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Design of an offshore wind farm and power fluctuations handling via thermal power plants and energy storage

A case study of Vindplats Göteborg

Master of Science Thesis in Sustainable Energy Systems

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Division of Energy Technology
CHALMERS UNIVERSITY OF TECHNOLOGY
Göteborg, Sweden, 2012
Report No. T2012-379

MASTER OF SCIENCE THESIS

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Abstract

This report consists of two distinct parts. The first one is focused on the design of an offshore wind farm based on a project called Vindplats Göteborg and led by Göteborg Energi AB. This survey encompasses the site assessment, the choice of foundations, cables and turbines as well as the optimization of the layout and the calculation of the energy output. The second part of this report is an investigation of the technical potential to compensate the power fluctuations entailed by the wind farm previously designed. Two major technologies have been explored to be used as energy back-up: the Rya Combined Heat and Power plant (CHP) owned by Göteborg Energi AB and a Vehicle to Grid (V2G) system to be implemented in Göteborg area.

The design of Vindplats Göteborg wind farm was performed in the perspective of learning engineering know-how within the field of wind power and trying to develop innovative tools to assess and optimize the power production of a wind farm. The study of the compensation of the fluctuations was driven by the significant growth of wind power in Europe entailing a strong dependence on the power exports, especially for countries that became large wind power producers. The issues related with power quality and frequency fluctuations involve a very small time resolution and will not be addressed in the present study.

The site assessment performed in the first section combined with the economic evaluation of the project indicate that the construction of 9 turbines Vestas V164 seem to be the most cost-effective and well adapted choice considering the available space in the prospected area. The optimization of the layout enables to reach the annual energy output of 200 GWh and the investigations on the potential power fluctuations shows that 20 MW/min ramp-down are to be expected under extreme wind conditions. The introduction of Vindplats Göteborg will save a significant amount of CO_2 and increase the local electricity production capacity even though power imports are still required to meet the highly fluctuating demand. A V2G system can back-up the wind farm in case of extreme wind conditions up to a 24h-outage but requires then almost 50% of the current fleet to be electric cars. The Rya CHP plant does not have the reserve power and a sufficient ramp-rate to back-up Vindplats Göteborg wind farm but several improvements could be done to ensure both the heat supply and a local steady electricity production. The fast-response of the V2G system combined with upgraded gas turbines could however be an optimal solution to compensate the wind power fluctuations and in term, the local consumption pattern, hence reducing the maximal transfer capacity and the dependence on the surrounding network.

Keywords: energy storage, power fluctuations, Rya CHP plant, V2G, Vindplats Göteborg, wind power, wind farm layout

Design av en offshorevindpark och hantering av dess kraftfluktuationer via termiska kraftverk och energilagring
En fallstudie av Vindplats Göteborg
Examensarbete inom masterprogrammet Hållbara Energisystem
Institutionen för Energi och Miljö
Avdelningen för Energiteknik
Chalmers Tekniska Högskola

Sammanfattning

Den här rapporten består av två distinkta delar. Den första fokuserar på designen av en vindpark som är baserad på projektet Vindplats Göteborg, vilket drivs av Göteborg Energi AB. Arbetet innefattar platsutvärdering, val av fundament, kablar och turbiner samt optimering av layouten tillsammans med beräkning av årlig energiproduktion. Andra delen av rapporten är en undersökning av den tekniska potentialen att kompensera fluktuationerna i elnätet som härstammar från den designade vindparken. Två betydande tekniker har utforskats i syftet att användas som backupsystem; Rya Kraftvärmeverk, drivet av Göteborg Energi AB, och ett elbilssystem för implementering i Göteborg.

Designen av vindparken för Vindplats Göteborg utfördes i syftet att utveckla ingenjörsfärdigheter inom vindkraftssektorn och för att försöka utveckla innovativa verktyg för undersökning och optimering energiproduktionen vid en vindpark. Studien av fluktuationskompensering drevs av den signifikanta tillväxten av vindkraft i Europa, vilket medfört ett starkt beroende av kraftexport, särskilt för länder som kommit att bli stora vindkraftsproducenter. Problemen relaterade till kvaliteten på el och frekvensfluktuationer ställer krav på väldigt fin tidsupplösning och kommer således ej undersökas i denna rapport.

Platsundersökningen utförd i den första delen kombinerat med den ekonomiska utvärderingen av projektet indikerar att en vindpark bestående av 9 stycken Vestas V164-turbiner kommer att vara det mest lämpliga och kostnadseffektiva valet för det tillgängliga utrymmet på den prospekterade platsen. Optimeringen av layouten möjliggör att det årliga energiproduktionsmålet på 200 GWh kan nås och undersökningen av fluktuationerna i energiproduktionen visar att 20 MW/min i nedrampning kan förväntas vid extrema vindförhållanden. Etablerandet av Vindplats Göteborg kommer innebära en betydande minskning av CO_2-utsläpp och en ökad lokal energiproduktion, även om Göteborg fortsatt kommer att behöva en energiimport för att möta det fluktuerande energibehovet. Ett system med elbilar som backup för vindparken klarar av fallet av extrema vindförhållanden i upp till 24 timmar men kräver då att nästan 50% av den befintliga bilmängden i Göteborg är elbilar. Rya Kraftvärmeverk har ej den reservkraft och inte heller den ramp-rate som erfordras av ett backupsystem för vindparken i Vindplats Göteborg, investeringar i modifieringar skulle dock kunna lösa detta. Den snabba responstiden i elbilssystemet kombinerat med ett uppgraderat Rya Kraftvärmeverk skulle kunna vara den optimala lösningen för att kompensera vindkraftens fluktuationer och på lång sikt; det lokala konsumtionsmönstret genom reducering av den maximala överföringskapaciteten och beroendet av omkringliggande nätverk.

Nyckelord: elbilssystem, energilagring, kraftfluktuationer, Rya Kraftvärmeverk, vindkraft, vindparkslayout, Vindplats Göteborg

Preface

The present study was done in the context of an exponential growth of wind power in Europe. The upcoming high penetration of wind in the energy system is likely to provoke large power outages locally depending on the climatic conditions and this will make the wind power producers gradually more dependent on their neighbors. As the energy demand steadily increases, the stress on the network over borders is intensified, requiring even more transfer capacity. The local compensation of these power fluctuations may be a transitional mean to alleviate the saturation of the network while improving the reliability of the power supply. Vindplats Göteborg is a first step towards a larger wind capacity in Göteborg and Göteborg Energi AB is since 2008 installing fast-loading points for EVs and leading investigations for the implementation of a V2G system in Göteborg area (1). Rya CHP plant is still operated to comply with the heat demand and the electricity produced is for now a valuable by-product. This thesis work is trying to evaluate the potential of Göteborg to ensure its electricity supply while limiting the energy import in case of an increased wind power penetration.

This Master Thesis is concluding our Master of Science in Sustainable Energy Systems at Chalmers University of Technology. This project, corresponding to 30 credits ECTS, started in January 2012 and was presented in June 2012.

We would like to express here our sincere gratitude to our supervisor and examiner Lars-Erik Åmand who made this work possible and supported us all along the project. His interest into the renewable energy field as well as his passion and deep knowledge within the thermal plant industry was of a great help during this thesis. We address a special thanks to Ola Carlsson who has made available his support in a number of ways, and provided us with guidance and priceless advice. We are deeply indebted to Filip Johnsson for the financement of our participation to the EWEA conference and to David Pallares for his advice and administrative support. We would like to thank Mikael Odenberger, Lina Reichenberg, Shemsedin Nursebo, Henrik Jilvero and Pontus Markström for their constructive participation to this thesis and for the interesting discussions we had.

We are grateful to our supervisor Jonas Cognell to have made possible the collaboration with Göteborg Energi AB and for having given us the opportunity to meet valuable actors of the energy production system of Göteborg during our thesis work. We specially thank Peter Maksinen to have introduced us to the energy trading department and Pontus Hidborg to have provided us with precious help and data and who made our stay at Göteborg Energi AB very enjoyable and helpful in many ways. We would like to show our gratitude to Martin Rokka and Victor Karlsson for their very helpful assistance and the enriching study visit of Rya CHP plant, and we send hereby a big thank to Thomas Johnson to have made this meeting possible. We are very thankful to Paul Leinberg and his colleagues for their help and enlightening explanations of the internal mechanism of energy trading. Finally we would like to gratefully acknowledge Jon Angelbratt to have provided us with invaluable wind data for the thesis and Lotta Peterson to have introduced us to Göteborg Energi AB.

Yours sincerely,

Eric Rådegård **Marc Thévenot**

Tables of Contents

I. List of abbreviations
II. Nomenclature
III. Figures
IV. Tables
V. Equations

I. List of abbreviations

2D	Two dimensions
3D	Three dimensions
A	Ampere
a.m	Ante meridiem
BEV	Battery based Electric Vehicles
CHPs	Combined Heat and Power plants
D	Diameter
DOD	Depth Of Discharge
EMD	Energi- og Miljødata
EVs	Electric Vehicles
g/mol	Gram per mole
g_C	Gram of carbon
g_{CO2}	Gram of CO_2
GECs	Green Electricity Certificates
GHGs	Green House Gases
GW	Gigawatt
GWh	Gigawatt Hour
HEV	Hybrid Electric Vehicles
HRSG	Heat Recovery Steam Generators
IEC	International Electro-technical Commission
ISO	International Organization for Standardization
kg_{CO2}	Kilo of CO_2
kg_{Coal}	Kilo of coal

km	Kilometer
kV	Kilovolt
kW	Kilowatt
kWh	Kilowatt Hour
Li-ion	Lithium-ion
m	Meter
m/s	Meter per second
mAh	Milliampere Hour
min	Minute
MJ	Megajoule
MJ/kg	Megajoule per kilo
MW	Megawatt
MW/min	Megawatt per minute
MWh	Megawatt Hour
M€	Million euros
NGCC	Natural Gas Combined Cycle
O&M	Operation and Maintenance
p.m	Post meridiem
p.u	Per unit
p.u/min	Per unit per minute
SMHI	Sveriges Meteorologiska och Hydrologiska Institut
SOC	State Of Charge
ton_{CO2}	Ton of CO_2

TWh	Terawatt Hour
V2G	Vehicle-to-Grid
WAsP	Wind Atlas Analysis and Application Program
Wh	Watt Hour
Wh/km	Watt Hour per kilometer
€/L	Euros per liter

II. Nomenclature

C_t	Thrust coefficient [-]
k	Characteristic slope of the wake effect [%]
$P_{mean}(n)$	Average power at a time n [p.u]
P_{ramp}	Power ramp rate [p.u/min]
u	Wind speed [m/s]
U	Wind speed before the turbine [m/s]
V	Wind speed after the turbine [m/s]
X	Distance inter-turbine [m]
Z_0	Roughness of the terrain [m]

III. Figures

IV. Tables

V. Equations

1 Introduction

1.1 Background

The European energy market is currently experiencing one the most interesting transformation period ever. The price of fossil fuels is skyrocketing, the nuclear industry safety is more and more questioned and the share of renewable energies is steadily increasing. Wind power is now the standard bearer of the renewable energies, currently supplying 5.3% of the electricity in Europe, and likely to reach more than 15% of the electricity produced by 2020 (2). *Figure 1* below illustrates the dynamism of the wind power market for the last decades and stresses the fast expansion of the offshore industry.

