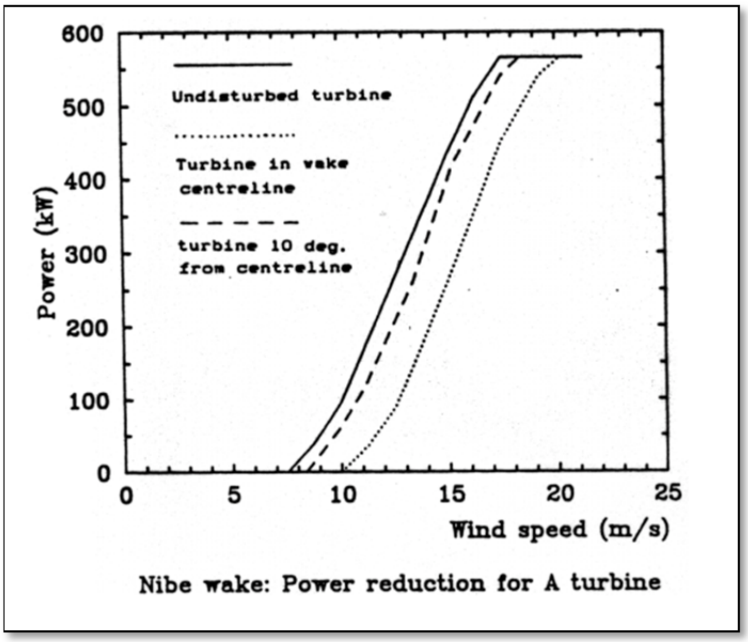

Figure 21: Output versus wind-speed curve for turbine-A when operating in the wake of turbine-B. (Katic, Höjstrup, & Jensen, 1986)

There has been extensive research into how wake effects can reduce the efficiency of single wind turbines or entire wind power plants, which has led to more and more optimised turbine layouts since the 1990s.

Even though the wake effect phenomenon is easy to understand, it can be very difficult to model and predict exactly how the wake, i.e. the reduced flow behind a turbine, will behave since it is related to varying wind speed, direction, turbulence and atmospheric stability (Barthelmie & Jensen, 2010). These losses need to be calculated accurately when designing a WPP to get a good estimate of the power production.

Many different theoretical models for determining wake effects have been developed, and they can be divided into different subgroups (Vermeer, Sörensen, & Crespo, 2003). The broadest way of separating wake models is in the *near* or *far* types. *Near wake effects* occur right behind the wind turbine and the individual effect of each rotor blade can often be distinguished. These models extend from a few meters up to several rotor diameters behind the turbine, but for the perspective of wake effects in a large WPP, it is more appropriate to use the so-called *far wake modeling*. These models take into consideration the power losses experienced further away from the turbine.

In terms of calculation methods there are different approaches. There are *kinematic models*, which are based on factors of decay and wake expansion to calculate velocity reduction profiles. These were the first models to be developed, and are quite simplified since they do not take the turbulence into consideration, so they work best when coupled with a turbulence model. There are also *Eddy Viscosity* models using more advanced fluid mechanic theory to give more realistic results at the cost of higher computational requirements. In recent years WPPs have grown larger and there has been an increasing demand for three-dimensional models which include the atmospheric layers above the turbines. called *boundary layer models*.

2.3.5 The Jensen and Katic (Park) models

One of the earliest and most well-known kinematic models is the Jensen model, developed in the early 1980s. It is a very quick and simple model used to calculate the velocity deficit profile downstream a single turbine. Because it is so easy to work with, it does a good job for modelling small-scale single turbine scenarios. The following equation describes the velocity deficit.

$$\pi r_0^2 v_0 + \pi(r^2 - r_0^2)u = \pi r^2 v \qquad (6)$$

v_0 is the velocity just behind the rotor, and v is the velocity in the wake at a distance x from the rotor. The wake radius, r, can be expressed as:

$$r = \alpha x + r_0 \qquad (7)$$

where r_0 is the rotor radius and α is a wake decay constant. The variables and a schematic overview of the equation can be seen in Figure 22 below.

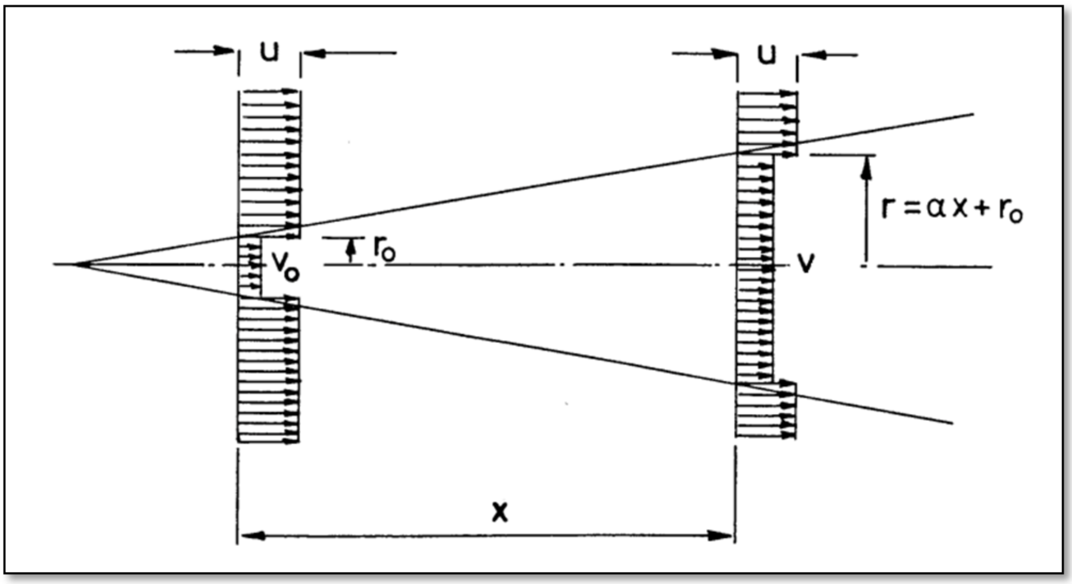

Figure 22: Schematic overview of the Jensen wake model. (Jensen, 1983)

Because the Jensen wake model does not take into consideration the characteristics of the wind turbine, nor the turbulence or atmospheric stability, Katic et al (1986) further developed the equations in the mid-1980s. Their model is called the Katic, or sometimes Park, model. It uses the following equation to calculate the wind speed u_2, at a distance x from the wind turbine (Peña, Réthoré, & van der Laan, 2016):

$$1-\frac{u_2}{u_1}=\frac{1-\sqrt{1-C_T}}{(1+\frac{k_w x}{r_r})^{2}} \quad (8)$$

Where u_1 is the upstream wind velocity at the rotor, C_T is the thrust coefficient of the turbine (dimensionless number describing the thrust force experienced by the wind turbine), and k_w is the wake decay constant, which varies on several factors such as ambient turbulence intensity, turbine induced turbulence and atmospheric stability (Manwell et al., 2009). r_r is the rotor radius. The thrust coefficient C_T is a function of the wind speed, so at different wind speeds the array losses will change. This means that for a WPP design, it is important to calculate the losses for each wind speed at which one or more turbines are operating.

Although this model is not specifically designed for near wake effects, it works best in proximity to the wind turbine, up to two rotor diameters away. Further down, it does not accurately represent the true wake (Peña et al., 2016).

For small and medium sized WPPs these simple models have shown reliable compared with actual data from the operating farms, but as the wind farms grow larger, it seems like the wake effect is underestimated. Traditional models like the ones described above assume that as the wake dissipates while receiving energy from the ambient free flowing wind, the surroundings are unaffected by this exchange. This is not realistic, which starts showing in large plants. When multiple arrays of turbines are operating, they ultimately start affecting the layer of wind above the plant. It can be viewed as if the wake is expanding upwards, creating a slower moving layer of air on top. This effect, sometimes called the deep-array wake effect, is becoming more and more pronounced in large WPPs, and recent data from operating plants are supporting this hypothesis (M. C. Brower & Robinson, 2012). This has led to an initiative to create new models, able to simulate deep-array effects reasonably well. This requires knowledge of quite complex atmospheric conditions, such as temperature, speed and pressure gradients in both the horizontal and vertical directions. One such model has been developed by DTU in Denmark. An extension of their WAsP program, called Fuga, has detailed wake calculation models using linearized computational fluid dynamics based on eddy viscosity, which takes into account the atmospheric interference. This is the wake calculation software used in this thesis. WAsP, used for building the turbine layouts, also has a built-in wake loss calculator, but it does not calculate the atmospheric boundary layer and will not work well for larger WPPs or to calculate external wake effects.

2.3.6 External wake effects

One aspect which has not yet been researched widely, partly due to the lack of real world data, are the external wake effects. This means the wake effects produced by a whole farm, rather than for an array, or a single turbine. Up until now, large WPPs have mostly been built very far away from each other, and interference is small or non-existent. But this type of external impact might play an important role in the coming decades when large clusters of WPPs are built around a single HVDC transmission line. Large plants will affect each other's production if they don't have enough distance in between for the wind speed to recover. This calls for research on how to optimize the placement and turbine densities of WPPs.

To optimise a wind turbine layout for low wake losses one can use clever turbine layouts. Common ways include shifting every other array of turbines or avoiding straight arrays, and building the plant in an arch. Two interesting turbine layout concepts can be seen in Figure 23. Horns Rev 2, built by DONG Energy has been in operation since 2010 and is built using an arch type layout and small (Siemens 2,3 MW) turbines. For Horns Rev 3 however, Vattenfall AB has chosen a very different strategy using large (Vestas 8 MW) turbines spread out over a larger area in a quite irregular pattern. Horns Rev 3 is under construction at the time of writing (early 2017). These layouts illustrate how differently one can approach a WPP design, and since production and wake losses are often kept as company secrets, it can be hard to compare which way is better.

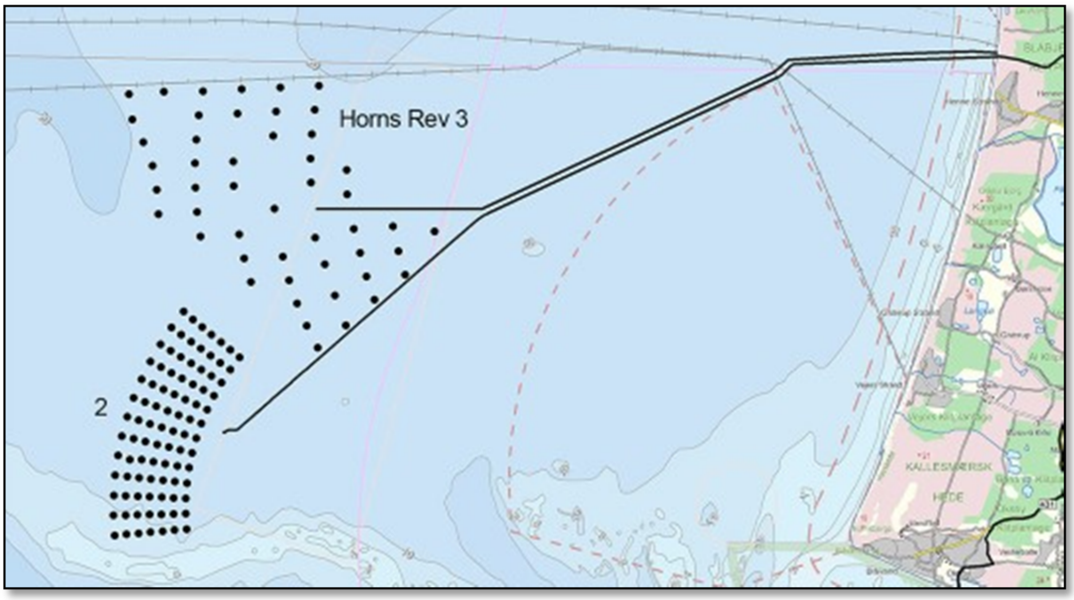

Figure 23: Image showing the turbine layouts for Horns Rev 2 & 3. (Vattenfall, 2016b)

There will always be wake losses, as long as there are more than one turbine, and how much to accept is up to each individual project. In this thesis, it is assumed that wake losses around 10 % will be a fair value to aim for. This is based on revenue and wake losses from other plants and the experience of supervisor Jörgen Svensson.

3.4 Method – WPP design and micrositing

Here follow the more in-detail method chapter for the scaling and turbine layout processes. First, I could be useful to understand how WAsP and Fuga operates. The initial steps are done in WAsP, which is a software in which one can design a WPP, and analyse power production, internal wake losses and various other information about the plant. Here, it is necessary to import a map with associated surface roughness, a wind climate, the coordinates for all turbines and their desired turbine generator. The turbine sites can be sorted into groups, to have more control over unique wind power plants. An overview of the main window in WAsP can be seen in Figure 24.

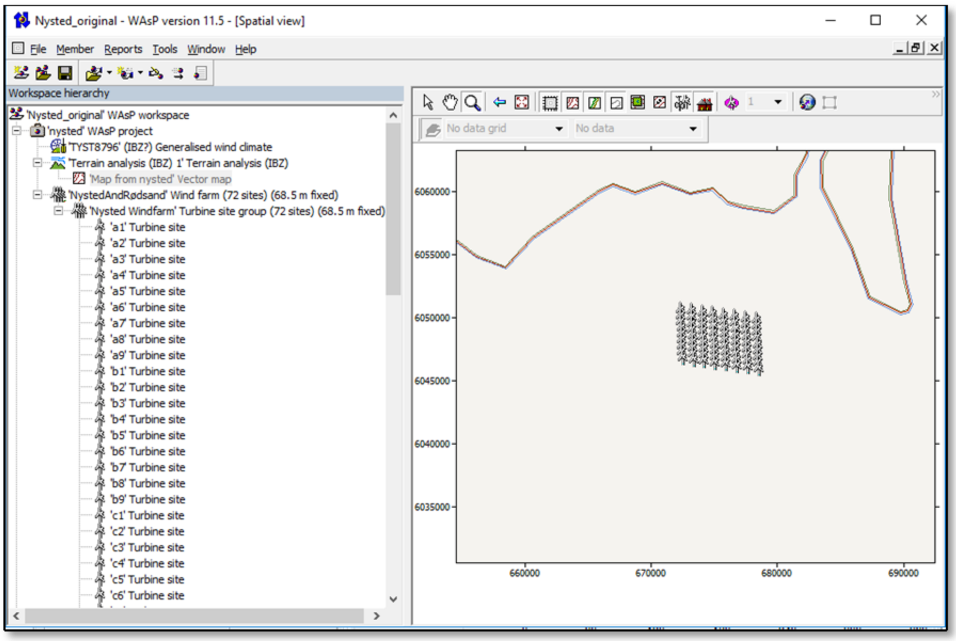

Figure 24: Overview of WAsP with the Nysted WPP loaded.

WAsP itself uses a more simplified wake calculator than Fuga, so to analyse how several parks interact with each other, we export the WAsP “workspace” file into Fuga. Here it is necessary to decide upon an atmospheric boundary layer case. This is essentially how the atmosphere is going to affect the wake in terms of turbulence, temperature gradient and pressure. This was set to default in all simulations to keep the calculation loads down. An overview of Fuga’s windfarm wake window is shown in Figure 25.

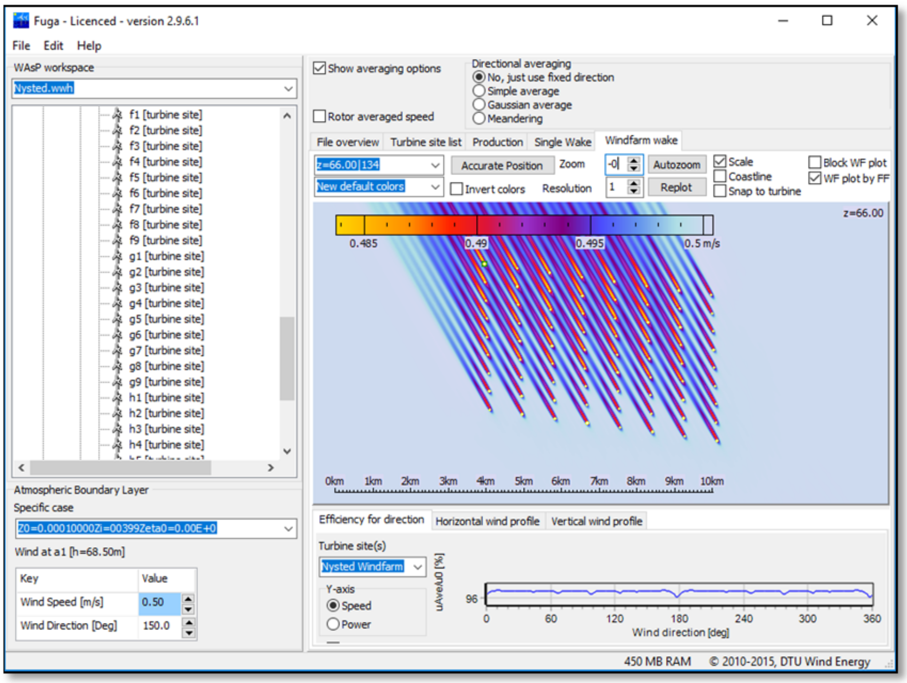

Figure 25: An overview of Fuga's windfarm wake window. Nysted WPP is shown.

3.4.1 Step 1: WPP scaling analysis

The scaling test was done in two main parts.

1. The turbine size test
2. The Nysted test

The turbine size test - with constant area

This test was done to analyze how turbine size can affect wake losses. The analysis was done on a squared area of $10 * 10$ km^2 with 8 different turbine types (rotor diameter in parenthesis):

1. *Siemens 2,3 MW (82,4 m)*
2. *Siemens 3,6 MW (120 m)*
3. *Senvion 5 MW (126 m)*
4. *Senvion 6,2 MW (152 m)*
5. *Vestas 7 MW (164 m)*
6. *Vestas 8 MW (164 m)*
7. *Hypothetical 10 MW (180 m)*
8. *Hypothetical 12 MW (200 m)*

The power curve (power vs wind speed) for the Siemens 2,3 MW turbine came from the manufacturer itself. For all other turbines besides the two hypothetical ones, the power curves were obtained from WindPowerProgram (2016). Wind turbine manufacturers do not publicly hand out thrust curves of their turbines, so the same thrust curve was used for all turbines (from Vestas V-112 3,0 MW).

The first step was calculating the number of wind turbines to use in each case by dividing 1000 MW with the rated power of each turbine, then taking the square root of this value to estimate how many turbines was needed on each side of the area. Because the number of turbines cannot have a decimal, the closest integer was chosen. This gives a small error which is hard to get around. The distance between each turbine in a squared, non-shuffled, grid was found by dividing 10 km (each side of the proposed area) by the number of turbines on each side minus 1.

The coordinates were then placed as vector points in QGIS and exported into WAsP to prepare for simulations. The same wind data file (from Nysted) was used during all the calculations, which were performed in Fuga. Results are presented in chapter 3.5.1.

The Nysted test – with constant number of turbines

The Nysted WPP was used in this test. It was built in 2003 and consist of 72 turbines from Siemens, each rated with a power of 2,3 MW. Consider the idea that a new WPP is built with the exact same layout, but instead of 2,3 MW turbines with a rotor diameter of 82,4 m, it is built using 12 MW turbines with a 200 m rotor. Using the original turbine spacing (10,5 rotor diameters in E-W direction and 5,8 rotor diameters in N-S direction), the distance between each turbine would be scaled to:

$$200 * 10{,}5 = 2100\ m$$
$$200 * 5{,}8 = 1160\ m$$

According to the hypothesis, a lower spacing ratio should be enough to reach a satisfying plant efficiency.

The test consisted of finding the internal wake effect of Nysted for four different scenarios while keeping the number of turbines constant at 72, with 9 turbines in the North-South direction and 8 turbines in the East-West direction.

Scenario 1: Base case. The original turbines (2,3 MW) and the original layout size. See Figure 26. Total installed power is 165,6 MW.

WPP area: 23,2 km^2
Turbine Power: 2,3 MW
Turbines: 72
Turbine density: 7,15 MW/km^2

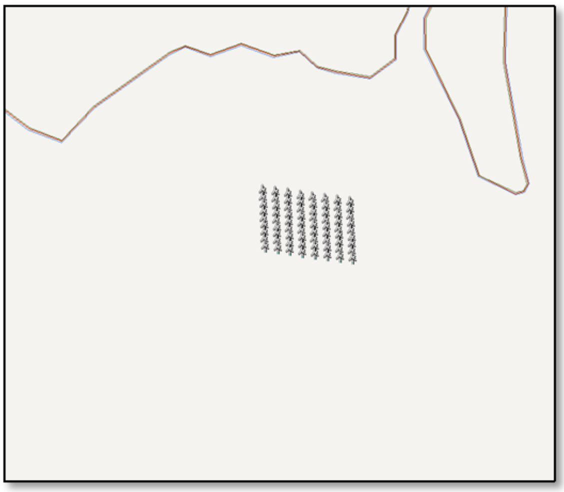

Figure 26: Overview of scenario 1. Nysted WPP in its original formation and the original turbines.

Scenario 2: The original layout size. Turbines have been changed to 12 MW ones with 200 m rotor diameter (see Figure 27). Total installed power is 864 MW.

WPP area: 23,2 km^2
Turbine Power: 12 MW
Turbines: 72
Turbine density: 37,3 MW/km^2

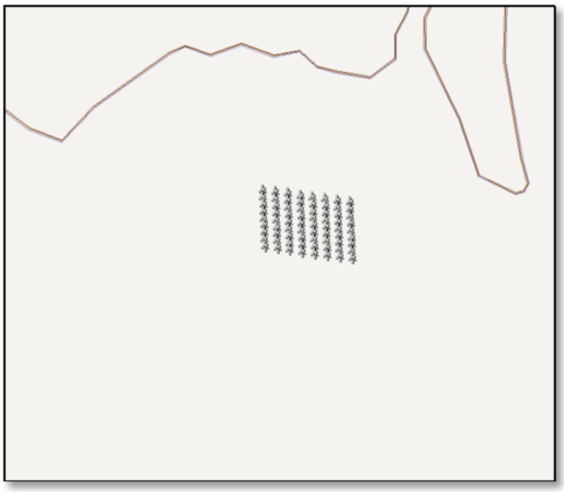

Figure 27: Overview of scenario 2. Nysted original spacing but with 12 MW turbines.*

**Do not be confused if in the figure it is not possible to see the change in rotor diameter. The software uses the same icon for all turbines.*

Scenario 3: Still using 12 MW turbines. Layout is scaled up to a proportional size for a 200 m rotor diameter using the same turbine spacing ratio (10,5:5,8), see Figure 28. Total installed power is 864 MW.

WPP area: 136,4 km^2
Turbine Power: 12 MW
Turbines: 72
Turbine density: 6,3 MW/km^2

Figure 28: Overview of scenario 3. Nysted layout scaled relative to rotor diameters using the 12 MW turbines.

Scenario 4: 12 MW turbines, layout scaled up with more realistic parameters to preserve a similar wake effect as the original park (6,8:3,8 rotor diameters). See Figure 29 below. The calculations of the parameters are based on the ratio of the volume of air passing through the rotors (method described below). Total installed power is 864 MW.

WPP area: 57,9 km^2
Turbine Power: 12 MW
Turbines: 72
Turbine density: 14,9 MW/km^2

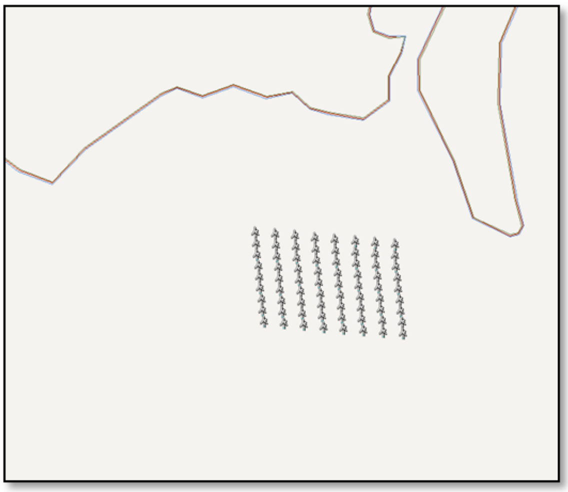

Figure 29: Overview of scenario 4. Nysted layout scaled according to volume calculations.

The calculations upon which the spacing in scenario 4 are based follow the idea that the turbine rotor volume, V_{Turb}, to total volume of the area, V_{Area}, ratio should be equal in both scales to reach the correct wake loss. In other words:

The total volume, or block, of air which enfolds the turbine rotors equals the total plant area multiplied with the rotor area. In the case of Nysted:

$$(7*10,5 * 82,4\,m + 82,4\,m) * (8 * 5,8 * 82,4\,m + 82,4\,m) * 82,4 = V_{Area} = 1,95\,km^3 \quad (9)$$

7 and 8 are the spaces in each direction, 10,5, and 5,8 are the spacing constants in rotor diameters, and the last rotor diameter is added because the rotors at the edges each span one blade length outside the area.

If you view the turbine rotor area as a volume by multiplying it with 1 m, the volume of all rotors become:

$$R^2 * \pi * 1 * 72 = V_{Turb} \quad (10)$$

The volumetric ratio becomes:

$$V_{Turb}/V_{Area} = 0{,}00038/1{,}95 = 0{,}00197 = 0{,}197\% \quad (11)$$

If we keep this ratio and calculate in reverse, with the same number of turbines but with a new rotor diameter (200 m) to find new spacing constants, we eventually find them to 6,8:3,8.

To summarize what was done here. If we scale up a WPP based on the rotor diameter of the turbines and keeping the spacing constant of the small WPP, the wake losses should become very low. One can retain the same wake losses by placing the larger turbines with smaller distances (measured in rotor diameters) between them. These new distances can be calculated from the ratio between *the total rotor volume* of the turbines, with the *total volume* of the area. This ratio has no unit, which makes it easy to use. One could also use the ratio between the *total rotor area* to the total volume. In this case, we set the thickness of the rotor to 1 m, so the area and the volume have the same value, simply to remove the units.

3.4.2 Step 2: Turbine layout

To come up with a layout, a first idea was prepared in QGIS using the 12 MW turbines and a 9:9 turbine spacing ratio (1800 m in the dominating wind direction, 1800 m perpendicular direction). The spacing was then shifted, meaning that every second row was moved 900 m to avoid some wakes between turbines in the dominating direction. Ideally, a site with a dominating wind angle would be best designed with a longer distance between turbines in this direction. But it makes sense to use a squared grid for experimenting, since a grid with longer distances in the dominating wind direction (as is often seen in real WPPs) varies depending on the specific spacing. A 9:5 spacing may give different results as a 10:7 spacing. Using a grid built in squares is also a much faster way to replicate the process and change layouts during experimentation. When the final turbine densities were found using the experimental methods, the layout was eventually made into a rectangular spacing for slightly lower wake losses.

The coordinates were produced in QGIS and exported into WAsP. To be able to simulate, a WAsP Observed Wind Climate file was created from the wind data file. The data included wind speed and direction for each hour in one year. The map of SMB and the wind data were converted into WAsP-formats using the conversion software included with the installation. In WAsP, the turbine coordinates were divided into 4 areas of turbines according to Figure

30. The reason for this division was to analyze how the production changes in one group when the turbine density is changed in the others. As can be seen in the figure, area 2 is more shaded than any of the other areas, and both area 1 & 4 cover it from the dominant wind angles.