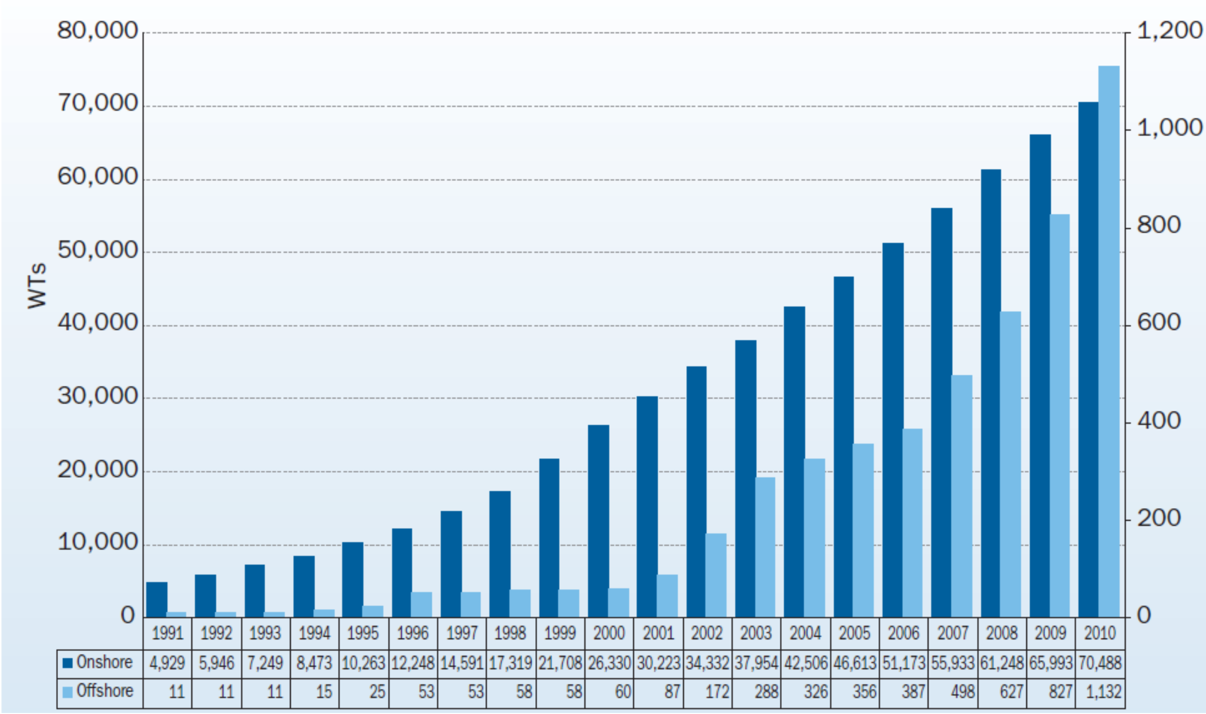


Figure 1. *Cumulative number of wind turbines installed in the European Union (2)*

Accounting for a third of the greenhouse gases (GHGs) emissions in Europe 2007, the energy sector is advantageously benefiting from this wind power expansion to cut the carbon emissions while relying on a safer energy source from a supply and an operation point of view (3).

However, this expansion is strongly dependent on the flexibility of the infrastructure to support this large-scale integration. Massive investments are needed in Europe to achieve a fast-responding generation system and an extended and upgraded distribution network that could enable the integration of a larger share of renewable energies. The limitations are hence not inherently due to wind power technical limitations but to the current weaknesses of the European grid (4).

1.2 Sweden

Following the trend like its European neighbors, Sweden has for objective to increase its share of wind power from the 2163 MW installed in 2010 to 10 GW by 2020 (2). The Swedish authorities are also massively investing on biomass cogeneration as it can be seen in *Figure 2*. The hydro power reserves are constant but the share from biomass (excluding peat) and wind power is steadily increasing for the last decade. By adding the large resources of hydropower and the upcoming production from biomass and wind power, 17.3 TWh of green certificates were produced in 2010 out of the 132 TWh of electricity consumed at that time (5).

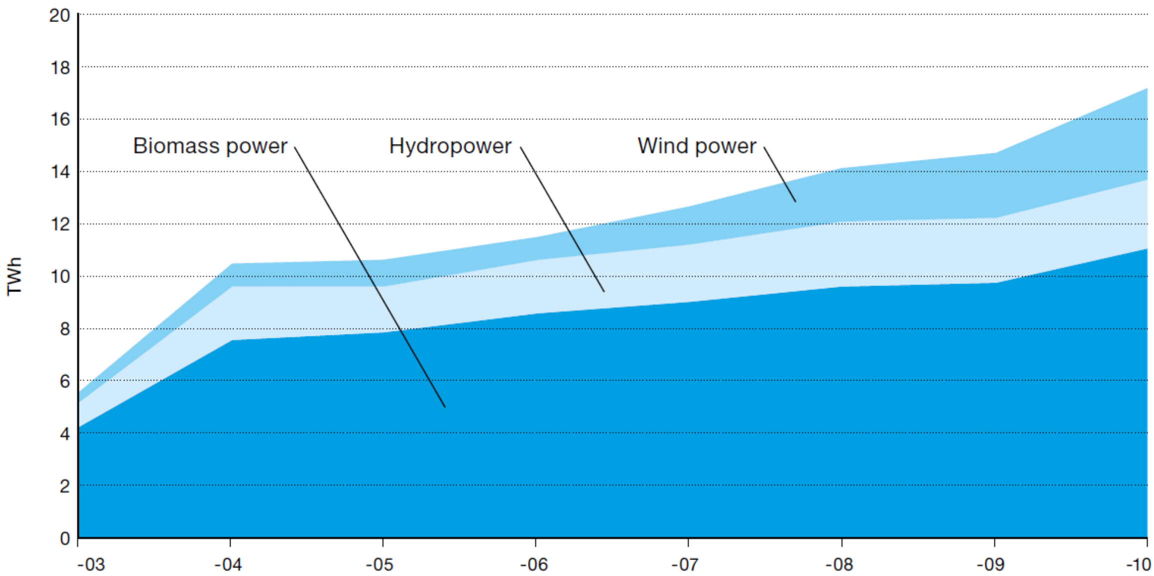


Figure 2. *Renewable energy generation in Sweden from 2003 to 2010 (5)*

In order to support and convey this significant amount of renewable energy, Sweden also intends to improve its network. Last December, a contract was signed to install cables and converters between the Baltic States and Sweden. However, in order not to entail any local increase of the electricity prices, the internal transmissions are also expected to be strengthened and extended, enabling for example the transmission of the hydro power located in the north down to the main load points in the south of the country (6). From a more general perspective, the development of the connections between the hydropower and the different European states has been largely fostered by the need for storage entailed by the wind power expansion.

1.3 Göteborg

Second city of Sweden, Göteborg (also called Gothenburg) counts today more than 500 000 inhabitants. This growing population is currently consuming 4400 GWh of electricity and 4700 GWh of heat per year. Göteborg Energi AB, the leading energy supplier, is facing this extending demand by providing the city with electricity, gas, district heating and cooling since 1990 (7). *Figure 3* illustrates the geographical situation of Göteborg, located on the west coast of Sweden and facing the Denmark, the pioneer which introduced large scale wind power in Europe.

Figure 3. *Map of Sweden with the two main cities of the country represented (8)*

In compliance with the national incentives, Göteborg Energi AB has made large investments in the biomass sector and intends to increase the share of wind power overtime to reach a production of 500 GWh per year by 2017 (9).

1.4 Vindplats Göteborg

Initiated in 2010, Vindplats Göteborg is one of the several wind farm projects owned by Göteborg Energi AB, which will contribute to the national ambitions of 25 TWh of renewable energy by 2020 (10). With a target of 200 GWh of electricity annually produced, the farm should not exceed 16 turbines. The prospected area is located in Hake Fjord, approximately 15 km west offshore of Göteborg center. *Figure 4* below is a picture of the zone considered seen from above. Appendix A is showing the area of the whole Göteborg commune in addition to the sea side.

Figure 4. *Satellite view of Hake Fjord*

The yellow line delimitates the focused area considered in this study and is based on the early stages of the project from January 2012. The current scope has evolved towards a slightly wider area but the former restricting dimensions were adopted in order to keep a marginal security.

Hake Fjord is interesting for the implantation of wind turbines for many aspects. Since it is located offshore, the farm will benefit from steady and relatively high speed wind conditions. This specific area is located next to a potential connection point to the grid in Torshamnen, which considerably reduces the investment costs for power transmission. Finally the area considered is characterized by a very low water depth between 3 and 8 meters which decreases the expenditures associated with the construction phase (10).

However, despite the apparent available space that can be observed on the satellite view, the Hake Fjord area is limited by numerous constraints, visible or not. *Figure 5* below is a navigation map of Hake Fjord area that shows the ferry routes limiting the area to the North and to the South.

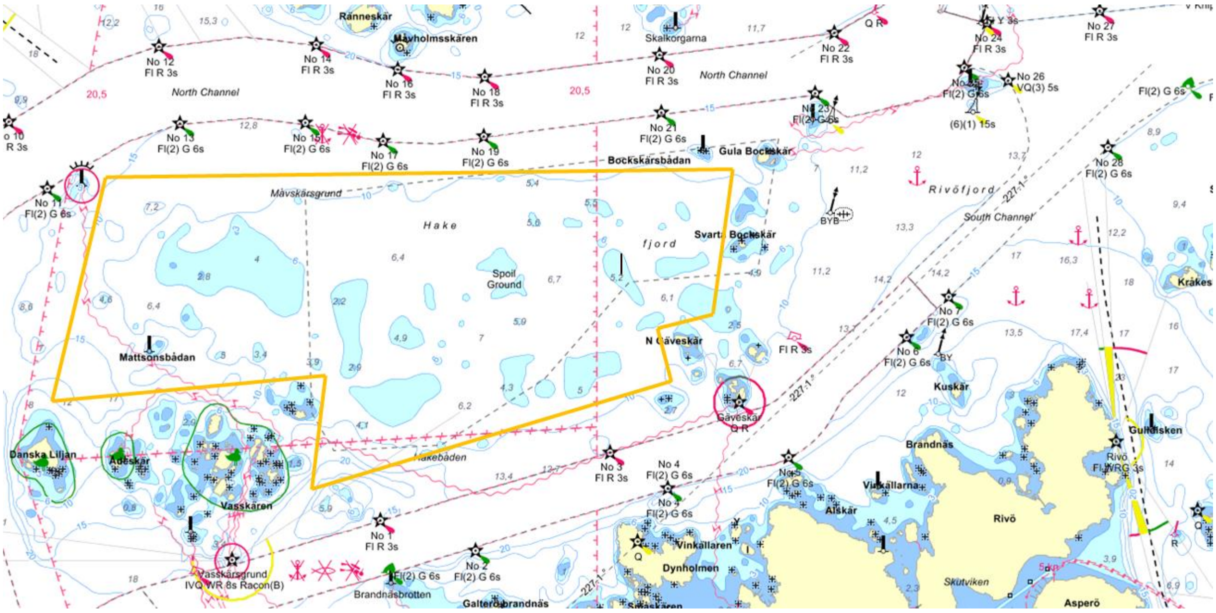


Figure 5. *Marine navigation map of Hake Fjord (11)*

In addition to the marine traffic, the different archipelagos, the water depth and the underneath rocks also are limiting factors explaining the constraints on the west and east sides. Finally the environmental impacts on the bird migration and the local marine fauna and flora currently are under investigation by Göteborg Energi AB and might affect the present prospected area. Different public consultations are planned by the company to present the final aspect of the wind park, as illustrated on the cover picture, and in case of public acceptance the construction phase could start by 2016 (10).

2 Purpose

This thesis work is aiming at two distinct objectives:

- The design of Vindplats Göteborg wind farm
- The investigation of the technical potential to compensate the power fluctuations induced by the park by the use of the local Rya CHP plant and the implementation of a Vehicle-to-Grid (V2G) system in Göteborg

A secondary goal consists in assessing the relation between the power fluctuations and the size of the wind farm in order to draw specific conclusions for Vindplats Göteborg.

Another secondary objective is to study the production mix of Göteborg area in order to assess the impact that the wind power penetration will have on the current energy market.

3 Method

This project is articulated around 6 modules. These different parts were created to structure the work into independent tasks that could eventually be performed in parallel. This splitting of the work load is also a way to obtain clear and understandable secondary results which provide a better comprehension of the overall achievement.

Each module is characterized by a specific objective, method and conclusion. The modules are here presented in chronological order since it is a simple way for the reader to follow the natural line of reasoning adopted in this work.

The design of the wind farm was performed by assessing first the wind conditions using local measurements and statistic tools. Mainly the wind speed and its direction were used to have a picture of the wind resource from Hake Fjord. Additional tools such as the wind shear were introduced to be used in the following module.

Once the potential of the site was identified, different commercially available turbine models were then selected and compared from their ability to fulfill the energy target within the available space. An economic assessment was performed including several factors such as the electricity prices and the green certificates prices, the foundation and cable costs as well as the investment costs for the turbines and the expenditures associated with their maintenance. Once the best candidate is chosen, the optimization of the layout can start taking into account the shadowing effect and the limitations of the area.

The study of the power fluctuations consists in comparing existing farms and assessing the impact of the number of turbines, the shape of their power curve as well as the size of the farm on the amplitude of the fluctuations and the ramp rates of the installation. A wind farm located next to Hake Fjord is used as reference and enables to check the validity of the extrapolation made from other existing farms.

The investigation on the production mix in Göteborg is taking into account the local production utilities and the consumption of the city in order to assess how much electricity is imported. The reduction of carbon emissions due to Vindplats Göteborg project can then be calculated based on the electricity import figures and an additional survey on the Nordic electricity market.

The use of a V2G system to damper the power fluctuations was investigated in the whole Göteborg commune. A preliminary study of the commercially available electric cars was first carried out, in addition to a survey on the use of cars in Göteborg area. The potential for EVs to back-up Vindplats Göteborg was calculated based on previous reports on this topic and additional assumptions. This evaluation of energy storage was however done in a concern to be specific to Göteborg region.

The investigation of Rya CHP plant starts with the review of the technical specifications of the installation. The available capacity is then studied to determine if the whole wind farm output can be compensated by Rya CHP plant alone and the ramp-rate is finally being investigated to assess the ability of the installation to react after a sudden wind outage.

4 Scope

From a time perspective, the data used for the wind conditions assessment were measured between 2002 and 2011 with a resolution down to the hour, but the single values reached by extreme temperatures for instance, come from a more general timeframe starting in 1973. The energy production calculations are based on the modeled year 2012 and all the data considered to build this model were taken from the last decade. Finally most of the scenarios of wind power expansion considered here are taken from the European ambitions target for 2020.

From a geographic perspective, the design of the wind farm is exclusively considering the area prospected by Göteborg Energi AB in Hake Fjord. However, the study of the local production mix as well as the investigation of the fluctuations compensation is encompassing the whole Göteborg commune. Since the energy market is deregulated, the study of the wind penetration and the fluctuations compensation will be carried out in the context of a Nordic electricity market shared by the Scandinavian countries.

Regarding the design of the wind farm, the only economic factors taken into consideration were the one affected by the number of turbines used. As a result, this economic evaluation were not aiming at giving an accurate investment cost for the overall project but was an efficient tool to sort the turbines mainly depending on the number of units required in each case.

Concerning the power fluctuations, the time resolution is the minute or the hour meaning that the frequency instability and the signal quality issues entailed by wind power were not considered in the present study.

5 Modules

Modules 1 and 2 are mainly dealing with the wind conditions assessment of Hake Fjord and the design of the wind farm to give a final layout and wind turbine model as an output. Module 3 is focused on the power fluctuations from Vindplats Göteborg in order to dimension the right back-up technology in the rest of the study. Module 4 is an investigation of the power production and consumption in Göteborg, enabling to assess the future impact of Vindplats Göteborg. Modules 5 and 6 are evaluating the potential from a V2G system and Rya CHP plant respectively to back-up Vindplats Göteborg.

5.1 Module 1 – Meteorological conditions at Hake fjord

5.1.1 Objective

The aim of the first module is to examine the meteorological conditions at Hake fjord and to make a prediction of the wind conditions for 2012. The parameters investigated are wind speed, wind direction and ambient temperature. Data used for the analyses of wind speed and direction were acquired from Göteborg Energi AB and measured at Risholmen which is a peninsula located 2 km northeast of the investigated area of Hake fjord with its sensor located at 40 meters height. Temperature data was obtained from SMHI and it was measured with a sensor placed in the city of Göteborg (12). All data used in the first module are inspected in Microsoft Excel and then imported to MathWorks MATLAB which is used for all the calculations (13).

5.1.2 Wind speed

5.1.2.1 Method

The basis for the investigation consists in wind speed measurements from 2002-2011 with an hourly time resolution. All the years are not entirely complete which is why the dataset is cut down to six full years with just a few interpolations. As no specific trends regarding the everyday fluctuations were detected, an overall mean value was calculated from the full dataset. To make a model of the 2012 conditions, the dataset for 2011 was extracted and translated so that its mean value matches to the overall mean value of the whole dataset.

5.1.2.2 Results

The resulting model for 2012 has a mean wind speed of 6.93 m/s and its fluctuating intensity over the year can be seen in *Figure 6*, based on a 40 m height measurement of 2011.

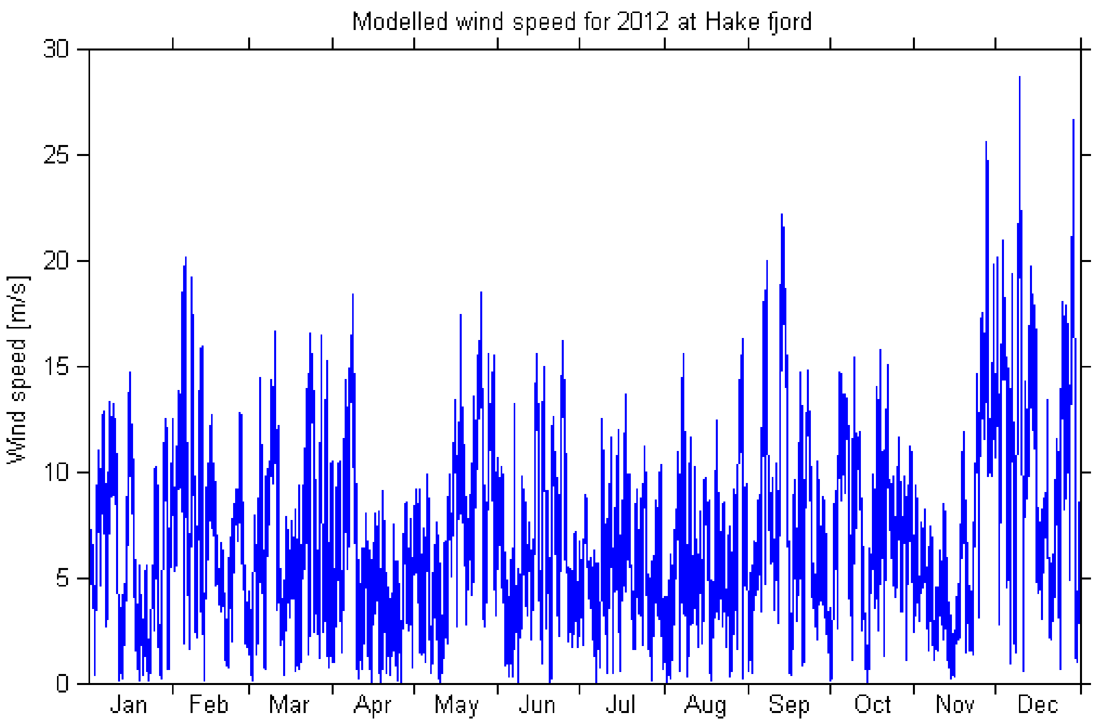


Figure 6. *Modeled wind speed for 2012 at Hake fjord*

The dataset for the 2012 model was sorted to construct a duration curve, see *Figure 7*, where it is possible to see the frequency of occurrence for different wind speed limits. The maximum wind speed occurring was 28.7 m/s.

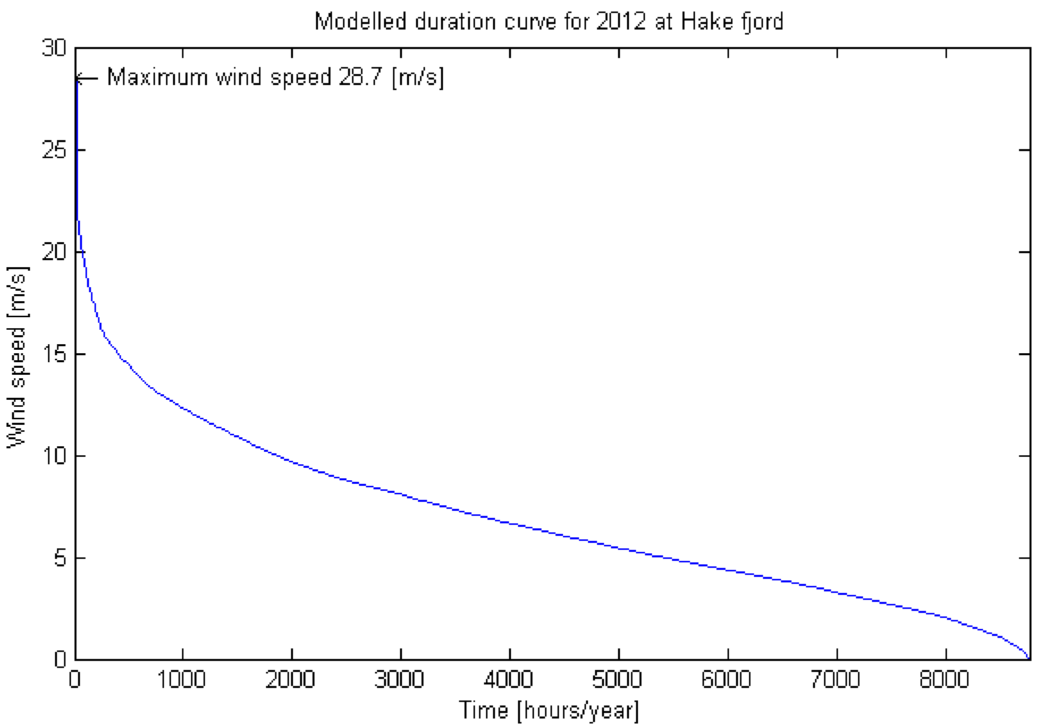


Figure 7. *Modeled duration curve for 2012 at Hake fjord*

5.1.2.3 Discussion
The sensor for the data source is placed close to the investigated region which makes it an accurate source for the project. It is also placed high enough from the ground so that the wind speed measurements are not notably affected by the surrounding terrain.

For November and December it is clear that the wind speeds were in general higher than for the rest of the year. This trend is in line with general studies of wind speed in Sweden (14).

5.1.3 Wind profile and modeling of wind speed at hub heights

5.1.3.1 Introduction
When the wind blows through the park, the average speed is not the same depending on the altitude considered. This phenomenon is due to the viscosity of the air combined with the roughness of the terrain. As a consequence, the highest layers of wind are faster than the lower layers at the ground level, which can be compared with the water flowing through a pipe that experiences a low speed on the walls but a maximum speed in the center. The modeling of this wind profile is nowadays of importance since there is a need to know the wind speed at a certain hub height, and that the measurements from masts installed offshore are scarce, expensive and often not high enough.

5.1.3.2 Method
The wind profile can be modeled by a logarithmic or an exponential law. Many different models have been developed to simulate this profile offshore and they mainly differ from each other because of different choices of parameter regarding the roughness of the terrain.

The wind data available at Hake Fjord consisted of 1 hour averaged wind speed measured from a 40 meter mast on the shore. A wind speed of 10 m/s is arbitrary chosen in order to represent the four models on the same basis. The most pessimistic model from an energy production point of view was retained.

5.1.3.3 Results
Figure 8 below shows the evolution of the Danish recommendation law, based on the logarithmic law commonly used in the offshore industry. The GL-Regulations and the ISO standards are represented as well, both being based on the exponential law used in the wind industry in general.