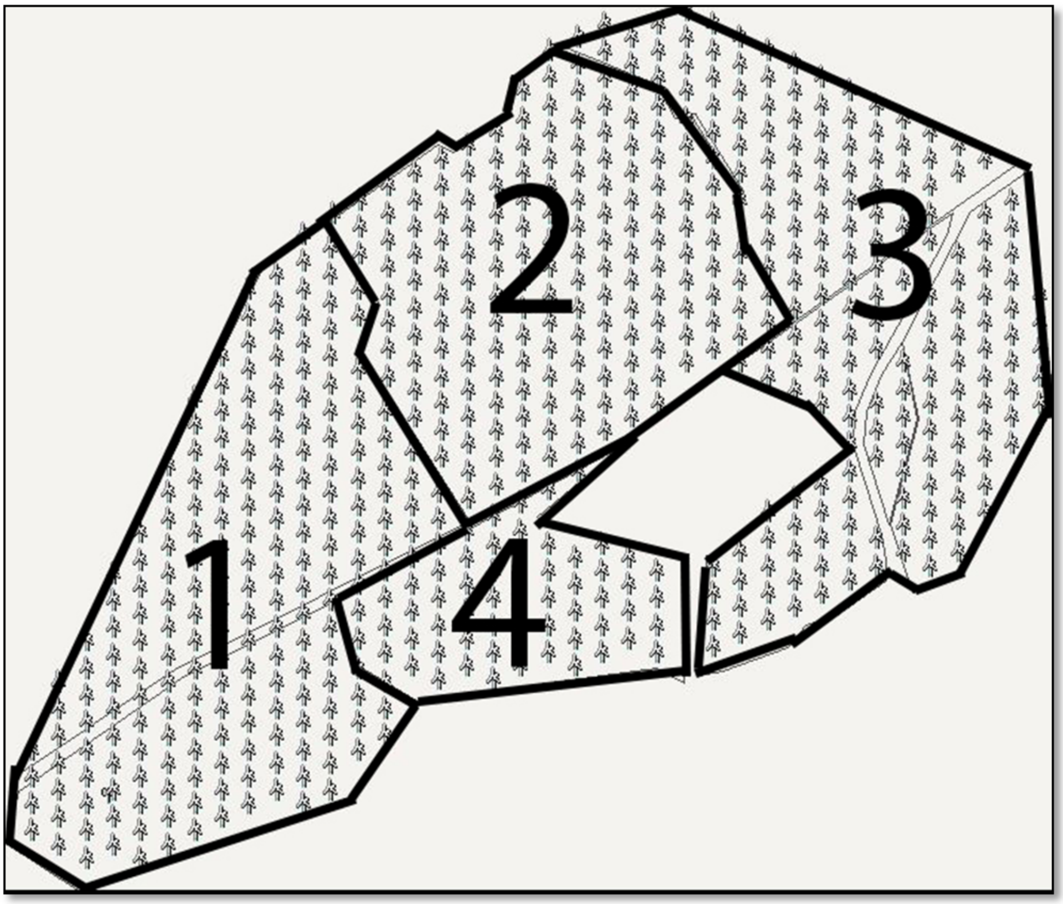

Figure 30: The simulation areas of SMB.

In the base case, all turbines in groups 1-4 are identical 12 MW turbines. The idea of the simulations is to see whether a lower turbine density in Group 1 & 4 will benefit the production of Group 2 and 3.

The software, Fuga, takes into account the atmospheric conditions in its calculations. Stable and unstable atmospheric boundary layers will have different effects on the wake. In the large models built (> 800 turbines), the software had problems calculating for unstable atmospheres, so all calculations are based on the default atmospheric boundary layer case of Fuga, with an Obukhov-length of $L = \infty$. This means that the atmosphere is under neutral conditions, i.e. that the temperature gradient is equal to the dry adiabatic lapse rate, so that a lifted air mass will not be heavier or lighter than the surrounding air.

The simulations were done in steps, changing the turbine density of the different areas for each simulation to cover all interesting scenarios. The recorded parameters for each group in each scenario were:

1 Wake losses [%]
2 Number of turbines
3 Total installed capacity [MW]
4 Spacing expressed in rotor diameters and meters
5 Turbine density [MW/km^2]
6 Production after wake losses per year [GWh]
7 Production per turbine per year [GWh]
8 Production per installed MW [GWh/MW]

When a layout with good turbine densities had been found using a squared spacing, the distance in the dominating direction was made longer, and in the perpendicular direction shorter, while keeping the installed MW/area constant. As can be seen in the wind rose in Figure 16, the dominating wind direction is not extremely clear. The data upon which this wind rose is based was only collected during one year, but it should be a safe assumption to consider the dominating wind angle to be around 225 °. Based on this, the entire turbine grid was eventually rotated -30 degrees from 0 (North) to have a more appropriate alignment with the winds.

All resulting tables can be seen in APPENDIX A, with the most important ones presented in the next chapter.

3.5 Analysis and results

3.5.1 WPP scaling analysis

Turbine size test

The results from the simulations can be seen in Table 4 below. Figure 31 shows the relationship between turbine and wake losses. The main outcome is that wake effects drop when turbine size increases.

Table 4: Results from the WPP scaling analysis simulations.

Turbine Model (RD)	Turbines Tot.	Rows/Col.	Turb. Dist. [m]	Turb. Dist. [RD]	Inst. P [MW]	Deviation	Wake effects
2,3 MW Siemens (82,4 m)	441	21	500	6,07	1014,3	1,43%	**20,09%**
3,6 MW Siemens (120 m)	289	17	625	5,21	1040,4	4,04%	**23,62%**
5 MW Senvion (126 m)	196	14	769,23	6,11	980	-2,00%	**18,20%**
6,2 MW Senvion (152 m)	169	13	833,33	5,48	1047,8	4,78%	**16,91%**
7 MW Vestas (164 m)	144	12	909,09	5,54	1008	0,80%	**15,93%**
8 MW Vestas (164 m)	121	11	1000	6,10	968	-3,20%	**13,11%**
10 MW (180 m)	100	10	1111,11	6,17	1000	0,00%	**8,96%**
12 MW (200 m)	81	9	1250	6,25	972	-2,80%	**7,69%**

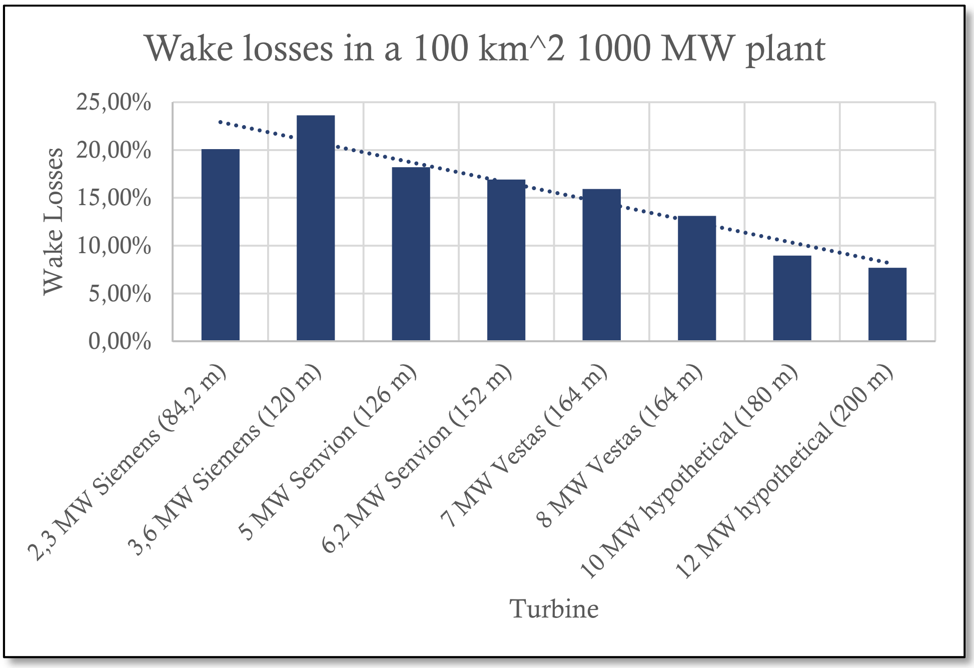

Figure 31: The wake losses for a 10*10 km area with ~1000 MW installed capacity for turbines of different sizes.

The Nysted test

In Table 5 below are the results from the Nysted test. One can see that wake losses are very low in Scenario 3, where the plant is scaled up based on the rotor diameter of the larger turbines. By tightening the turbine density in Scenario 4, the wake losses return to around 10, which was the original value in Scenario 1. In other words. Larger turbines allow for relatively shorter distances between them, in terms of rotor diameters.

Table 5: The results from the Nysted simulations.

Nysted Test Results	Turbine (MW)	Rotor Diameter (m)	Wake Loss (%)	Spacing	Total power (MW)
Scenario 1	2,3	82,4	**9,49**	10,5D:5,8D	165,6
Scenario 2	12	200	**18,2**	10,5D:5,8D*	864
Scenario 3	12	200	**5,75**	10,5D:5,8D	864
Scenario 4	12	200	**10,07**	6,8D:3,8D	864

* The spacing here is based on a rotor diameter of 82,4 m.

3.5.2 Turbine layout analysis

Analyzing the simulation results in Appendix A, a few important conclusions can be drawn.

- Changes in Area 1 does not affect Area 4 noticeably.
- Changes in Area 2 affects Area 3 more than vice versa.
- Changing the turbine density in one area affects the Area's own production more than it changes that of the surrounding areas'.

Based on this information, one can start thinking of a good turbine layout for SMB. When using a spacing of 1600:1600 m in all areas, see Table 6, the wake losses range from 7,9 % to 10,9 %. Production per installed MW is in the range between 4,25 to 4,4 GWh/MW.

When reducing the turbine densities in area 1 and 2, wake losses decrease in all areas (see Table 7). The production per installed MW increases for all areas as well.

Table 6: Wake losses and production for a layout where all areas have equal quadratic turbine spacing of 1600:1600 m.

Iteration	Area 1	Area 2	Area 3	Area 4	Total
Wake Loss	**7,9%**	**10,9%**	**10,2%**	**10,1%**	**9,6%**
Nr. Turbines	153	128	140	47	468
Total installed cap (MW)	1836	1536	1680	564	5616
Spacing (rotor diameters)	8:8	8:8	8:8	8:8	
Spacing (m)	1600:1600	1600:1600	1600:1600	1600:1600	
MW/km^2	4,65	4,56	4,43	4,36	4,50
Net Production (GWh/year)	8074	6530	7203	2422	24229
Prod. Per turb (GWh/year)	52,77	51,02	51,45	51,53	
Prod. GWh/Installed MW	4,398	4,251	4,288	4,294	17,231

Table 7: Wake losses and production for a layout where area 1 & 2 have a lower turbine density (1700:1700) than area 3 & 4. Still with a quadratic turbine spacing.

Iteration	Area 1	Area 2	Area 3	Area 4	Total
Wake Loss	**7,0%**	**10,0%**	**9,8%**	**9,5%**	**8,9%**
Nr. Turbines	135	110	140	47	432
Total installed cap (MW)	1620	1320	1680	564	5184
Spacing (rotor diameters)	8,5:8,5	8,5:8,5	8:8	8:8	
Spacing (m)	1700:1700	1700:1700	1600:1600	1600:1600	
MW/km^2	4,10	3,91	4,43	4,36	4,20
Net Production (GWh/year)	7194	5670	7233	2438	22535
Prod. Per turb (GWh/year)	53,288	51,545	51,664	51,872	
Prod. GWh/Installed MW	4,441	4,295	4,305	4,323	17,364

The turbine layout in Table 7 gave satisfactory results. This design was further adjusted into a rectangular spacing with the same turbine density as before. The spacing ratio was chosen to 10,2:7,1 rotor diameters in area 1 and 2, and 9,6:6,7 diameters in area 3 and 4. These spacing ratios preserved the turbine densities found using squared grids while giving more distance in the dominating wind direction for the wakes to recover. The turbine layout is also rotated -30 degrees from zero to align the turbines better toward the prevailing wind angle.

3.6 Final turbine layout

The final turbine layout can be seen in Figure 32, and in Figure 33 with illustrated wakes coming from a 270 degree wind angle. Details for the production and wake losses are in Table 8.

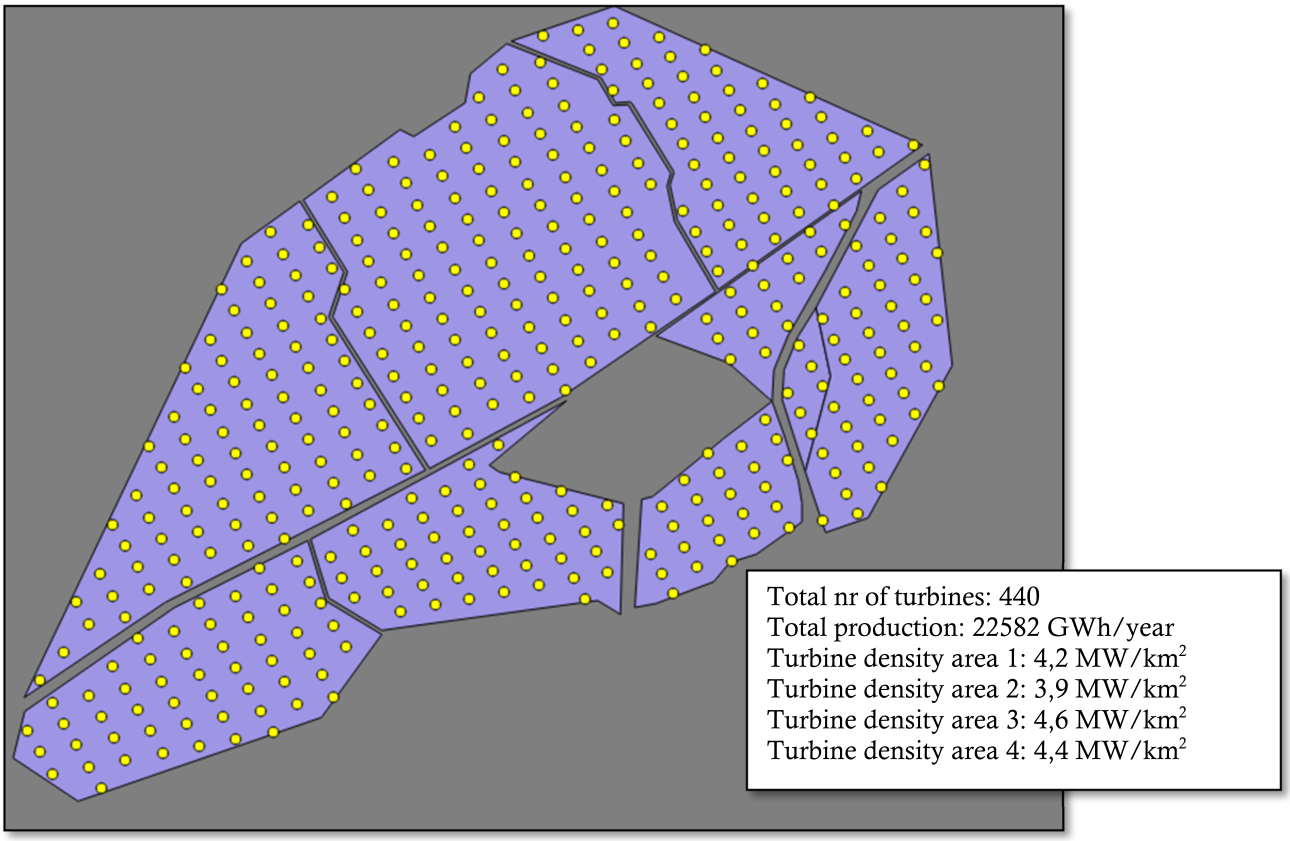

Figure 32: The final layout suggestion using a 10,2:7,1 rotor diameter's spacing in areas 1 and 2, and 9,6:6,7 diameters in area 3 and 4. The layout is rotated -30 degrees from North.

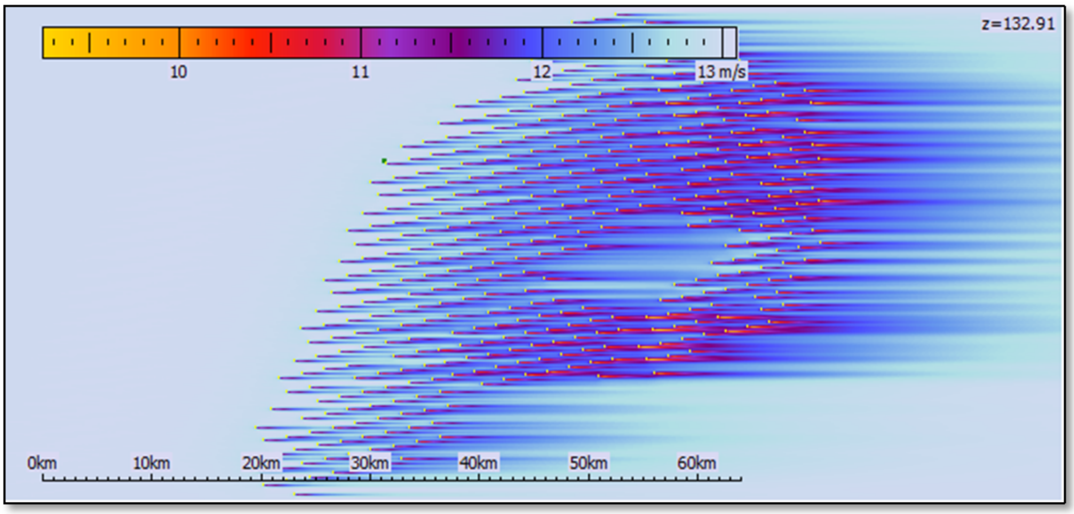

Figure 33: Plot illustrating the turbine wakes for the final layout suggestion when winds are coming from 270 degrees. Area 1 and 2 have a slightly lower turbine density than area 3 and 4 to compensate for covering the dominating wind direction.

Table 8: Final turbine layout suggestion with a 10,2:7,1 rotor diameter spacing and a lower turbine density in area 1 and 2.

Final Turbine Layout	**Area 1**	**Area 2**	**Area 3**	**Area 4**	**Total**
Wake Loss	**6,7%**	**9,8%**	**9,7%**	**9,4%**	**8,8%**
Nr. Turbines	132	113	140	47	432
Total installed cap (MW)	1584	1356	1680	564	5184
Spacing (rotor diameters)	10,2:7,1	10,2:7,1	9,6:6,7	9,6:6,7	
Spacing (m)	2030:1422	2030:1422	1910:1340	1910:1340	
MW/km^2	4,19	3,88	4,62	4,36	4,26
Net Production (GWh/year)	7054	5845	7242	2441	22582
Prod. Per turb (GWh/year)	53,439	51,725	51,728	51,936	
Prod. GWh/Installed MW	4,453	4,310	4,310	4,328	17,402

After all the tests had been performed, I received an update on the average wind speed at the site. E.ON has a wind measuring mast in SMB, and were kind enough to share the average wind speed at the site, which was slightly higher than what was used in the original simulations (9,4 m/s compared to 9,1 m/s). The original wind data was adjusted to fit the new average wind speed, and the final layout was run through simulations again. Wake losses were unchanged, while the expected production increased slightly (see Table 9).

Table 9: Production from the final layout with updated wind data.

Final Layout with new wind data	**Area 1**	**Area 2**	**Area 3**	**Area 4**	**Total**
Net Production (GWh/year)	7372	5631	7554	2439	22996
Prod. Per turb (GWh/year)	55,848	49,832	53,957	51,893	
Prod. GWh/Installed MW	4,654	4,152	4,496	4,324	17,627

When adding the rest of the losses, we get a total production of about 21,8 GWh, see Table 10.

Table 10: The losses and final production from the WPP cluster.

Losses	
AEP with only wake losses (kWh)	22995000
Turbine availability	0,99
Grid availability	0,995
Wake losses	included in AEP
Dirt, insects, ice and high wind hysteresis	0,99
Internal electrical losses	0,985
Transmission losses	0,985
Total losses	**0,946162935**
AEP after losses (kWh)	**21757016,69**

3.7 Cable layout

With the turbine layout set, it is time to design where to dig the cables. The turbines are connected via a 66 kV grid to the transformer stations, where the voltage is increased to 300 kV before reaching the HVDC rectifiers. To avoid extended cables, the transformer stations are placed near the rectifiers, and in strategic locations relative to the turbines. With smaller turbines it might have been troublesome to place the transformer stations in front of the turbines in the dominating wind direction, but with a hub height of 135 m, this will likely not affect the 12 MW turbines significantly. When calculating cable lengths, one must remember to consider several factors. The distance between each turbine is obviously the main part, but the cables are trenched into the bottom, and there need to be enough length to reach up to the turbine, even when the actual connection point may be a bit above the surface. Some extra cable may be included at the ends. An illustration of this can be seen in Figure 34.

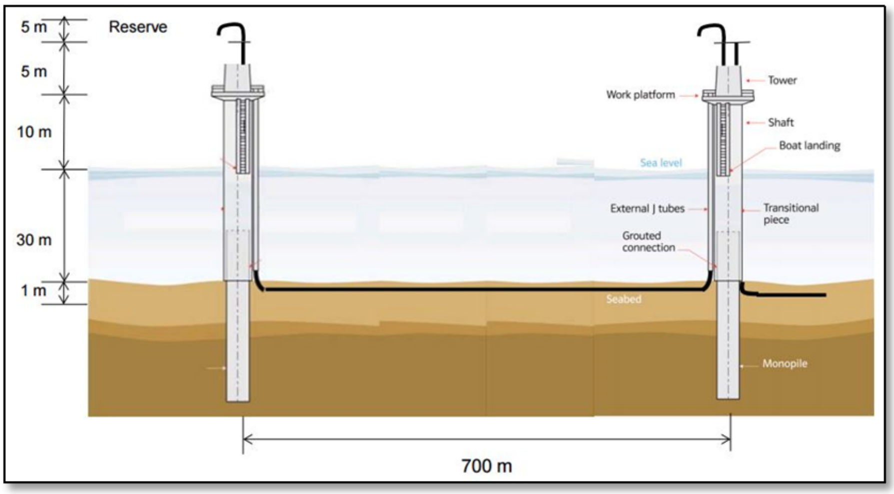

Figure 34: Illustration of the cable length needed between two turbines.

The average bottom depth was assumed to 37 m, with the platform being 10 m above the surface with 5 m loose cable at the ends. The suggested cable layout can be seen in Figure 35. There are 3 different types of transformer stations to handle different amounts of power. They have a maximum of 7 arrays leading in, and to keep the cable dimensions down, there is no more than 7 turbines in each array. The red cables have a 630 mm^2 cross section area and are dimensioned to carry up to 84 MW. The blue cables have a 240 mm^2 cross section area and are meant to carry up to 48 MW. The white cables are the 300 kV external collection grid leading up to the four rectifiers. From the rectifiers, HVDC transmission cables are connected to shore. They are not included in the image.

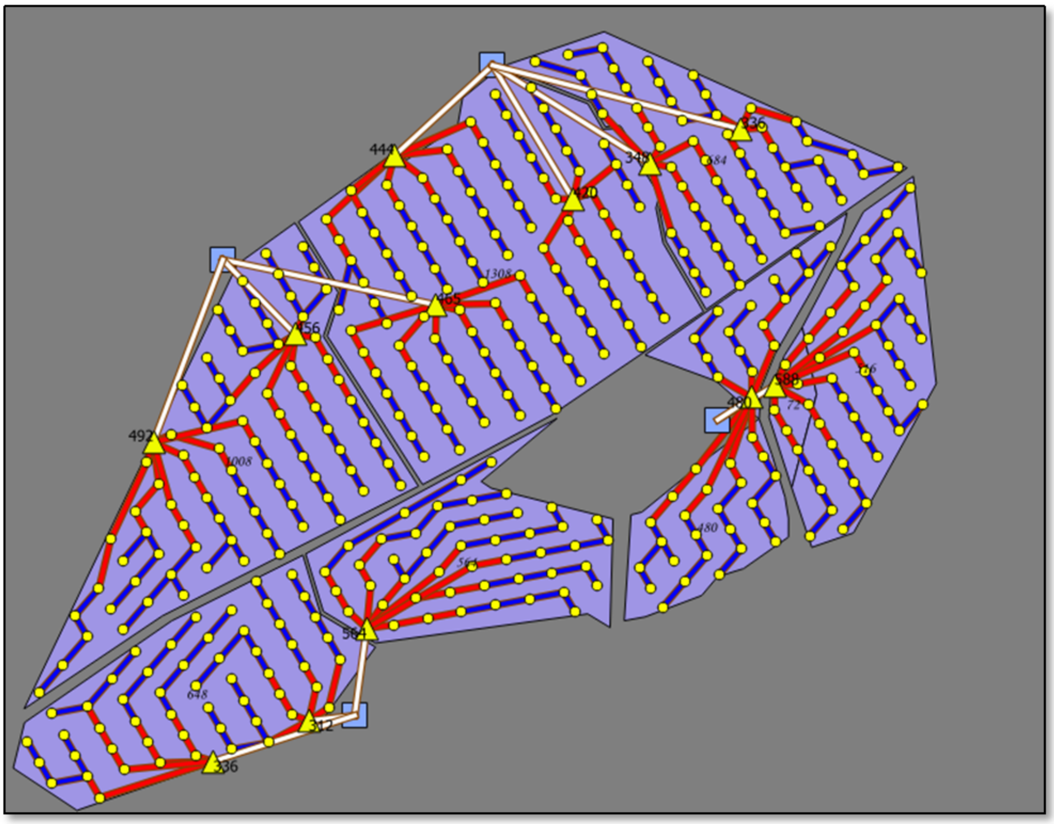

Figure 35: Cable layout suggestion including both cable types, transformer stations (triangles) and HVDC rectifiers (squares).

The cable type used is cross-linked polyethylene 3-core cables, illustrated in Figure 36. The multiple layers of protection are there to protect both the cable and the surroundings from each other. In a 3-phase AC system such as this, the cable needs to have three cores, which makes them more expensive than DC cables. The total cable length for each type can be seen in Table 11.

Figure 36: Illustration of an XLPE 3-core cable. (ABB, 2010)

Table 11: Cable lengths.

Cables	**185 mm2**	**800 mm^2**	**1000 mm^2**	**Total**
Cable length on bottom (km)	450	340	96	886
Cable length at turb. Site (km)	33	18	1,1	52,1

4. Power fluctuations

This chapter will answer how much and how fast the power output can change in the suggested turbine layout. Power fluctuations from wind power are often described as problematic and unpredictable. Even if we can forecast the wind to a certain extent, it can still change rapidly in a matter of minutes. The wind data over one year for SMB is illustrated in Figure 5, where it is possible to see the large fluctuations.

4.1 Power balance and frequency

The TSO is responsible for continuously balancing the supply and demand of electricity on the grid. In Sweden, and in most of Europe, the grid is built around a frequency of 50 Hz. This means that the AC current changes direction 50 times each second. All the power generators connected to the grid must be in sync with this frequency. The loads and the production must also match each other to keep the frequency at this level. Unpredictable production, or a drop in demand, can lead to a surplus of supply on the grid, which increases the frequency, or vice versa. Should the frequency change too much it can cause damage to electric equipment and generators connected to the system. To avoid this, production automatically increases when demand increases, such as in the morning when a lot of people wake up to boil tea. It works similarly to a car on cruise control if the road starts going up a hill. The engine needs to compensate by increasing power production to keep the speed constant. Large power grids have a stronger resilience than small ones, where fluctuations can have more severe effects.

The construction of more wind power in large plants therefore require extra actions in the rest of the grid. There need to be balancing power installed, ready to produce in minutes. Hydro power is good for this, but for dry years, or in countries without a large hydro power production, this can be a problematic task.