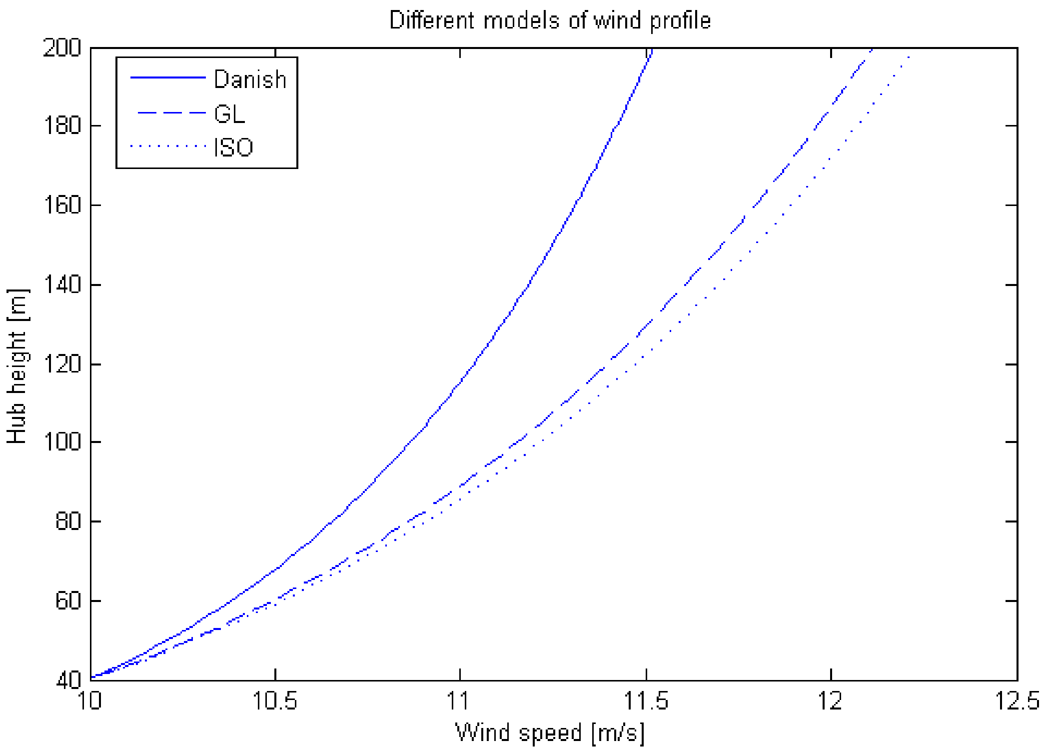


Figure 8. *Three models of wind profile based on a 10 m/s wind speed measured at 40 m height*

5.1.3.4 Discussion

In order to avoid an overestimation of the annual energy production from the park, the most pessimistic model has been adopted to follow the study. The Danish recommendations appear to give the most pessimistic results and have the advantage to consider the roughness that is specific to offshore conditions (15).

5.1.4 Wind speed distribution – The Weibull distribution model

5.1.4.1 Introduction

Hourly local wind speed conditions over a year represent a significant amount of data. The evolution of the speed follows a relatively random pattern and the interpretation of the chronologically ordered data might be tricky. The Weibull distribution is a probabilistic model used to get a clear overview of how fast and with which frequency the wind blows throughout the year. What this model performs can be summarized by the two following actions:

- sorting the data by speed level
- associating each speed level with the respective probability of appearance in hours per year

The mathematical expression in *Equation 1* represents the probability y for a value x (e.g the wind speed in m/s) to occur.

$$y = b.a^{-b}.x^{b-1}.e^{-\left(\frac{x}{a}\right)^{b}}$$

Equation 1. *Basic mathematical expression of the Weibull distribution (16)*

Two different parameters are used to characterize the Weibull distribution model, the scale factor (a) and the shape factor (b) (17).

The scale factor has the same dimension as x and generally is of the same order of magnitude. The value of the scale factor enables to stretch the Weibull curve on the x-axis. As represented in *Figure 9*, the scale factor characterize the average wind speed level of the location, and the larger the scale factor is, the most probable the high-speed winds are, making the location more interesting in terms of energy harvesting.

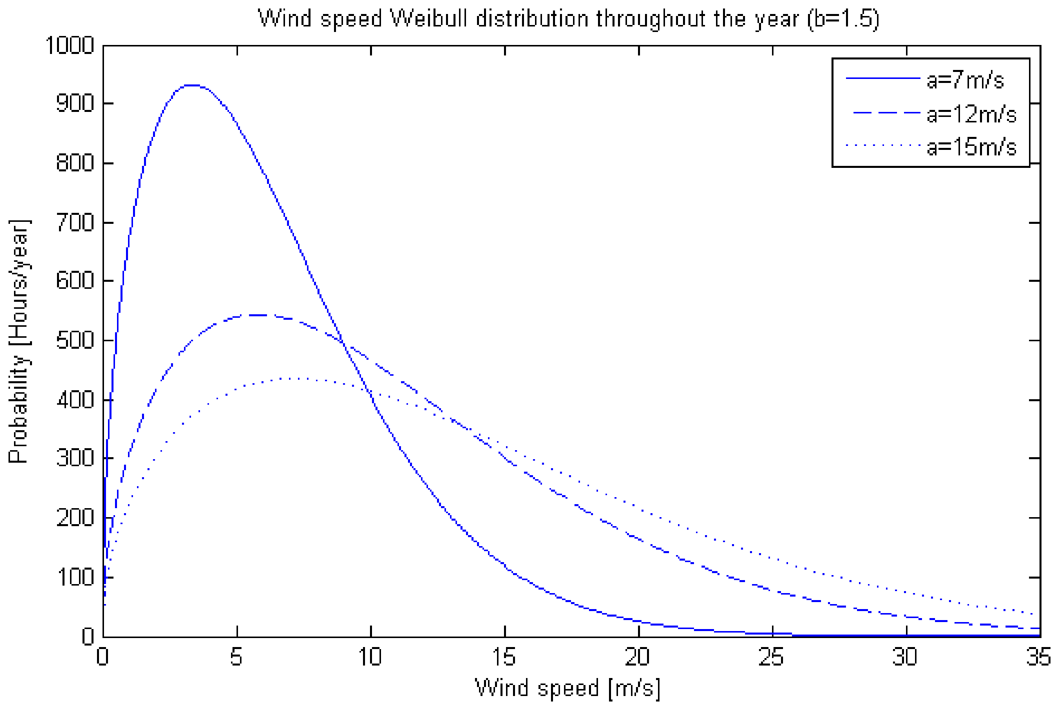


Figure 9. *Influence of the scale factor (a) on the Weibull distribution curve*

A typical offshore site can reach a scale factor from 10 m/s to 12 m/s. The average wind speed of the location can be estimated by the formula in *Equation 2* (18).

$$Scale\ factor = 1.128 * Average\ wind\ speed$$

Equation 2. *Correspondence between scale factor and average wind speed*

The second parameter is the shape factor, which is dimensionless. The value of the shape factor influences the shape of the Weibull curve. As it can be seen in *Figure 10* , the lower the shape factor, the wider the wind speed values can spread around the average.

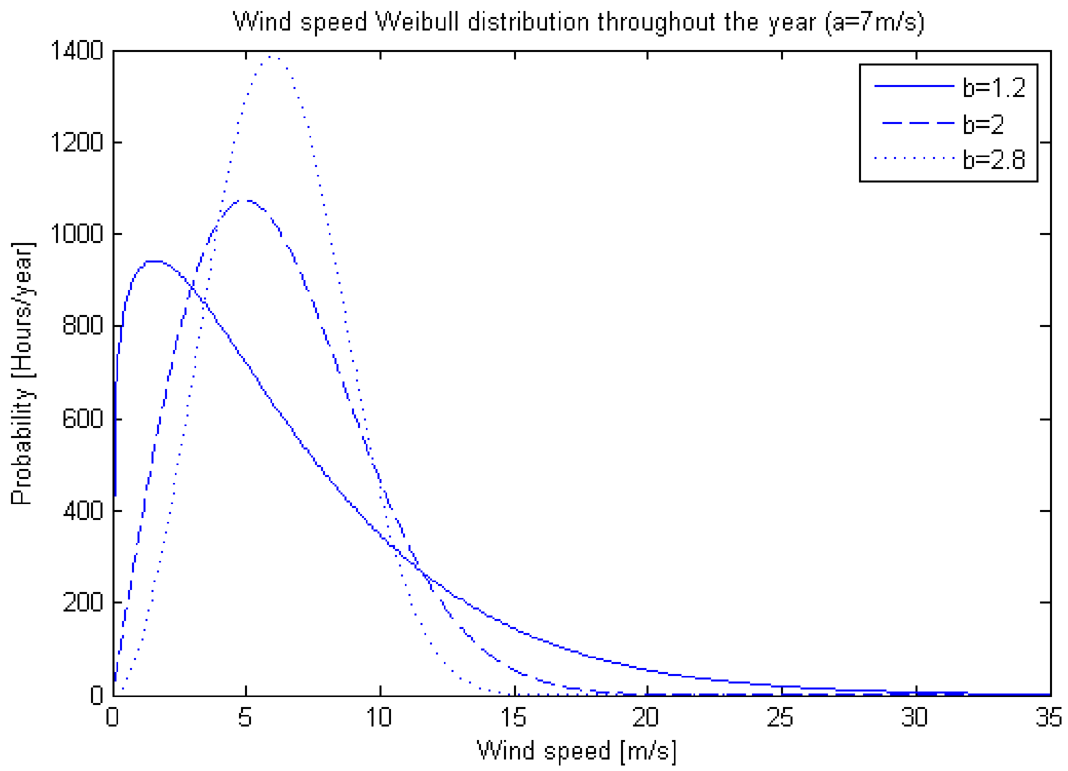


Figure 10. *Influence of the shape factor (b) on the Weibull distribution curve*

The shape factor is site specific and usually takes its value between one and three (16).

5.1.4.2 Method

The wind speed data is sorted out by speed level, resulting in a histogram composed of all the speed intervals associated with their respective hours of occurrence per year. By adjusting the width of the intervals to an appropriate value, the Weibull profile already appears at this stage.

A Weibull statistic function of MATLAB is then used to find the Weibull parameters that will match the wind data. An estimation of the mean wind speed can be done and compared with the real average taken from the wind data in order to assess the percentage of error induced by the Weibull model.

5.1.4.3 Results

As an example the wind speed conditions at 140 m height in Hake fjord have been modeled with the method described above and the results are presented in *Figure 11*.

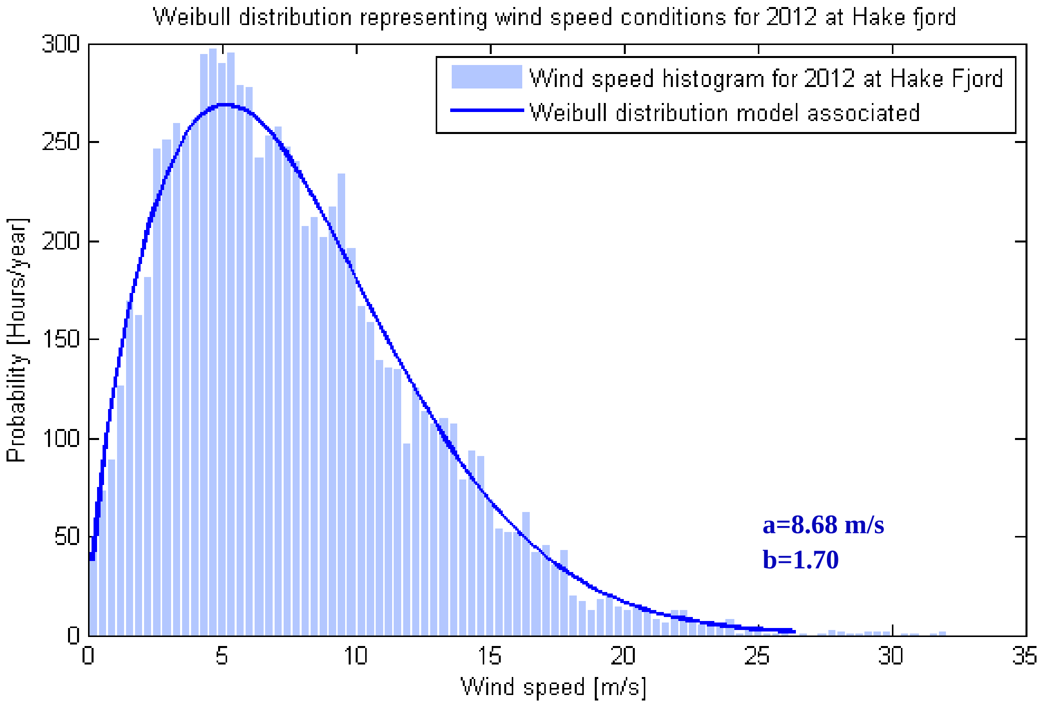


Figure 11. *Construction of the Weibull model for 2012 at 140 m height at Hake Fjord*

The results from the numerical analysis are given in *Table 1* which is a numerical analysis of the Weibull modeling results for Hake Fjord wind conditions in 2012 at 140 m height.