Wind turbines are designed to shut down at a certain speed, so when they are working near or at the cut-out speed they can go from full production to zero with a very small wind speed increase. Turbine designers have implemented control systems to avoid this behavior. Modern machines now pitch out the blades to drop gradually from full production to zero over a wind speed interval around the cut-out speed. This means that it is no longer the speed where the turbines are bluntly “cut out”, but rather the speed around which the power is ramped down. The power curve used for the hypothetical 12 MW turbines in these simulations did not have this slow decrease, and went from full power to zero at 25 m/s. Because of this, the power fluctuations due to wind speeds near the turbines cut-out speed could not be simulated accurately. Instead I had to find the highest wind speed increase below 25 m/s.

4.2 Scenario selection

In the wind data used for the simulations in Chapter 3, the highest wind speed change occurred on June 12, between 23:00 and 00:00 (see Table 12). The wind speed changed from 5,9 m/s to 21,2 m/s. This change might have occurred gradually over an hour, or instantly, the data resolution is not high enough to tell. Assuming that the change occurred instantly over an entire wind power plant, the wind turbines would go from producing very little at 5,9 m/s to full power at 21,2 m/s in a very short time. This would be close to the case in small plants. A benefit to building large scale plants is that the turbines would not increase their power output all at once. In this chapter, the power fluctuations at SMB during these power fluctuations are simulated. The final turbine layout suggestion from the previous chapter is used as the base for power calculations in Fuga.

Table 12: Table showing the highest wind speed change of the year at Nysted in 2004 between 23:00 and 00:00.

Hour Nr	Date and time	Direction	Speed	Change from last hour
3933	2004-06-12 20:00	90	18,9	8,249556
3934	2004-06-12 21:00	70	16,5	-2,357016
3935	2004-06-12 22:00	40	9,4	-7,071048
3936	2004-06-12 23:00	60	**5,9**	-3,535524
3937	2004-06-13 00:00	90	**21,2**	15,320604
3938	2004-06-13 01:00	80	14,1	-7,071048
3939	2004-06-13 02:00	50	14,1	0
3940	2004-06-13 03:00	50	9,4	-4,714032
3941	2004-06-13 04:00	60	8,2	-1,178508

A weather front moving across a WPP cluster does not necessarily move with the same speed as the wind. But in a worst case scenario where the wind angle is the same as the front's direction of movement, they can have the same velocity. Therefore, this model uses the speed of the moving weather front equal to the wind speed. Also, the wind and the front move in the same direction. (Hellström, 2017)

4.3 Method – Power fluctuations

The power fluctuations model was built in Microsoft Excel and supplied as an attached file with this thesis. It uses the final turbine layout and simulates the power output during a wind speed increase from 5,9 m/s to any speed with full power production. The wind angles supported are 90-270 ° with 10 degree increments (see Figure 37).

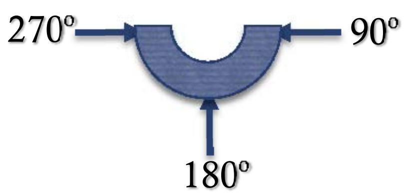

Figure 37: Illustration of the wind angles included in the model.

The power output for each turbine site at 5,9 m/s was calculated in Fuga and collected in a table. The table includes all 19 wind angles for all 440 turbine sites, and thus contains 8360 cells. The turbine site locations were then imported to Excel in the coordinate system ETRS89. This system uses meters as units which makes it easy to calculate distances. The model assumes a wind front approaching as a straight line with the equation

$$Y = KX + M$$

Where Y are coordinates in the north-south direction, X in the west-east direction, K is the slope of the line calculated from the wind angle, and M is the point where the line crosses an imaginary Y-axis at the westernmost turbine site. A wind front coming from 150 degrees is illustrated in Figure 38 as a straight line. The M value for the first turbine is -11853, but this value is outside the graph.

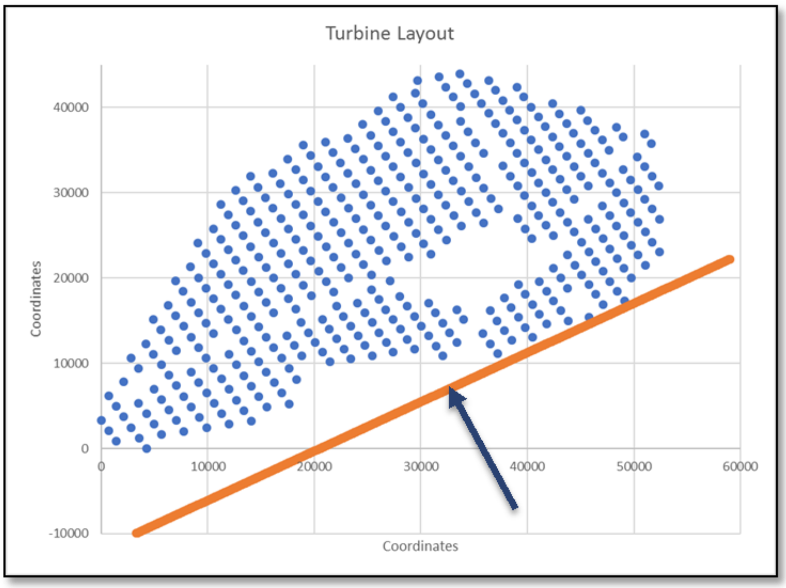

Figure 38: Graph from the power fluctuation model in Excel illustrating the turbine layout and a wind front approaching from 150 degrees.

The model calculates a unique M value for each turbine site based on the wind angle as input. From that it computes the span between the minimum to the maximum M value. This span is the distance the wind front needs to travel in the Y direction to pass through the WPP cluster. In other words, the lowest M-value represents the first turbine to meet the approaching front, and vice versa. How fast the wind front travels along the Y-axis is calculated based on the wind speed and angle. The total time it takes for a wind front to pass is then matched with the M-value for each turbine, to find the point in time at which each site is met by the wind front. That means the time when each turbine increases from its production at *5,9 m/s* to full production. The total power output from SMB can then be plotted over time as a wind front is passing through the plants.

The model collects the appropriate power output for each turbine from the data table. It is designed from the worst wind speed increase, i.e when the wind speed changes from 5,9 m/s to any other wind speed, assuming that at the second speed, all turbines are working at full capacity (12 MW). After tests in Fuga, the wind speed where all turbines operate at 100 % efficiency when the wind is coming from 150 degrees is 16,7 m/s. This wind angle is the one which generates the highest wake losses because of the tighter turbine spacing in the direction perpendicular to the dominating wind angle. So 16,7 m/s can thus be seen as the minimum high wind speed for the model to give accurate results.

One obvious error with the model is that it assumes the wind front travelling with a constant velocity. Realistically the front would slow down after passing a turbine. For simplicity, and since we are modelling the worst-case scenario, it is assumed that the wind front keeps its initial speed through the entire plant.

4.4 Results – Power fluctuations

Presented in this chapter are some graphs showing the total output from all areas of SMB during a wind increase from 5,9 to 21,2 m/s for different wind angles. The interesting directions are: one with a very smooth power increase (180 degrees), one where a wind front passes through very fast (150 degrees) and one close to the dominating wind direction (240 degrees). One graph is included, again for 150 degrees, to show the difference in time when the wind front instead arrives with a speed of 25 m/s. Last of all is a graph showing the total power output for 9 different angles collected in a single figure (Figure 43).

In Figure 39, one can see the total power output when a wind front is passing from south (180 deg.). The front will pass in around 35 minutes, and increase the power output from 618 to 5280 MW. The curve is smooth since the arrays of the turbines are not aligned with the wind angle.

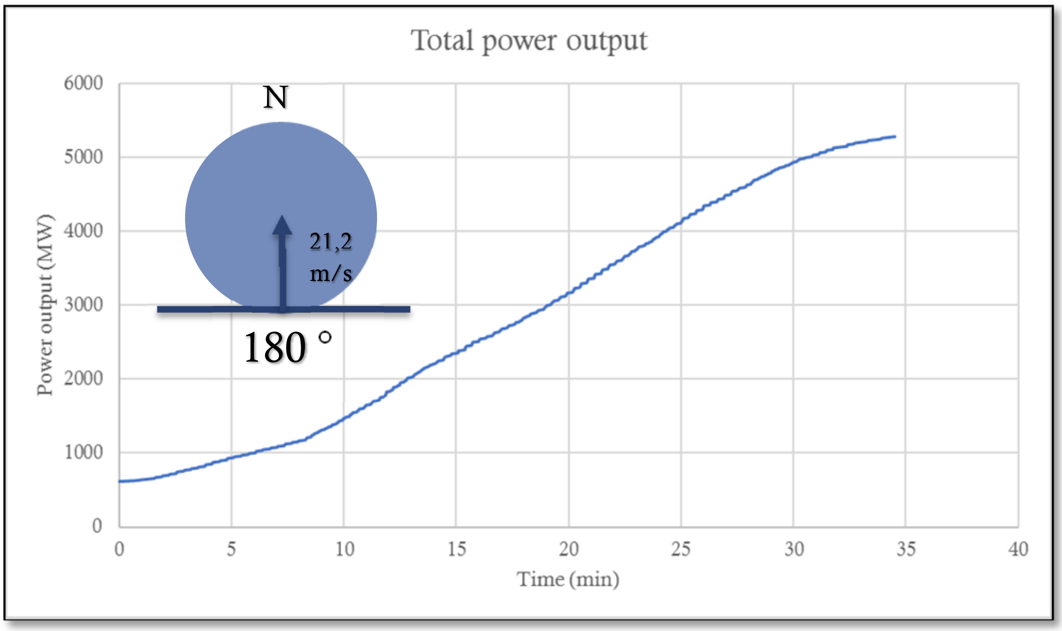

Figure 39: Total power output from SMB during wind increase (5,9 to 21,2 m/s) for wind angle 180 degrees.

Contrary to the smooth line in Figure 39, the line in Figure 40 below increases in very distinct steps. This is because at this angle (150 deg.), the passing wind front will encounter entire arrays of turbines at a time. The time it takes for the wind front to pass is around 25 minutes, and the total power increase is slightly higher than in the last figure (275 to 5280 MW) due to the wake losses at the lower wind speed.

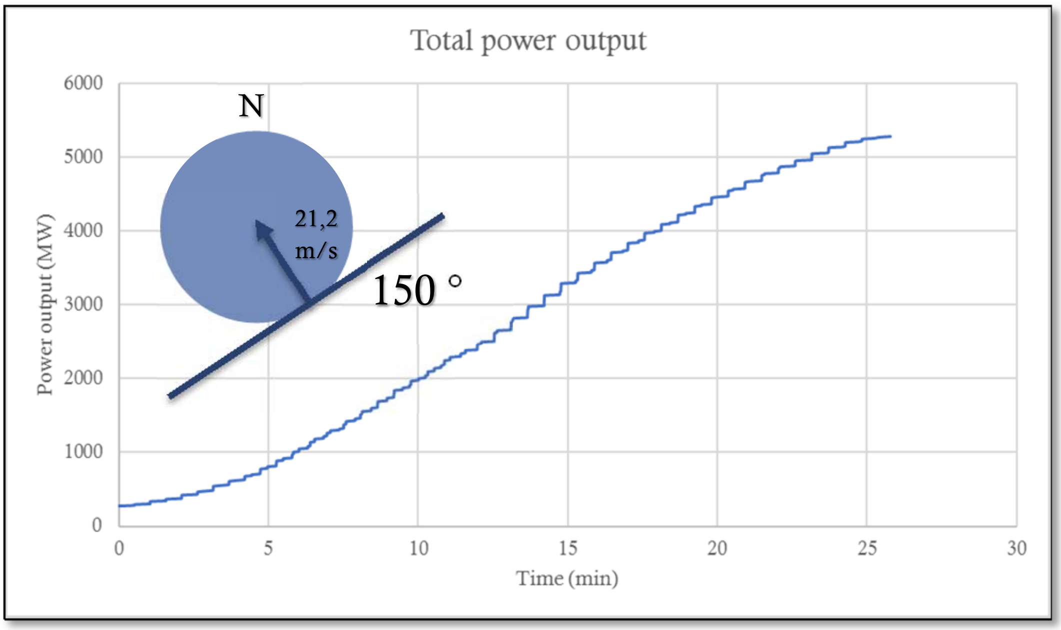

Figure 40: Total power output from SMB during wind increase (5,9 to 21,2 m/s) for wind angle 150 degrees.

Figure 41 shows the power output for a wind front coming from 240 degrees. The angle is near south west, and the distance through the WPP cluster is quite long. This is reflected in the time it takes for the front to pass, which is about 50 minutes. The wind angle is 90 degrees from 150, and so the power output increases in steps again, due to alignment with arrays.

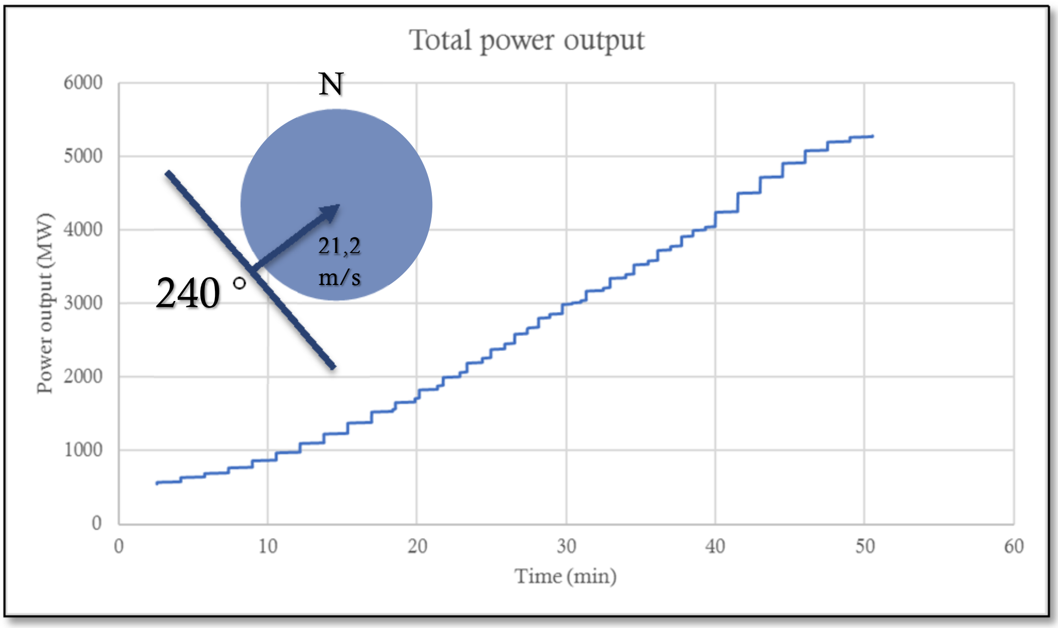

Figure 41: Total power output from SMB during wind increase (5,9 to 21,2 m/s) for wind angle 240 degrees.

The graph in Figure 42 shows what happens when the wind front has a speed of 25 m/s instead of 21,2, when the angle is 150 degrees. The time for the wind front to pass is about 22 minutes. This is the worst-case scenario from the simulations, although higher wind speeds may cause worse situations when turbines shut down and production drops faster.

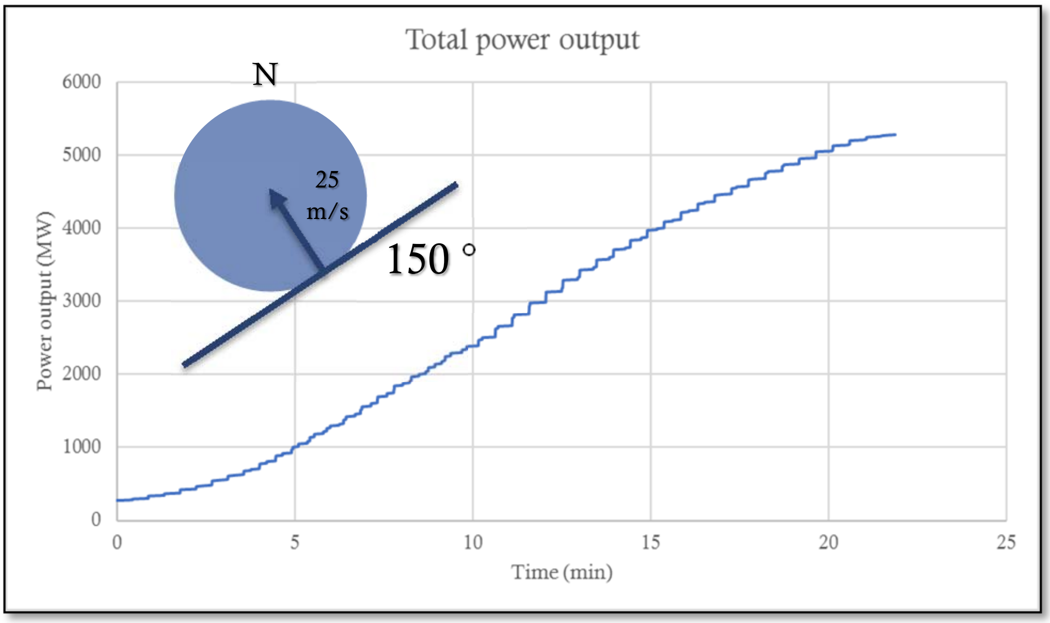

Figure 42: Total power output from SMB during wind increase (5,9 to 25 m/s) for wind angle 150 degrees.

In Figure 43 we see the power output for nine different wind angles. Note that 160 and 140 degrees are the angles with the shortest power increase time. 240

degrees clearly show the step-wise increase seen previously in Figure 41. The curves start at different power outputs depending on the wake losses they have at the wind speed 5,9 m/s. The figure includes a step increase, to show how it would look if all turbines increased production at once.

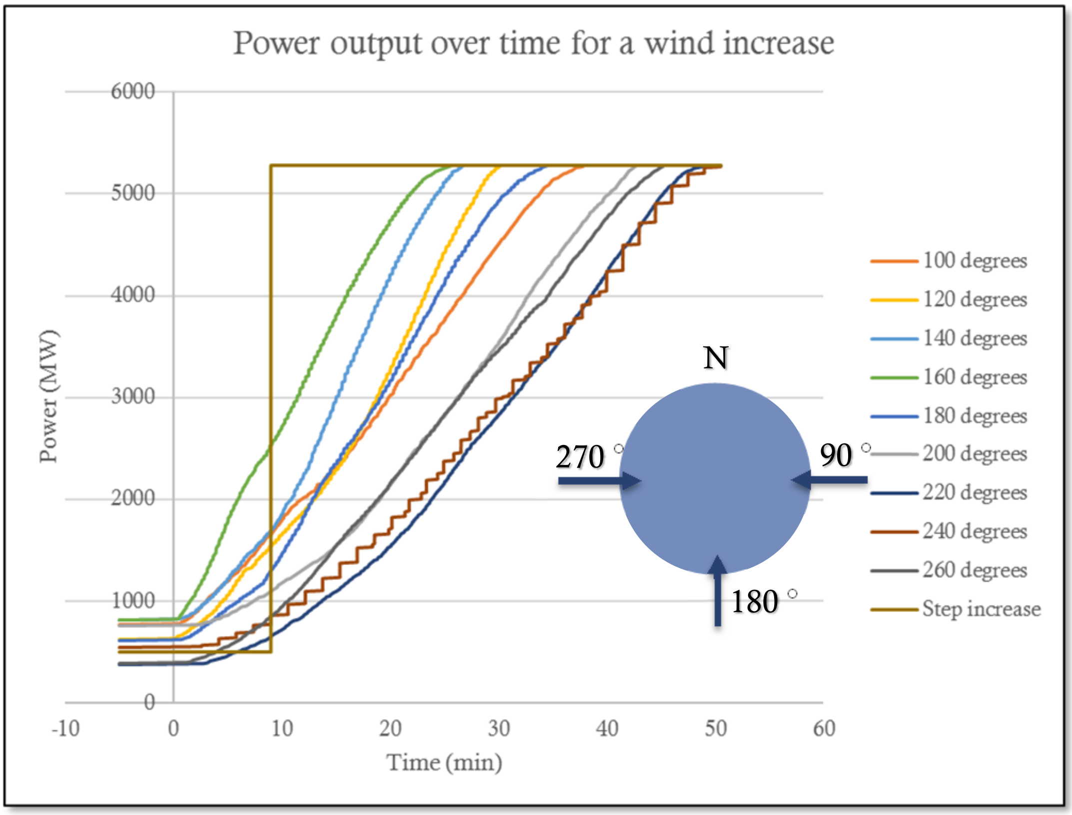

Figure 43: Power output from SMB with a wind increase from different angles between east and west. Includes a step increase to show the difference.

Additionally, a wind front travelling with a velocity of 40 m/s would pass through the plant in 13,7 minutes at a wind angle of 150 degrees. Because this is far above the cut-out speed, the Excel model will not be useful, but the time is still of interest since this is the highest wind speed during the year when the data was collected. If a wind front like this came to SMB when all turbines operated at full power, they could all drop to zero production in 13,7 minutes.

To summarize. The variations in power are large for a WPP cluster of this size. The wind angle and speed both contribute to the magnitude of the fluctuations. However, they do not occur instantaneously in the entire WPP cluster, which could leave enough space for the TSO to activate balancing power.

5. Cost analysis

The yearly electricity production from the final layout was presented in chapter 3, but it is hard to relate to an arbitrary value of energy. It does not mean much before you compare it with money. Here follows a rough estimation of the costs to indicate whether the project is viable or not. Many of the costs are hard to forecast since the whole industry is undergoing a radical price drop now. Also, most of the equipment will be subject to negotiation which can potentially change the prices drastically because of the quantities needed in a plant of this size. Despite the uncertainties, the economic model is still important as a complement to the production calculations in chapter 0. Most prices are assumed based on price indications in course material by Jörgen Svensson. Some prices have been calculated using the total cost for Horns Rev 3 and applying a cost breakdown from DTI (2007).

5.1 Component overview

In Table 13 is a summary of the main components included in the cost analysis.

Table 13: Summary of the main components needed for the WPP cluster.

Turbines	
Rated power (MW)	12
Number	440
Foundations	
Type	Jacket
Number	456
Transformer stations	
Nr 300-400 MW power	4
Nr 400-500 MW power	6
Nr 500-600 MW power	2
HVDC stations	
Number	4
Power capacity (MW)	1500
240 mm2 cables	
Length on bottom (km)	449,975
Length at turbine site (km)	33,003
Total length (km)	482,978
630 mm2 cables	
Length on bottom (km)	340,135
Length at turbine site (km)	18,012
Total length (km)	358,147
1000 mm2 cables	
Length on bottom (km)	95,981
Length at turbine site (km)	1,128
Total length (km)	97,109

5.2 Components and prices

Based on expectations, cost breakdowns from other projects and price calculations from Svensson (2013) the following components and prices have been assumed for the simulations and designs.

Turbine

The turbines plus installation have been priced to 1070 000 €/MW, based on adjusted values from course material by Svensson (2013).

Foundations

Based on the bottom depth at SMB being over 50 m in some areas, the jacket type foundation is likely to be the choice. The price for foundations and installations have been assumed to 576 000 €/MW (Svensson, 2013).

Collection grids

The collection grids are composed of three cable types, described in chapter 3.7. Two cable types are for the internal collection grid and one for the external grid leading up to the HVDC rectifiers. The reason for choosing several cable types is due to costs. A large cable can transfer more power, but will be significantly more expensive. In the outer parts of a wind turbine array, it is cheaper to use a smaller cable. The reason for choosing only three types, and not tailor every stretch of cable in the plant with the optimal cable dimension is because of the benefits of keeping few components. Prices can be seen in Table 14.

Table 14: Details for the two cable types used.

Cable	Type	Cross section (mm^2)	Cost per km (incl. installation)
1	XLPE 3-core copper conductor	240	500 000,00 €
2	XLPE 3-core copper conductor	630	800 000,00 €
3	XLPE 3-core copper conductor	1000	1 100 000,00 €

Transformer station

Because of redundance, each transformer station will consist of two smaller transformers dividing the load. There will likely be a need for three different sizes of transformer platforms. One handling up to 360 MW of power, one for 500 MW and one for 600 MW. This means that we will use transformers able to handle 180, 250 and 300 MW. The prices can be seen in Table 15 below.

Table 15: Transformer platform prices. (Svensson, 2013)

Transformer station	**Cost per MW**
360 MW power	180 000,00 €
500 MW power	170 000,00 €
600 MW power	160 000,00 €

Project management and other costs

The project management and planning costs have been estimated to 50 000 000 €, while 'other costs' are expected to be 160 000 000 €. Note that these values are for the entire WPP cluster. These prices were assumed by the breakdown of plant costs from DTI (2007) and the stated project cost for Horns Rev 3 (4cOffshore, 2017), upscaled relative to installed power to match our project.

5.3 Total cost and LCOE

All the components and installation costs can be seen in Table 16.

Table 16: Cost summary of the project.

Investment	Total Cost
Turbines + installation	**5 645 623 457,67 €**
Trafo station + installation	**990 000 000,00 €**
Cables + installation	**634 826 500,00 €**
Foundations + installation	**3 041 280 000,00 €**
Project management	**50 000 000,00 €**
Other costs	**158 400 000,00 €**
SUM	**10 520 129 957,67 €**

Key figures

LCOE

55,7 €/MW.

Specific values for the calculations can be seen in Appendix B. Compare this LCOE with the expected one from the study by Ernst & Young (2016), saying that offshore wind by 2030 will have a cost of 90 €/MW.

Investment per installed capacity

2 394 000 €/MW.

Investment per energy produced over one year

712 €/kWh

6. Discussion

6.1 Discussion – WPP scaling analysis

The results show a clear relationship that increased turbine size will give lower wake losses. This answers the scientific question number 3 and is a promising conclusion for the offshore wind industry. Newer turbine models are bigger, and as they are implemented, we may see more efficient power production and more revenue. These trivial facts should not be groundbreaking news to large WPP companies, but according to 4cOffshore.com we still see new plants being built using relatively small turbines. Gemini Wind Park, a 600 MW plant in the Netherlands, was fully commissioned in April 2017 using 4 MW Siemens turbines. Simultaneously, Horns Rev III in Denmark is constructed using 49 Vestas turbines, rated at 8 MW. These two WPPs are both in the North Sea and should have similar wind resource, and yet they have chosen very different turbine sizes. It seems like there is a lack of knowledge about the benefits of large turbines in the industry today. Good sales of large-size turbines will further increase incentives to develop new models, and drive the industry toward even more cost-effective plants.

Larger turbines can be spaced with fewer rotor diameters distance, making it possible to install more power per area. One reason for this is that a WPP built with larger wind turbines concentrate the power extraction to fewer points, creating fewer (although heavier) wakes. The number of wake-interactions decrease and more turbines can work undisturbed.

Another reason is that longer rotor diameters exponentially increase the actuator disk area, i.e. the area swept by the blades. This increases the volume of air moving through each turbine. The power extracted from the wind is directly related to the swept area, so when the diameter increases, the energy captured from the wind is increased by the square. This makes large wind turbines more efficient for their size. If you think about the volume of air passing through a plant as a block, then the energy contained in the block is higher when using big rotor diameters, since the height is increased. Large turbines capture more energy, which means that we need fewer turbines to reach the same installed capacity. As we can see from the Nysted test, the wake losses can be quite accurately predicted when scaling up a plant by looking at volume ratios. It is perhaps time that the industry starts talking more about installed power per volume, instead of per area, which is the norm today. Of course, the term installed power per area is important, but it does not tell the whole story without somehow including the rotor diameter and turbine power. This could for instance be included by analyzing a plant's rotor areas per plant volume, or rotor volume per plant volume to have a unitless ratio.

The free-flowing wind around a WPP and the atmospheric turbulence is what determines the refueling of a wake, i.e. the time it takes for the wake behind a turbine to regain energy. These factors do not change depending on the type of turbine we use. Although a large WPP may slow down the surrounding air by the so called deep array effect, it will be more pronounced with more and smaller turbines. A wind turbine wake can be seen as being in 'contact' with, and thus regaining energy from the surrounding wind. The longer the wake, the more energy is going to return to the wake per second. In other words, larger turbines should have relatively shorter wakes. This might be another reason why large turbines can be placed with fewer rotor diameters distance from each other. This could be an interesting field for further studies on the subject.