Table 1. *Weibull modeling against wind data for the wind conditions of 2012 at 140 m height*

Scale factor (a) from the Weibull model (m/s)	Shape factor (b) from the Weibull model	Average wind speed from the wind data (m/s)	Average wind speed from the Weibull model (m/s)	Relative error (%)
8.68	1.70	7.7474	7.7470	0.0049

Figure 11 shows a relatively good matching between the Weibull model and the wind data from Risholmen that it is based on from an average point of view.

5.1.5 Wind direction

5.1.5.1 Method

The acquired dataset with an hourly time resolution contains a little more than two years of wind direction measurements, from the autumn 2009 until the end of 2011. To predict the wind direction for the 2012 model a wind rose was constructed from the dataset. A wind rose displays the wind direction of a dataset with the wind speed and its probability of occurrence. To conclude on the wind direction for 2012 the probability was used to calculate the amount of hours per year when the wind occur from different directions, classed in 4 different blocks: northeast, northwest, southwest and southeast.

5.1.5.2 Results

The wind rose shows that the wind is dominant from the southwest, see *Figure 12*. It is also shown that the highest intensity of wind speed comes from that direction.

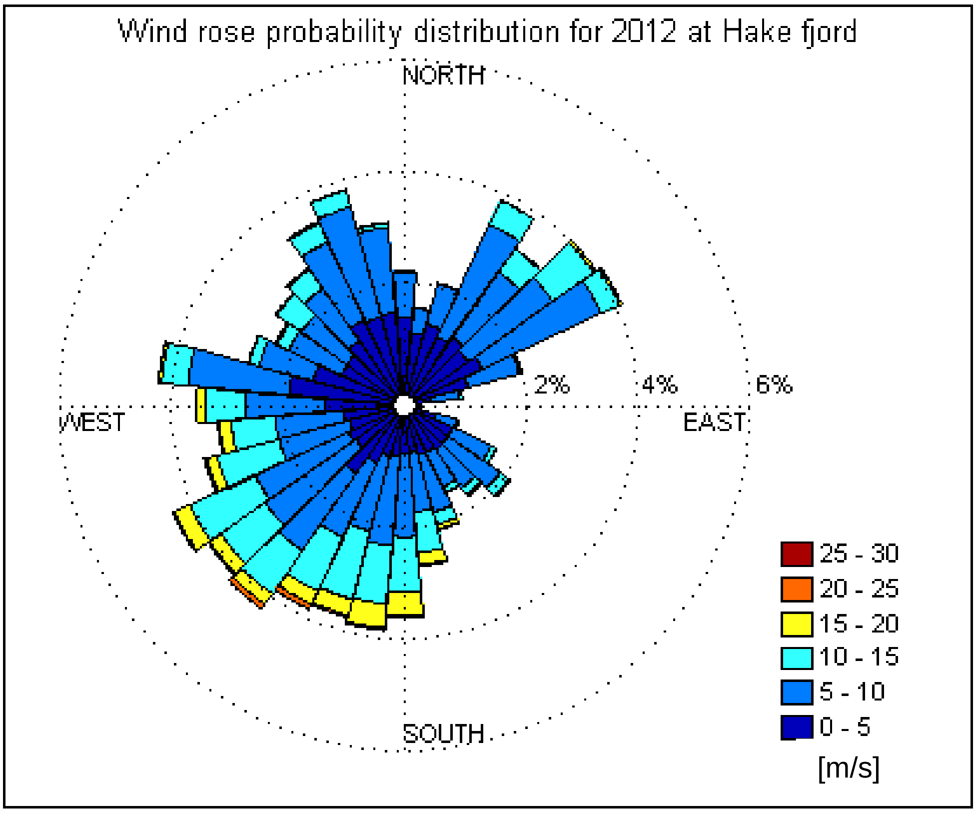


Figure 12. *Wind rose probability distribution for 2012 at Hake fjord*

When applying the probabilities on a full year the distribution gets clearer, see *Figure 13* and *Table 2*.

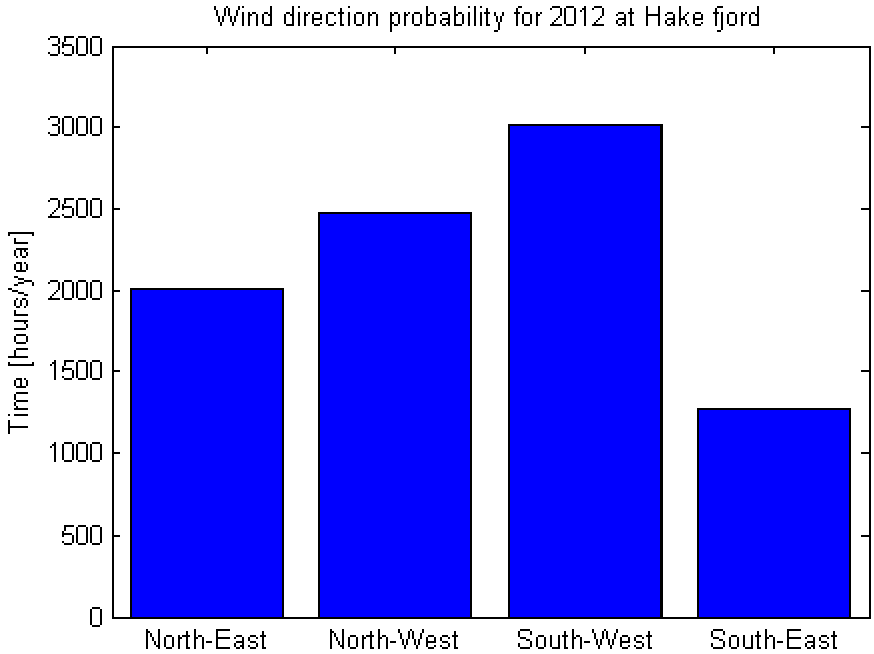


Figure 13. *Histogram of wind direction probability for 2012 at Hake fjord*

Table 2*. Wind direction*

Wind direction	North-East	North-West	South-West	South-East
Hours/year	2003	2471	3017	1269

5.1.5.3 Discussion

There is almost no wind registered from the straight east direction, plus/minus a few degrees. Something is disturbing the anemometer in that direction and this is most probably depending on how the measurement device is mounted on the mast.

The result that the wind direction is dominant from southwest is correct according to empirical studies of the Swedish conditions in general (14).

5.1.6 Temperature

5.1.6.1 Method

The acquired temperature data was measured during 1973-2010. The whole dataset is not complete but a full 30 years of measurement is usable. The data includes daily average temperature as well as daily maximum and minimum temperatures. Wind turbines are limited by an operating temperature range and this explains why the extreme temperatures in Göteborg are of interest.

5.1.6.2 Results

Duration curves are constructed to visualize the extreme temperatures, see *Figure 14*. During this time period the minimum temperature is -23.5°C and the maximum temperature is 33.8°C.

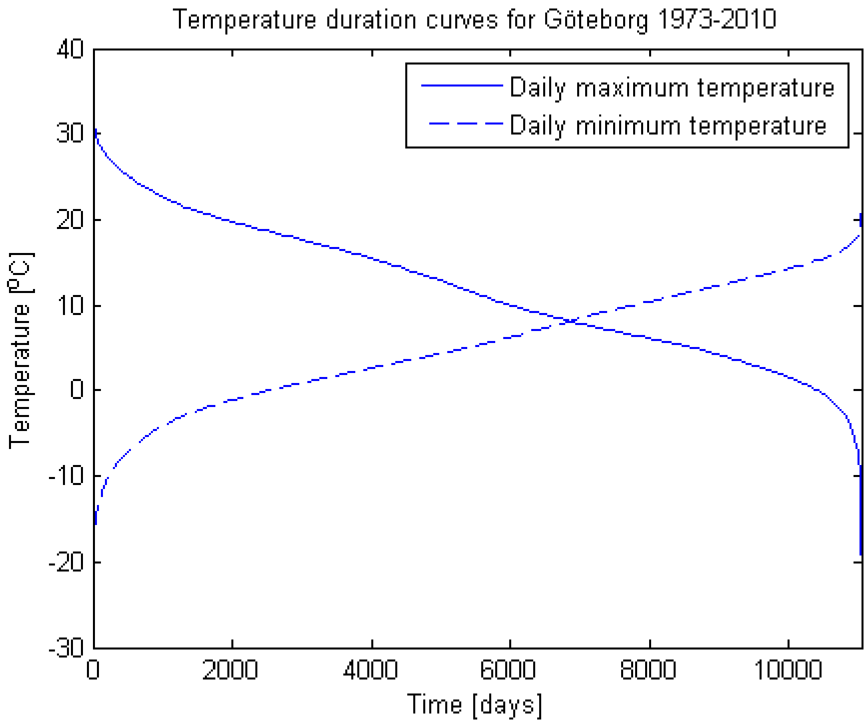


Figure 14. *Temperature duration curves for Göteborg 1973-2010*

5.1.7 Conclusion

As a conclusion, the module 1 provides essential information about the local climatic conditions of Hake Fjord:

- The wind speed profile was modeled in real time for 2012 and is also expressed as a duration curve to be further used as a basis for energy calculations. A logarithmic law was implemented to enable the modeling of this wind speed at any hub height. A Weibull model was used to provide an additional insight of the probability reparation of the wind speeds at Hake Fjord along the year.
- The wind direction was studied through the use of a wind rose to visualize the angular repartition of each level of speed. A histogram was traced as well in order to stress the dominance of the south-west winds.
- The temperature was studied and displayed in a duration curve both for negative and positive extremes to show how scarce the extreme temperature episodes are in Göteborg.

5.2 Module 2 – Wind farm modeling

5.2.1 Objective

The second module involves modeling of the wind farm where the main objective is to construct a static model of the annual power output. The two sub-objectives are to select, out of commercially available turbine models, the turbine with the best economic performance and thereafter to make an optimized layout of the wind farm considering wake effects. The annual energy production target to reach for Vindplats Göteborg is 200 GWh using a maximum of 16 units in the area.

5.2.2 Investigated turbine models

Four different models were selected among the current commercialized turbines present on the market. The selection of these specific models has been driven by two main criteria. Firstly, the manufacturers of these turbines are in the top 10 in terms of capacity installed, according to a study dated from 2010 (19). This gives a relative token of reliability and the evidence that those products are commercialized and readily available. Secondly, those manufacturers provide all the information required for the further stages of the study in their specification sheets. The turbine models are presented in *Table 3* with their main characteristics. The temperature operating range for all the selected turbines are within the limits calculated in Module 1.

Table 3. *Investigated turbine models (20), (21), (22), (23)*

Turbine model	Capacity [MW]	Rotor diameter [m]	Hub height [m]	Cut-in speed [m/s]	Cut-out speed [m/s]
Vestas V112	3	112	94	3	25
Vestas V164	7	164	140	4	25
Repower 5M	5	126	90	3	30
Enercon E126	7.5	127	135	3	25

Two large capacity turbines have been chosen because they are assumed to be the most competitive, and will hence supposedly constitute relatively interesting candidates to reach the objectives at a lower cost. The two smaller capacity turbines have been chosen to show that those capacities might not enable to reach the production target within the given area, or might represent an extra cost compared to larger turbines.

5.2.3 Turbine performance evaluation

5.2.3.1 Introduction

This evaluation is carried out on all four turbine models to assess the number of units that is required to reach the annual 200 GWh target. The wind scenario used is the modeled year 2012 from Module 1.

5.2.3.2 Method

Data from the different turbines was extracted from performance curves, with specific figures regarding cut-in and cut-out wind speeds, supplied by the manufacturers. An interpolation method was used to complete the performance data in-between the given data points. The wind speed data for each turbine was matched with the performance curve to achieve the corresponding power output for the full modeled year. In order to calculate the total amount of energy produced, the four power curves were added which then gave the number of turbines required to fulfill the annual production target.

5.2.3.3 Results

The performance of the four investigated turbine models is presented as duration curves in *Figure 15*.