In the Nysted test, the results show that using the rotor diameter as a measuring system is not an accurate way to think about turbine spacing. This further supports the idea that larger turbines can be spaced closer to each other and increase the installed power per area. The plant using 2,3 MW turbines has a density of 7,15 MW/km^2 and comparable wake losses with a plant with a density of 14,9 MW/km^2 built with 12 MW turbines. Worth noticing is that the power curve for the original Siemens 2,3 turbine does not exactly match the upscaled Vestas V-112 3,0 MW, but the wake calculations should not be affected noticeably.

In terms of cost reduction for offshore wind, larger turbines do increase in manufacturing costs per turbine, since they are larger, but each turbine will also generate more electricity, so fewer turbines are needed. Fewer turbines to install directly reduces the cost of foundations and cables. While a large turbine is more expensive to install than a small one, fewer installations may still reduce the total cost of construction. The increased height of larger turbines also decrease the total wake losses because the average wind speed is higher at altitudes. Higher wind speeds mean more full load hours and less wake losses, since wakes do not cause production losses when an entire WPP is working above rated wind speed. Newer turbines are also more efficiently built, as technology advances, with optimized rotor sizes and blade geometry.

There are drawbacks to using large turbines too. The high towers and large blades can be hard to transport, both on land and by boat to the construction site. The vessels used for lifting the nacelle and rotors to the top of the tower need to be able to handle the increased turbine sizes. These new vessels are likely going to be more expensive to rent for the WPP commissioner. Perhaps we will come to a future where wind turbine manufacturers provide the installation as a service, using their own vessels. This might turn out to be cheaper overall, since the same type of vessel and procedure can become standard and be used in every installation.

The results seem reliable and can be logically explained, although is important to note that all included turbines in this test do not have the same power to rotor size ratio. For instance, the Siemens 3,6 MW used in these tests has a 120 m rotor. An earlier version of the same turbine, also rated at 3,6 MW, had a rotor diameter of 107 m. A turbine with a large rotor and a relatively small power generation will create more wake losses in a plant. This explains the high value seen in Figure 31 when the 1000 MW plant is filled with this type of turbine. The decrease in losses seen in the graph when going from the 8 MW to the 10 MW turbine can have several explanations. The hypothetical turbines (10 MW, 12 MW) are scaled up from the power curve of a much smaller turbine (Vestas V-112 3.0 MW) and although power curves generally look similar between turbines, this scaling is an assumption which could possibly underestimate the wake losses. This is important to note for the turbine layout, which is based on the same turbine.

The method used in these tests is purely theoretical. It would be interesting to compare production and wake loss data for real WPPs and different turbine sizes. It might be hard to accurately draw conclusions since all plants have unique layouts, but with enough statistics it could be possible to see trends.

Conclusively for the scaling analysis, larger turbines provide lower wake losses than small turbines when building large scale plants. This relationship might be one of the main contributing factors to reduce the cost for offshore wind energy in the coming decades.

6.2 Discussion – The Layout

The results from the simulations show that nearby plants do affect each other, in line with the hypothesis, and that decreasing the turbine density of one plant will reduce the wake losses for other plants behind it. In the case study analyzed here, this is more noticeable in the dominating wind direction. Because of this, the chosen design has a slightly lower turbine density in area 1 and 2. The density of Area 4 seems to be of little importance to the other areas because of its size, which is considerably smaller than the other areas. Although changing the turbine density in one area affects the nearby areas, the biggest variation in production occurs in the changed area itself. It will probably be important to regulate the turbine densities in situations like this, where nearby plants are close enough to affect each other. It is complex and will require a lot of research for each case, but without any regulations, companies are going to compete over the best locations and optimize them to perfection. This is going to reduce the value of nearby locations, and possibly make them useless. To avoid companies from doing this, we need to come up with a system of restrictions. Perhaps the auction system used in Denmark, Great Britain and Germany may be a useful starting point. In this system, the authorities identify areas suitable for offshore wind and put them up for auction. Companies then bid on building a WPP for the lowest cost, and the winner gets permission. These contracts may include some sort of restrictions to avoid harming the value of nearby locations. For instance by setting an upper limit on the turbine density.

It is also possible to encourage lower external wake losses without modifying the turbine density. For example, according to the results in this thesis, a plant with the turbine density 3 MW/km^2 using 5 MW turbines will have higher wake losses than one built with 12 MW turbines. Influencing companies to use larger turbines is one way of reaching better efficiency.

The 12 MW model chosen for these simulations proved to be a feasible turbine size, but it is likely that an even larger model would give better outcomes. However, in the scope of this thesis there was not enough time to analyze other turbine types. Almost certainly, larger turbines *will* exist on the market at the time of construction, but the balance between average wind speed at the site and turbine cost may discourage from choosing bigger. On the other hand, it is possible that the added benefits of a larger turbine will outweigh the higher cost.

All tests in this thesis rely heavily on the calculations of WAsP and Fuga to be accurate. When comparing Fuga's production estimation for Nysted with real world data and the experience of supervisor Jörgen Svensson, the software seemed to underestimate the wake losses slightly. This can be explained by the atmospheric condition settings in Fuga. When setting up calculations, it is necessary to state the atmospheric conditions. The neutral atmospheric conditions used as the standard setting, under which all wake calculations were done, are slightly optimistic. Realistically, we should expect higher wake losses. Atmospheric conditions change all the time, and it is likely that the atmosphere at SMB is on the unstable side, rather than neutral, most of the year. A reasonable assumption could be to add 1-2 % in wake losses for these reasons. This was taken into consideration when choosing the suggested layout, and the final wake losses after this correction would still be acceptable.

The strategy to balance production between plants in this layout is to change the turbine density in the first areas. This is done by dispersing the turbines more, but using the same 12 MW model. One can reduce the installed power per area by choosing smaller turbines as well, but that would give increased losses, related to using smaller turbines. However, smaller turbines would have a smaller tower, and work in a lower layer of the atmosphere. In that sense, some of the wind would pass undisturbed over the first plants to reach the larger turbines at the end of the cluster. This would increase the production slightly in area 3 and 4. On the other hand it is not desirable to create wakes which only hit the lower part of a rotor since the loads will be uneven and damage the turbine.

The wind data used in the wake loss calculations is from Nysted, and not from SMB. It is possible that the wind rose and energy rose for the two locations look different. The data also only contains values for one year, and per hour, which is a source of error. Each year is different, and to get a complete picture of the wind before going further in a real WPP project, one needs to have data for several years. These facts could possibly have altered the results.

6.3 Discussion – Power fluctuations

There is undoubtedly going to be large variations in the wind energy during the year. The results of chapter 4 show that large power fluctuations are likely to happen, but that they will not be instantaneous. Depending on the wind angle, the fluctuations will vary in time and total power change. In the fastest case, the wind front took about 20 minutes to pass through the WPP cluster.

During this time, the cluster increased its power output with around 5 GW. The electric grid is not built to handle these variations and will require upgrades. The new era of renewable energy puts pressure on TSO's to act well before these plants are built since grid advancements take time and can be costly. The power fluctuations do not happen in the entire WPP cluster at once which might give the TSO time to react accordingly when the wind speed rises. In one large plant like this it is possible to estimate the power output from the plant in advance right when the first turbines are hit. This would be much harder for several small plants spread out over a larger area, which is one of the benefits of clustering wind power plants together.

Countries connected to large wind power plants need to be aware of these fluctuations to solve associated problems. This include things like reinforcing the connection point and the electric grid and considering what electricity production methods to use for balancing the grid during sudden wind speed variations. The balancing power plants needs to have a fast startup time, so nuclear and coal power plants are not the ideal choice. Sweden has its hydro power, which can reach high power production in just a few minutes. Poland on the other hand, do not, and may have to rely on gas turbines. This is a big problem associated with phasing out the fossil based electricity generation.

The worst-case direction, where a wind front passes in the lowest amount of time is at 150 degrees. The absolute worst case scenario in terms of power fluctuations would be if the wind speed increased past the cut-out speed instantly. A storm or wind front with a velocity of 40 m/s could potentially drop the production from full to zero in 14 minutes, which is a very high change for the electric grid. It would require large resources to balance the grid-frequency in a scenario like that. It is however unlikely that a wind front above the cut-out speed would arrive as a surprise.

One way of dealing with these large power fluctuations could be to use some sort of energy storage. Many storage options produce high losses and require large investments. Batteries are efficient but still very expensive. For this scale, it is hardly practicable to build a battery storage. A hydro power plant could perhaps be used to pump water and store it in a dam. This would require the storage to be quite close to SMB avoid losses. Unfortunately, most hydro power plants in Sweden are in the northern part. An energy storage could also be of interest for times when free wind energy would go to waste due to low demand.

The curves in the result section of chapter 4 look a little different from each other. The first graph (180 degrees) has a very smooth line, while the line for 150 and 240 degrees has steps related to the wind angle being aligned with the WPP arrays. These steps are troublesome since the power increases very rapidly. In reality this outcome is quite unlikely. First because the model is assuming that the wind front arrives as a perfectly straight line, which is not very realistic. Secondly because all the arrays in this layout are aligned with each other. As mentioned before, when this area is constructed, it will most likely be done by multiple companies, and they are probably not going to align their plants according to each other. Perhaps they will not even place their turbines in straight lines at all.

6.4 Discussion – Cost analysis

When designing a layout, we are looking for a good balance between park-interactions and production. The parameter called "production per installed MW" is a good indicator of how well the park is functioning, but no real conclusions can be drawn without comparing with the economic aspect. A park with a higher turbine density will have a lower production per turbine, because of wake losses. On the other hand, it will produce and sell more energy in total, so based on the overall efficiency it may or may not be worth to invest in. The cost of projecting offshore WPPs have gone down significantly in the last few years as the commissioning companies learn from their mistakes. It is likely that a WPP, with what is an unacceptable wake loss today, can be profitable in 15 years when the other parts of commissioning become cheaper. The economic analysis is purely based on speculation since these prices are very hard to forecast. The economic assessment got a very good LCOE. Although the prices are uncertain, it is likely that the scale of this project is what drove down the cost. The prices for components and installations are assumed from a collection of various sources, and it is likely that they will drop even further until 2030. Ultimately it is hard to assess the feasibility of a project this far in the future, but the aim is not to give a definite answer to whether this project should be realized or not, but more as to give an indication.

7. Conclusions and future work

The turbine sizes will continue to grow, and by 2030, a WPP cluster like the one suggested at Södra Midsjöbanken may be built using 12 MW turbines or larger. Turbine size is directly related to wake losses in a plant. The bigger the turbine, the lower the losses. The industry should be careful with the concept of using rotor diameters for turbine spacing since they are only applicable for certain turbines. There are guidelines for turbine spacing which are outdated and old, and it is not accurate to use the same ratio of rotor diameters for two different turbine sizes. Larger turbines can be sited with fewer rotor diameters between them than smaller turbines. This may be one of the main contributing factors in reducing the cost of offshore wind energy.

The suggested layout for SMB presented in this report has variations in turbine density for the different areas. The first plants seen from the dominating wind directions will have a lower turbine density than the areas behind. This is to balance the production and maintain profitability throughout the entire cluster.

When clustering WPPs this close, they are going to affect each other negatively, but there are also benefits of congregating plants together around HVDC connections in a meshed grid. Even if some equipment will make the investments expensive, there are environmental and socioeconomic benefits. When an area has been identified as useful for offshore wind, we need to make sure that it stays attractive even if nearby areas become occupied with other plants. Some sort of auction system could easily implement restrictions.

The power fluctuations during a sudden wind increase will be high in large WPP clusters. However, because of the size, right when a plant is hit by an approaching wind increase, the TSO will know, and can calculate the appropriate reaction. Power fluctuations from many small plants dispersed over a large area would be harder to counteract. However, the fluctuations from an area such as SMB can still be very large. The grid may need to manage changes of around 5 GW of power in less than 15 minutes. All affected power systems need to be aware of these fluctuations well in advance before anything is built. There needs to be research into how to manage these variations, and to find how much can the grid can handle.

Here follow some other areas which may be of interest for future research around the subject of this thesis:

- More research can be done on the subject of energy storage to handle excess power production and large power fluctuations.

- The concept of thinking in installed capacity or installed rotor areas per km^3 instead of km^2 could be investigated more.

- There needs to be research into how we best can solve the problem with restrictions on certain areas. Development of an auction system which can handle such regulations would be appropriate. The restrictions need to consider several parameters. Simply putting a limit on the installed power per area is not enough, since larger turbines have been shown to give lower wake losses, and one can achieve the same MW/km^2 using different sizes. Perhaps it is more accurate to involve the rotor diameter in some way, and still consider the installed power as well. The regulations should include follow-ups and consequences for companies that do not follow the rules, to minimize the risk of dishonesty. There are so many variables in play that this could be a complex task.

- Research on how DC systems can be used in the internal collection grids.

- Analyze how the suggested turbine layout is affected with larger turbine sizes.

- More research could be carried out on guidelines for micrositing. The spacing rules used in the wind industry earlier are outdated and we need modern and more accurate ways to efficiently design plants. Ways which consider both turbine size and installed power.

Appendix A

Table 17: Area 2 alone with tightest spacing.

Test 1	**Area 1**	**Area 2**	**Area 3**	**Area 4**	**Total**
Active	no	yes	no	no	
Wake Loss	-	**12,10%**	-	-	
Nr. Turbines	-	221	-	-	221
Total installed cap (MW)	-	2652	-	-	2652
Spacing (rotor diameters)	-	6:6	-	-	
Spacing (m)	-	1200:1200	-	-	
Area (km^2)	394,9	337	379,2	129,4	
MW/km^2	-	7,869436	-	-	7,869436
Net Production (GWh)	-	11127	-	-	11127
Prod. Per turb (GWh)	-	50,34842	-	-	
Prod [GWh]/Installed MW	-	4,195701	-	-	4,195701

Table 18: Area 3 alone with the tightest spacing.

Test 2	**Area 1**	**Area 2**	**Area 3**	**Area 4**	**Total**
Active	no	no	yes	no	
Wake Loss	-	-	**10,92%**	-	
Nr. Turbines	-	-	252	-	252
Total installed cap (MW)	-	-	3024	-	3024
Spacing (rotor diameters)	-	-	6:6	-	
Spacing (m)	-	-	1200:1200	-	
Area (km^2)	394,9	337	379,2	129,4	
MW/km^2	-	-	7,974684	-	3,987342
Net Production (GWh)	-	-	12858	-	12858
Prod. Per turb (GWh)	-	-	51,02381	-	
Prod/Installed MW	-	-	4,251984	-	4,251984

Table 19: Area 2 and 3 with the tightest spacing.

Test 3	**Area 1**	**Area 2**	**Area 3**	**Area 4**	**Total**
Active	no	yes	yes	no	
Wake Loss	-	**13,69%**	**15,33%**	-	
Nr. Turbines	-	221	252	-	473
Total installed cap (MW)	-	2652	3024	-	5676
Spacing (rotor diameters)	-	6:6	6:6	-	
Spacing (m)	-	1200:1200	1200:1200	-	
Area (km^2)	394,9	337	379,2	129,4	
MW/km^2	-	7,869436	7,974684	-	7,92206
Net Production (GWh)	-	10927	12221	-	23148
Prod. Per turb (GWh)	-	49,44344	48,49603	-	
Prod/Installed MW	-	4,120287	4,041336	-	8,161623

Table 20: Area 2, 3 and 4 with the tightest spacing.

Test 4	**Area 1**	**Area 2**	**Area 3**	**Area 4**	**Total**
Active	no	yes	yes	yes	
Wake Loss	-	**15,15%**	**16,45%**	**10,56**	**15,03**
Nr. Turbines	-	221	252	86	559
Total installed cap (MW)	-	2652	3024	1032	6708
Spacing (rotor diameters)	-	6:6	6:6	6:6	
Spacing (m)	-	1200:1200	1200:1200	1200:1200	
Area (km^2)	394,9	337	379,2	129,4	
MW/km^2	-	7,869436	7,974684	7,97527	7,939797
Net Production (GWh)	-	10741	12060	4406	27207
Prod. Per turb (GWh)	-	48,60181	47,85714	51,23256	
Prod/Installed MW	-	4,050151	3,988095	4,26938	12,30763

Table 21: All areas using the tightest spacing.

Test 5	**Area 1**	**Area 2**	**Area 3**	**Area 4**	**Total**
Active	yes	yes	yes	yes	
Wake Loss	**13,21**	**18,35%**	**17,14%**	**16,76**	**16,22**
Nr. Turbines	249	221	252	86	808
Total installed cap (MW)	2988	2652	3024	1032	9696
Spacing (rotor diameters)	6:6	6:6	6:6	6:6	
Spacing (m)	1200:1200	1200:1200	1200:1200	1200:1200	
Area (km^2)	394,9	337	379,2	129,4	
MW/km^2	7,566473	7,869436	7,974684	7,97527	7,846466
Net Production (GWh)	12378	10336	11961	4101	38776
Prod. Per turb (GWh)	49,71084	46,76923	47,46429	47,68605	
Prod/Installed MW	4,14257	3,897436	3,955357	3,973837	15,9692

Table 22: Area 1 has the most spread out spacing, area 2, 3 and 4 have the tightest.

Test 6	**Area 1**	**Area 2**	**Area 3**	**Area 4**	**Total**
Active	yes	yes	yes	yes	
Wake Loss	**7,25%**	**16,93%**	**16,83%**	**14,00%**	**14,76%**
Nr. Turbines	124	221	252	86	683
Total installed cap (MW)	1488	2652	3024	1032	8196
Spacing (rotor diameters)	9:9	6:6	6:6	6:6	
Spacing (m)	1800:1800	1200:1200	1200:1200	1200:1200	
Area (km^2)	394,9	337	379,2	129,4	
MW/km^2	3,768043	7,869436	7,974684	7,97527	6,896858
Net Production (GWh)	6586	10516	12005	4236	33343
Prod. Per turb (GWh)	53,1129	47,58371	47,63889	49,25581	
Prod/Installed MW	4,426075	3,965309	3,969907	4,104651	16,46594

Table 23: Area 1 and 4 have the most spread out spacing. Area 2 and 3 have the tightest.

Test 7	**Area 1**	**Area 2**	**Area 3**	**Area 4**	**Total**
Active	yes	yes	yes	yes	
Wake Loss	**6,83%**	**16,23%**	**16,34%**	**8,97%**	**14,02%**
Nr. Turbines	124	221	252	43	640
Total installed cap (MW)	1488	2652	3024	516	7680
Spacing (rotor diameters)	9:9	6:6	6:6	9:9	
Spacing (m)	1800:1800	1200:1200	1200:1200	1800:1800	
Area (km^2)	394,9	337	379,2	129,4	
MW/km^2	3,768043	7,869436	7,974684	3,987635	5,899949
Net Production (GWh)	6618	10605	12076	2220	31519
Prod. Per turb (GWh)	53,37097	47,98643	47,92063	51,62791	
Prod/Installed MW	4,447581	3,998869	3,993386	4,302326	16,74216

Table 24: Area 1, 3 and 4 have the most spread out spacing. Area 2 has the tightest.

Test 8	**Area 1**	**Area 2**	**Area 3**	**Area 4**	**Total**
Active	yes	yes	yes	yes	
Wake Loss	**6,73%**	**15,44%**	**10,63%**	**9,40%**	**11,67%**
Nr. Turbines	124	221	118	43	506
Total installed cap (MW)	1488	2652	1416	516	6072
Spacing (rotor diameters)	9:9	6:6	9:9	9:9	
Spacing (m)	1800:1800	1200:1200	1800:1800	1800:1800	
Area (km^2)	394,9	337	379,2	129,4	
MW/km^2	3,768043	7,869436	3,734177	3,987635	4,839823
Net Production (GWh)	6624,4	10705	6040	2232	25601,4
Prod. Per turb (GWh)	53,42258	48,43891	51,18644	51,90698	
Prod/Installed MW	4,451882	4,036576	4,265537	4,325581	17,07958

Table 25: Area 1, 3 and 4 have a spacing of 1600:1600 m. Area 2 has the tightest (1200:1200 m).

Test 9	**Area 1**	**Area 2**	**Area 3**	**Area 4**	**Total**
Active	yes	yes	yes	yes	
Wake Loss	**8,21%**	**16,02%**	**11,93%**	**10,70%**	**12,43%**
Nr. Turbines	153	221	140	47	561
Total installed cap (MW)	1836	2652	1680	564	6732
Spacing (rotor diameters)	8:8	6:6	8:8	8:8	
Spacing (m)	1600:1600	1200:1200	1600:1600	1600:1600	
Area (km^2)	394,9	337	379,2	129,4	
MW/km^2	4,649278	7,869436	4,43038	4,358578	5,326918
Net Production (GWh)	8044	10631	7062	2404	28141
Prod. Per turb (GWh)	52,57516	48,10407	50,44286	51,14894	
Prod/Installed MW	4,381264	4,008673	4,203571	4,262411	16,85592

Table 26: Area 1, 3 and 4 have 1600:1600 m spacing. Area 2 uses 1400:1400 m.

Test 10	**Area 1**	**Area 2**	**Area 3**	**Area 4**	**Total**
Active	yes	yes	yes	yes	
Wake Loss	**8,06%**	**13,18%**	**11,09%**	**10,46%**	**10,82%**
Nr. Turbines	153	171	140	47	511
Total installed cap (MW)	1836	2052	1680	564	6132
Spacing (rotor diameters)	8:8	7:7	8:8	8:8	
Spacing (m)	1600:1600	1400:1400	1600:1600	1600:1600	
Area (km^2)	394,9	337	379,2	129,4	
MW/km^2	4,649278	6,089021	4,43038	4,358578	4,881814
Net Production (GWh)	8058	8504	7130	2411	26103
Prod. Per turb (GWh)	52,66667	49,73099	50,92857	51,29787	
Prod/Installed MW	4,388889	4,14425	4,244048	4,274823	17,05201

Table 27: Area 1 and 2 have 1600:1600 m spacing. Area 2 and 3 uses 1400:1400 m.

Test 11	**Area 1**	**Area 2**	**Area 3**	**Area 4**	**Total**
Active	yes	yes	yes	yes	
Wake Loss	**8,10%**	**13,54%**	**13,11%**	**10,62%**	**11,67%**
Nr. Turbines	153	171	192	47	563
Total installed cap (MW)	1836	2052	2304	564	6756
Spacing (rotor diameters)	8:8	7:7	7:7	8:8	
Spacing (m)	1600:1600	1400:1400	1400:1400	1600:1600	
Area (km^2)	394,9	337	379,2	129,4	
MW/km^2	4,649278	6,089021	6,075949	4,358578	5,293207
Net Production (GWh)	8054	8469	9556	2406	28485
Prod. Per turb (GWh)	52,64052	49,52632	49,77083	51,19149	
Prod/Installed MW	4,38671	4,127193	4,147569	4,265957	16,92743

Table 28: All areas use a spacing of 1400:1400 m.

Test 12	**Area 1**	**Area 2**	**Area 3**	**Area 4**	**Total**
Active	yes	yes	yes	yes	
Wake Loss	**10,49%**	**14,52%**	**13,38%**	**13,48%**	**12,75%**
Nr. Turbines	206	171	192	63	632
Total installed cap (MW)	2472	2052	2304	756	7584
Spacing (rotor diameters)	7:7	7:7	7:7	7:7	
Spacing (m)	1400:1400	1400:1400	1400:1400	1400:1400	
Area (km^2)	394,9	337	379,2	129,4	
MW/km^2	6,259813	6,089021	6,075949	5,842349	6,066783
Net Production (GWh)	10562	8373	9527	3122	31584
Prod. Per turb (GWh)	51,27184	48,96491	49,61979	49,55556	
Prod/Installed MW	4,272654	4,080409	4,134983	4,12963	16,61768

Table 29: All areas use a spacing of 1600:1600 m.

Test 13	**Area 1**	**Area 2**	**Area 3**	**Area 4**	**Total**
Active	yes	yes	yes	yes	
Wake Loss	**7,88%**	**10,94%**	**10,18%**	**10,05%**	**9,62%**
Nr. Turbines	153	128	140	47	468
Total installed cap (MW)	1836	1536	1680	564	5616
Spacing (rotor diameters)	8:8	8:8	8:8	8:8	
Spacing (m)	1600:1600	1600:1600	1600:1600	1600:1600	
Area (km^2)	394,9	337	379,2	129,4	
MW/km^2	4,649278	4,557864	4,43038	4,358578	4,499025
Net Production (GWh)	8074	6530	7203	2422	24229
Prod. Per turb (GWh)	52,77124	51,01563	51,45	51,53191	
Prod/Installed MW	4,397603	4,251302	4,2875	4,294326	17,23073

Table 30: Area 1, 2 and 4 have a spacing of 1600:1600 m. Area 3 uses a spacing of 1400:1400 m.

Test 14	**Area 1**	**Area 2**	**Area 3**	**Area 4**	**Total**
Active	yes	yes	yes	yes	
Wake Loss	**7,92%**	**11,38%**	**12,39%**	**10,22%**	**10,63%**
Nr. Turbines	153	128	192	47	520
Total installed cap (MW)	1836	1536	2304	564	6240
Spacing (rotor diameters)	8:8	8:8	7:7	8:8	
Spacing (m)	1600:1600	1600:1600	1400:1400	1600:1600	
Area (km^2)	394,9	337	379,2	129,4	
MW/km^2	4,649278	4,557864	6,075949	4,358578	4,910417
Net Production (GWh)	8070	6497	9635	2417	26619
Prod. Per turb (GWh)	52,7451	50,75781	50,18229	51,42553	
Prod/Installed MW	4,395425	4,229818	4,181858	4,285461	17,09256

Table 31: Area 1 uses a spacing of 1400:1400 m. Area 2, 3 and 4 uses a spacing of 1600:1600 m.

Test 15	**Area 1**	**Area 2**	**Area 3**	**Area 4**	**Total**
Active	yes	yes	yes	yes	
Wake Loss	**10,11%**	**11,60%**	**10,34%**	**11,39%**	**10,65%**
Nr. Turbines	206	128	140	47	521
Total installed cap (MW)	2472	1536	1680	564	6252
Spacing (rotor diameters)	7:7	8:8	8:8	8:8	
Spacing (m)	1400:1400	1600:1600	1600:1600	1600:1600	
Area (km^2)	394,9	337	379,2	129,4	
MW/km^2	6,259813	4,557864	4,43038	4,358578	4,901658
Net Production (GWh)	10607	6481	7190	2386	26664
Prod. Per turb (GWh)	51,49029	50,63281	51,35714	50,76596	
Prod/Installed MW	4,290858	4,219401	4,279762	4,230496	17,02052

Appendix B

Table 32: Values for calculating LCOE and investment per MW & MWh.

LCOE (Euro/MWh)	55,70 €
Investment/MW	**2 934 024,20 €**
Investment/MWh	**28,48 €**
NPVcost	**15 491 647 794,95 €**
CRF	**0,078226718**
AEP (kWh)	**21757016,69**
Installed power (MW)	**5280**
r	**6%**
N (years)	**25**
Cc	**10 520 129 957,67 €**
Pd	**- €**
Pa	**822 955 241,75 €**
i	**2%**
k	**0,9622641509**
L	**25,00 €**
Y (k, L)	**15,75239678**
Y (r, N)	**12,78335616**
Fom	**3%**

NPVcost: Net present value of costs
CRF: Capital recovery factor
AEP: Annual energy production
r: discount rate
N: lifetime
Cc: Capital cost
Pd: Downpayment
Pa: Annual payment
i: inflation rate
k: discount rate factor
Y: functions to obtain the present value of a series of payments
Fom: annual operation and maintenance cost fraction (of system capital cost)

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