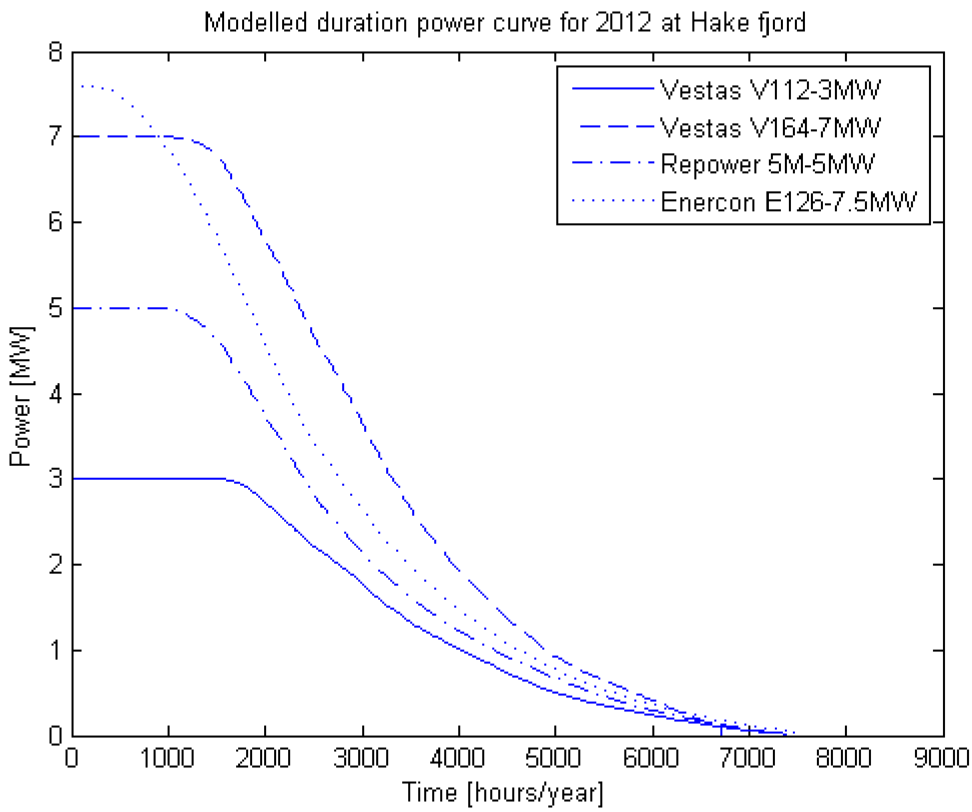


Figure 15. *Modeled duration power curve for 2012 at Hake fjord*

The performance is also presented in terms of energy produced, in *Table 4* with the number of turbines required for each model to reach the annual 200 GWh target.

Table 4. *Turbine performance for all investigated models*

Turbine model	Vestas V112	Vestas V164	Repower 5M	Enercon E126
Annual energy production [GWh/year]	10.83	23.29	15.66	20.62
Number of turbines to reach target	19	9	13	10

5.2.3.4 Discussion

The high capacity Vestas turbine seems to be the best of all alternatives regarding annual energy production and requires a low number of units to reach the annual target. The Enercon model has the highest capacity but due to the conditions at Hake fjord its performance curve was not proved to be optimal.

It can be clearly seen that the low capacity Vestas turbine produce less energy annually, compared to the other models, and hence requires a lot more units to fulfill the annual target. All models, except the low capacity Vestas, will reach the target within the 16-units limit. By this Vestas V112 is excluded from further investigation.

5.2.4 Layout of the farm

5.2.4.1 Introduction

The focus area in Hake Fjord has a certain geometry and specific dimensions that should be taken into account before going any further in this study. Because the turbines are affecting each other in the so called wake effect, they should be placed far enough from each other in order to keep a satisfying production rate. A study of the Lillgrund offshore wind farm, located 15 km south-east from Malmö in Sweden, was carried out by Vattenfall. It shows that the chosen distance between the turbines, equivalent to 3 times the rotor diameter, is too short and therefore entails a production loss of 80% in the turbines hidden by the first in row in case of alignment between the wind direction and the row (24).Recent studies have shown that a distance between 6 and 7 times the rotor diameter may be more adapted (25), (26).

5.2.4.2 Method

In order to check if each of the four models fit into the area of Hake Fjord, the following procedure is employed:
- Modeling of the area on CATIA at the scale 1:10
- Placement of the points representing the turbines by respecting a radius of 6 times the rotor diameter between each tower

5.2.4.3 Results

Figure 16 below represents the checking of the layout for the Repower 5M. The dark lines delimit the area of Hake Fjord and the blue circles have a radius equivalent to six times the diameter of the Repower 5M (i.e 756 m). On this example, all the units can fit into the zone of Hake Fjord.

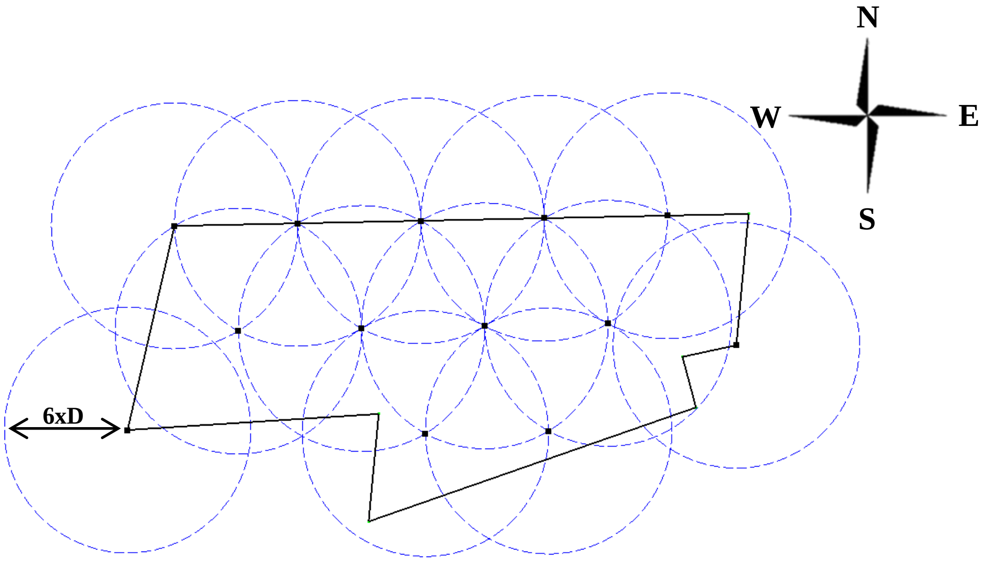


Figure 16. *CATIA model of the Repower 5M layout*

After the checking of the four models, it has been shown that the Vestas V112, which requires 19 units, cannot fit into the area if a safety zone of 6 times the diameter is established.

As a consequence, this model is discarded for the following of the study and the three left are kept to be further compared.

5.2.5 Cost analysis

5.2.5.1 Introduction

The objective of this analysis is to conclude on which of the turbine models has the best economic performance. Determining which model will bring the best profit does not necessary implies to include all the costs associated with a wind farm project. The costs included are the ones that will differ depending on turbine size, capacity and performance. This signifies that the only costs considered are the investment costs for the turbine, the foundations, the farm internal transmissions and the costs for operation and maintenance. The revenues taken into consideration are the sale of electricity and the sale of Green Electricity Certificates (GECs).

5.2.5.2 Turbine cost

The investment cost for the different turbines was approximated by the help of a report from the European Wind Energy Association (27). The conditions at Hake fjord were compared to the conditions of all major offshore wind power projects in Europe and an accurate match was found with Middelgrund Wind Farm outside Copenhagen in Denmark (28). The investment cost for the turbines at Middelgrund was divided by the total capacity and the result was used as the reference investment cost for all the turbine models used in this project. The turbine investment added to its transportation and installation costs resulted in 600 000 €/MW.

5.2.5.3 Foundation cost

5.2.5.3.1 Technical perspectives

Different types of foundations are readily available on the market and the choice of the technology to use greatly depends on the water depth characterizing the wind park area. Figure 17 gathers the most commonly used technologies nowadays, with the beige area representing the seabed and the blue waves illustrating the water level. It can be noted that the gravity based system is the only one merely lying on the ground, as opposed to the other alternatives that require drilling operations.

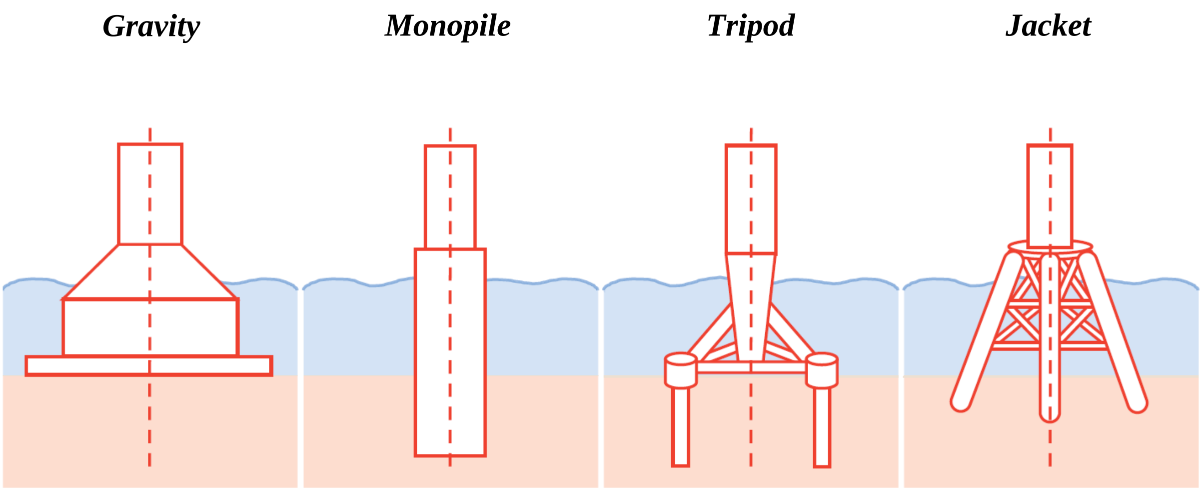


Figure 17. *The different types of foundation for offshore wind turbines (29)*

The two last systems, tripod and jacket, are adapted for very deep areas. The tripod foundation, which is an evolution of the monopile towards a better mass repartition, is technically and economically advantageous between 20 m and 40 m depth. The jacket foundation, derived from the platforms used in the oil & gas industry, turns out to be competitive from 20 m depth (30). However the seabed at Hake Fjord only lies between 2 and 7.2 m depth according to the navigation map, see *Figure 5*, which makes this area not suitable for the use of those two far-shore foundation systems.

From a depth point of view, both gravity and monopile systems are competitive. In order to select the best alternative, some more criteria need to be taken into consideration:

The gravity system requires a score protection around the infrastructure in order to prevent the erosion from affecting the anchorage. Such a dispositive is not compulsory with monopiles since the erosion can be forecasted and compensated by a deeper anchorage.

The gravity system is not appropriate for bottom consisting in loose sediments, but should be placed on a rocky seabed. At the contrary, the monopiles should not be used in boulders because of the stresses entailed during the piling operations and are
suitable for areas facing sediments movement phenomena like in Hake Fjord.

A large part of Hake Fjord is made of spoil ground, where mud residues are being deposited, which makes this environment more suitable for monopile foundations.

The gravity systems are suitable for icy conditions thanks to their ice-breaker cone located under the transition part, at the sea level. The monopile are not equipped with such systems and are vulnerable to the ice displacement on the sea surface. However, the west coast of Sweden where Hake Fjord is located is an ice-free maritime area, in contrast with the Baltic Sea, meaning that this phenomenon should not represent any danger for the future park (30).

As a conclusion, the monopile system seems to be the most relevant foundation for the wind farm from a technical point of view. This alternative also has the advantage to be well known and accounts for 80% of the foundations built between 2009 and 2011 (31). However, some technological breakthroughs regarding mix foundations, combining both gravity and monopile systems, are expected in the close future and this might lead to even more cost-effective solutions (30).

5.2.5.3.2 Economic perspective

The investment costs for both gravity and monopile systems are in the same order of magnitude, with a reference cost of 600 000 € per turbine. The deep water systems such as tripod foundations can reach 2 500 000 € per turbine, which can be explained by the larger amount of material used due to the additional depth and the harsher conditions it is designed to endure (32).

The two most economic alternatives left are gravity and monopile systems. However, the costs associated with those solutions do not have the same repartition in the two cases:
The gravity system mainly uses concrete, which is five times cheaper than the steel used in monopiles. The construction cost is then in favour of gravity systems.
The main cost for gravity system is due to the installation. The handling of heavy concrete structures to be deposited on soft soil is indeed at its early beginning and the preparation time and risks associated with this operation are significant. On the other hand, the installation of monopiles is a well-tried process that should not entail any extra cost (33).

According to the first phase of the Offshore Wind Farm Layout Optimization project (OWFLO), aiming at developing a program to optimize the design of offshore wind farm, the monopile system remains the cheapest alternative up to 10 m depth, which covers the range in which Hake Fjord seabed is located.
This study was based on cost analysis of different major wind farm projects led in Europe, and shows that the cost of the foundations does increase with the water depth. Considering an average depth of 5 m in Hake Fjord, the minimum cost is obtained with the monopiles with a price of 200 000 €/MW (34).

5.2.5.3.3 Environmental perspective

The environmental consequences caused by the foundations can occur during the installation, the operation phase and the dismantlement.

The most harmful phase is the installation and the causes can be divided into two groups:
The piling-related disturbances occur when a pile is plunged into the sea bed, which is a method typically used for monopiles, tripods and jackets. These disturbances are characterized by the emission of powerful sound pulses detectable up to 10 km away from the installation. This represents a risk for the local fauna, especially within 100 m from the pile (30).
The dredging-related disturbances occur when a large caisson is deposited on the seabed, which is observed when a gravity foundation is installed. The high concentration of sediment in suspension produced locally represents a danger for the fauna, especially in areas where the stream is weak (30).

The common recommendations for both cases consist of avoiding the biological sensitive periods, such as the reproduction season, when installing the foundations. Some efforts should be also put into the reduction of the maximal noise caused by the hammering. Eventually, the installations should be gathered in shorter but highly intensive periods, which are preferred to long term disturbances (30).

It has been reported that some low frequency noises might be emitted by the turbines in operation and transmitted to the marine environment through the foundations.
An appropriate setting of the production devices may enable to considerably decrease this effect (30).

Some positive impacts during the operation phase might be the reef effect created by the foundations, which would represent a colonization opportunity for marine invertebrates. This phenomenon might lead in term, to the further development of a local ecosystem.

Due to the lack of experience in this field, the data in relation with the dismantlement and the end of life phase are missing, which prevents from drawing any conclusions regarding the disturbances associated.

As a conclusion, gravity systems and pile-based systems imply different environmental consequences during the installation phase. The operation phase has the same impact in both cases, notwithstanding the fact that the monopile will have a reduced projected surface taken on the environment.

The monopile system will hence be the chosen technology for the wind farm because of its technical, economic and environmental advantages.

5.2.5.4 Farm internal transmission cost

5.2.5.4.1 Technical perspective

To construct a transmission grid for the park 30-33 kV cables are assumed to be used. This is based on the standard for offshore wind farms presented by Energi- og Miljødata (EMD) (35). This specific type of cable for the internal grid is also used at Middelgrund Wind Farm which, as previously mentioned, has the same type of conditions as the Hake fjord site (36).

5.2.5.4.2 Economic perspective

The cost for the internal grid cables is approximated to 100 €/meter, based on the EMD report. A cost for rolling out and washing down the cables is added with 50 €/meter (35).

5.2.5.5 Operation and maintenance cost

5.2.5.5.1 Technical perspective

The development of offshore wind power was stirred by the considerably high wind speeds offered by the marine environment, but it now suffers from a kickback: the price of the operation and maintenance (O&M). This cost is far above the one experienced onshore because of the following reasons:

- When the distance from the shore increases, the access to the turbine becomes both complicated and hazardous, especially under rough sea conditions, requiring the intervention of well-trained personal.
- The use of expensive large crane-vessels and helicopter is often required.
- The meteorological conditions might be responsible for a prolonged downtime because of the impossibility to reach the unit, entailing additional losses.

Some improvements can be done in order to lower these expenditures:

- The availability of the offshore turbines needs to be improved to a large extent.
- The use of redundancies must be increased.
- The development of especially-designed maintenance equipment must be investigated (37).

5.2.5.5.2 Economic perspective

The O&M phase represents up to 5% of the total investment cost of the wind farm (37), (38).This order of magnitude only gives an idea of the average cost entailed but do not provide the actual evolution of the O&M costs throughout the lifetime of the park.
The cost of O&M is initially around 2% and 3% of the total investment because the expenditures are covered by the insurance, which accounts for about 0.3 c€/kWh. However this cost gradually increases afterwards to reach 5% of the investment after 6 years of operation, meaning up to 0.7 c€/kWh (38).The costs occurring during the following years are not yet documented enough withstanding the relatively new expansion of the offshore wind power in Europe, but it is expected to follow a linear pattern with an increasing cost.

Figure 18 shows a typical evolution of the maintenance costs. The initial period is characterized by a low cost because of the warranty, the following step represents the possibility to extend this warranty, and the linear progression after 6 years reflects the increasing number of failures that have to be repaired using gradually expensive spare parts (39).

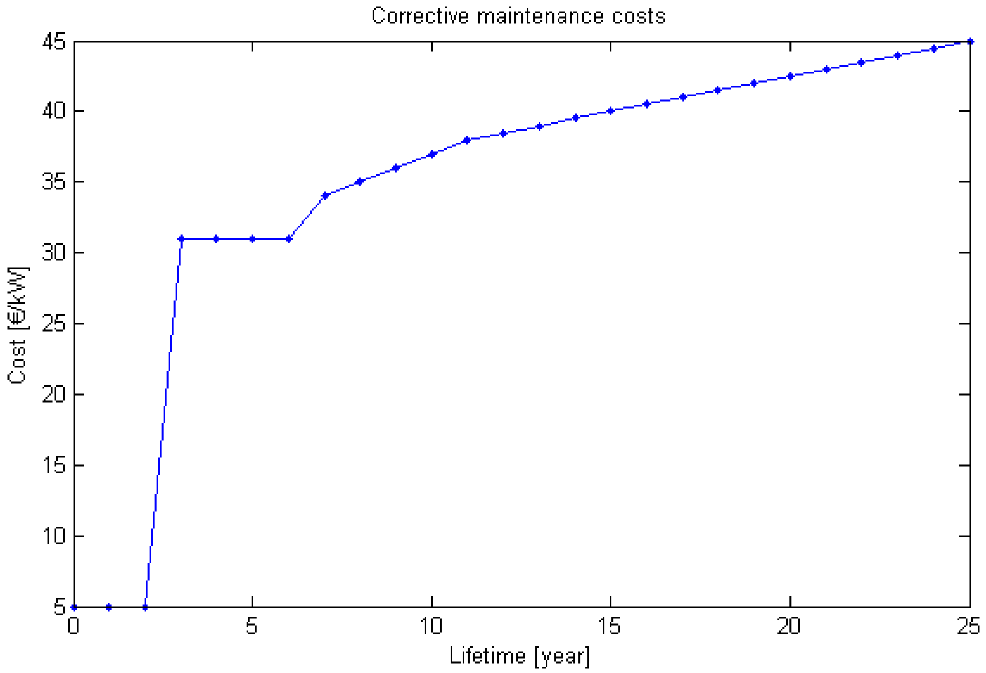


Figure 18. *Evolution of the O&M cost of 1kW offshore during 25 years*

In order to evaluate the O&M cost for each of the four turbines, the following procedure is employed:
- *Figure 18* is used as a reference for the evolution of the O&M price, for all the turbine models.
- Each of the annual cost per kW during a 25 year lifetime are summed up and multiplied by the total capacity of each alternative.

5.2.6 Revenues analysis

5.2.6.1 Revenues from electricity

5.2.6.1.1 Introduction

The Nord Pool Spot Market is a deregulated power market enclosing Sweden, Denmark, Norway and Finland which started in 1998. The electricity price is set by this market depending on the demand and the supply. However some congestion can occur in the network due to limited transmission capacity, which is why a bidding areas system has been introduced within each country in order to regulate the flows by implementing a differentiated pricing method. The electricity prices are set a day-ahead before the actual power use and hence correspond to a given ratio of supply and demand in a specific area (40).

5.2.6.1.2 Method

To be able to calculate the revenues from sold electricity in the area of Göteborg, the electricity price needed to be predicted for the simulated year 2012. Statistics of the electricity price for the last decade in Sweden was taken from the Nord Pool Spot Market (41). Annual averages were calculated and from that result a trend was spotted. An interpolation of the last six years was used to predict the average electricity price in 2012. A list of hourly electricity price for 2012 was constructed by modification of the hourly statistics for 2011 so that its average equaled the predicted average for 2012.

5.2.6.1.3 Results

The average electricity prices for the years of the last decade and the predictions for 2012 are presented in Figure 19.

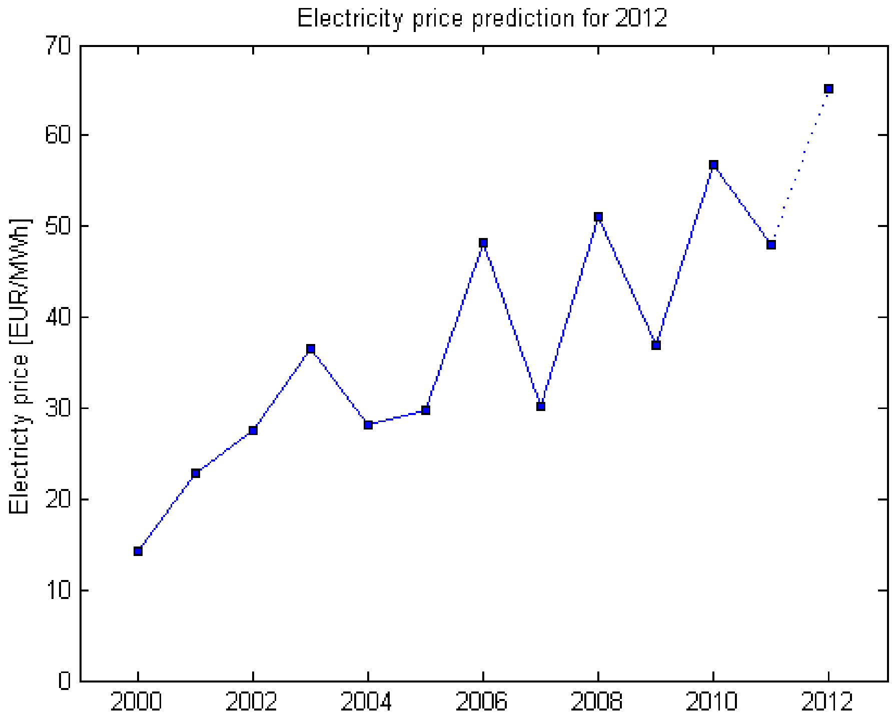


Figure 19. *Annual averaged electricity prices for Sweden*

The average electricity price for 2012 in Sweden was predicted to reach 65.22 €/MWh.

5.2.6.2 Revenues from Green Electricity Certificates

5.2.6.2.1 Introduction

The green electricity certificate system enables the states to support the development of renewable energies by introducing the obligation for energy suppliers to buy a certain amount of energy coming from renewable sources. The price of these certificates will fluctuate depending on the quota requirement, the energy demand and accumulated surplus (42).

5.2.6.2.2 Method

As one certificate is sold for each MWh of green energy produced, the wind farm will also draw benefits out of the Green Electricity Certificates (GEC). To be able to calculate the size of this revenue the price of GECs for 2012 needs to be predicted. Statistics of the GEC-price for the last five years was taken from the trading market Svensk Kraftmäkling (43).Annual averages were calculated but no particular trend was detected over years. Statistics on the amount of GECs issued and annulled were obtained from the Swedish Energy Agency, based on data from Svenska Kraftnät (44). By combining this data with the price data, a correlation was spotted between the price and the balance of the amount of GECs issued and annulled.

The data from Svenska Kraftnät was covering 2003-2010 so that an extrapolation was necessary to generate data for 2011 and 2012.

5.2.6.2.3 Results

A study of the evolution of the prices from one year to another depending on the number of issued and annulled GECs was performed and the result is presented in *Figure 20* below.

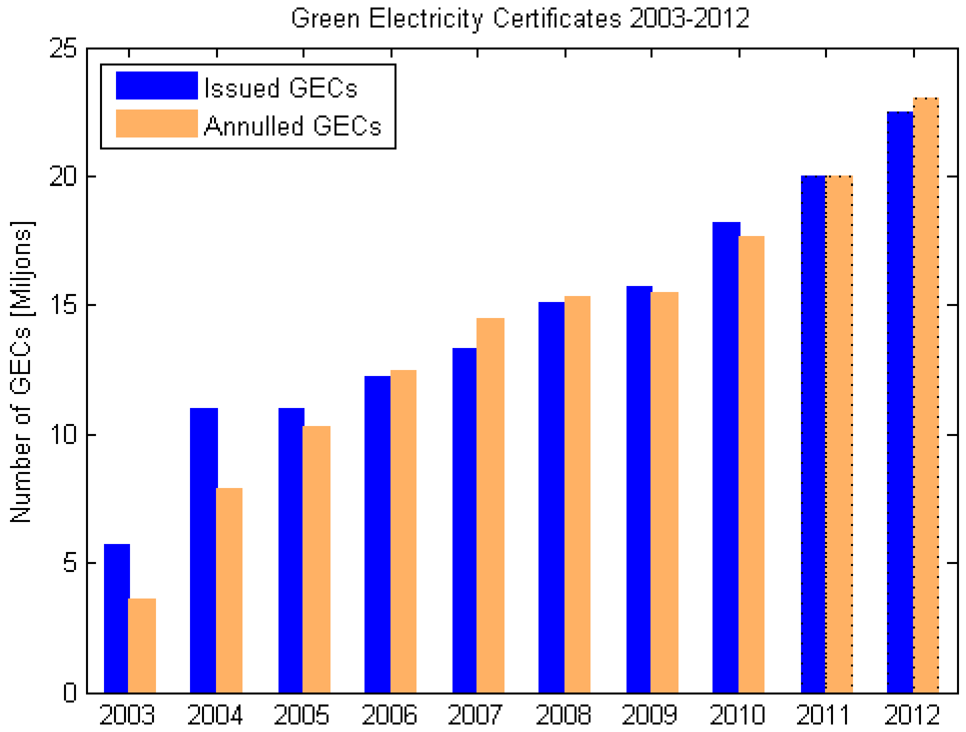


Figure 20. *Issued and annulled Green Electricity Certificates 2003-2012*

With this prediction it seems like the number of GECs annulled in 2012 is higher than the amount issued. According to the GECs price evolution in correlation with the evolution of the ratio annulled/issued performed in Excel, when the number of certificates annulled starts exceeding the number of issued certificates this is a sign of an increase in prices for the coming year. This implies here that the price for GECs will be slightly higher in 2012 than the previous year. The predicted price for GECs in 2012 is 22.5 €/MWh.

5.2.7 Economic results for the three turbines models scenarios

All the above presented cost and revenue categories are calculated for each turbine model scenario. The results are presented in *Table 5*, *Table 6* and *Table 7*.

Table 5. *Costs for the wind farm*

Turbine model	Vestas V164	Repower 5M	Enercon E126
Turbines and installation [M€]	37.8	39.0	45.0
Foundations [M€]	12.6	13.0	15.0
Transmission [M€]	1.4	1.5	1.1
O&M [M€]	56.6	58.4	67.4
Total costs [M€]	108.4	111.9	128.5
Annualised total costs [M€] Lifetime: 25 yrs, present-worth rate 5%	7.7	7.9	9.1

Table 6. *Revenues for the wind farm*

Turbine model	Vestas V164	Repower 5M	Enercon E126
Electricity sold [M€]	13.3	12.8	12.9
Green Electricity Certificates [M€]	4.7	4.6	4.6
Total annual revenues [M€]	18.0	17.4	17.5

Table 7. *Total economic result for the wind farm*

Turbine model	Vestas V164	Repower 5M	Enercon E126
Annual profit [M€]	10.3	9.5	8.4
Net present value: annual profit [M€] Lifetime: 25 yrs, present-worth rate: 5%	3.0	2.8	2.5
Profit per produced electricity [€/MWh]	14.3	13.8	12.1

The Vestas V164 turbine model is the most appropriate model for this project and thereby chosen as the model to use. The other models will hereafter be discarded due to their lower economic performance.

5.2.8 Wind turbulence intensity

5.2.8.1 Introduction

The wind flux passing through the wind farm is generally more complicated than a simple laminar flow. The same way the flow of a small river is agitated and disturbed by the rocks lying underneath, the wind flow is affected by the roughness of the sea and the stability of the atmosphere. As a consequence, the turbines have to resist to a fatigue load generated by these intermittent wind blasts. In order to design the turbines in accordance to these turbulent conditions, the local turbulence intensity can be modeled and compared with the so called IEC (International Electro-technical Commission) standards (45), (15).

5.2.8.2 Method

The measurements of the turbulence intensity at Hake Fjord are not available which is why turbulences models are used instead.
There are different models available to assess the local wind turbulence intensity depending on the height considered and on the roughness of the sea.

Figure 21 below shows the three different turbulence intensity models used for the Vestas V164 (i.e. at 140 m height) and compiled with the wind speed modeled for 2012.

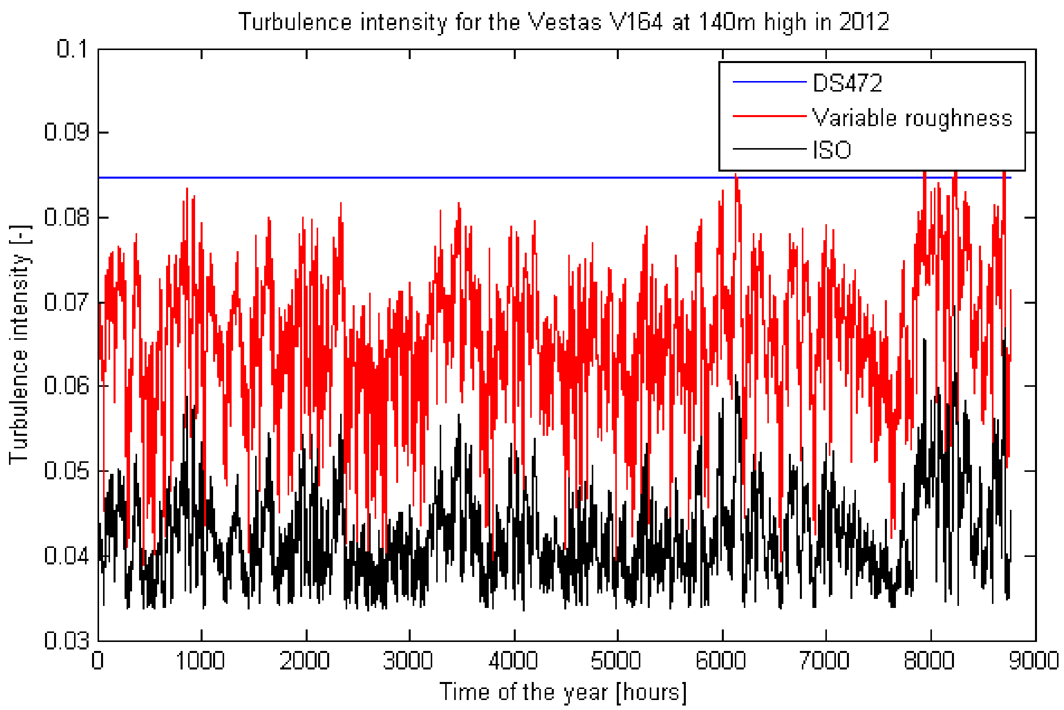


Figure 21. *The different models of the turbulence intensity for the Vestas V164 in 2012*

The ISO model gives the longitudinal turbulence intensity depending on the hourly based wind speed at hub height. The DS472 model recommends a simplified logarithmic law with a sea roughness constant and equal to 0.001 m under normal conditions (15). The model using a variable roughness is a combination of the DS472 model with a variable roughness parameter depending on the wind speed.

Indeed, the Charnok experiments (46) shows a strong dependence of the sea roughness on the wind speed, which was interpolated by the following power law:

$$Z_0 = 5.10^{-7}.u^{\,2.6052}$$

Equation 3. *Power law extrapolated from Charnok model*

Z_0 represents the roughness of the terrain (m) and u the wind speed (m/s).

5.2.8.3 Results

Figure 22 below shows the three different turbulence intensity models used for the Vestas V164 (i.e. at 140 m height) and compared with the class IEC B of the turbine.

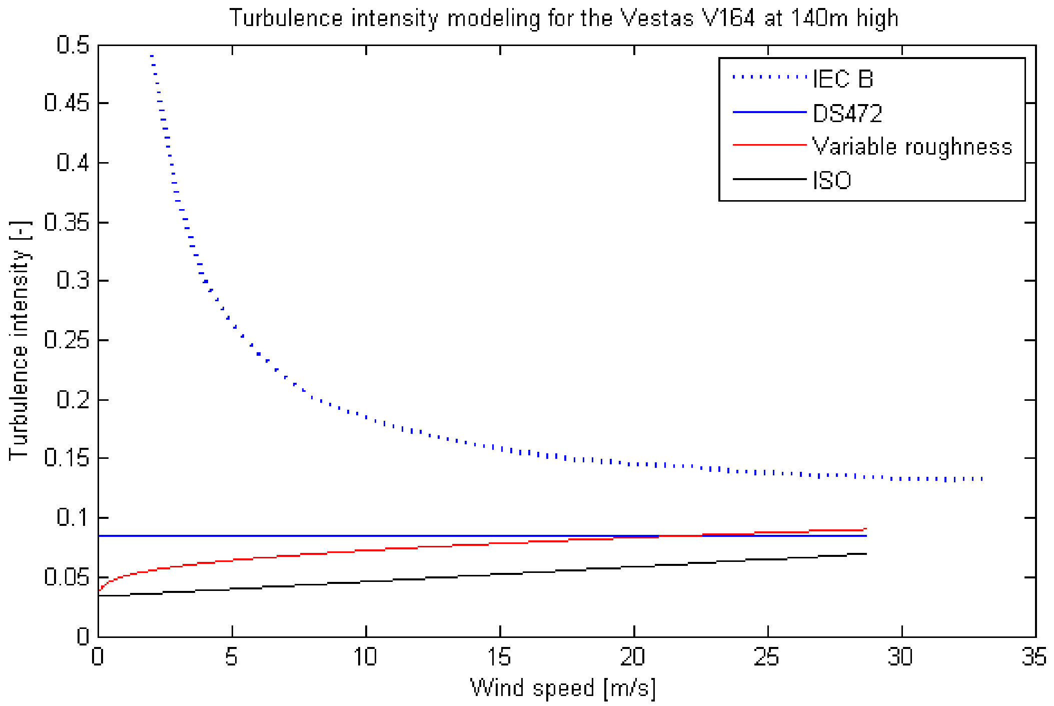


Figure 22. *The different models of the turbulence intensity compared with the IEC B standard*

It can be noticed that the three models agree to confirm that the Vestas V164 design is suitable for the local conditions of Hake Fjord, in which the wind speed should not exceed 28 m/s. However, it has been reported that below a wind speed of 5 m/s the reality tends to be radically different from the models used above (46), (47). The turbulence intensity can be three times higher than predicted which does not appear in *Figure 22* above, but justifies the exponential shape of the IEC standard. Realistic models of the turbulences combined with local measurements are hence required to enable a more accurate matching between the local wind conditions and the level of stress that can be endured by the structural design of the turbine.

5.2.9 Optimization of the layout

5.2.9.1 Initial layout

Before the economic considerations, a first checking of the scope had been done by using a safety zone equivalent to 6 times the rotor diameter between each turbine. This gave birth to a first version of the layout in which the turbines are regularly spaced by the same radius.
In order to optimize the available space and maximize the distances, a length of 7 times the rotor diameter was adopted between the turbines of the first row which can be observed in *Figure 23* below. This initial layout hence respects the safety zone for each of the nine turbines and the scope of Hake Fjord while maximizing the distances equally around the turbines.

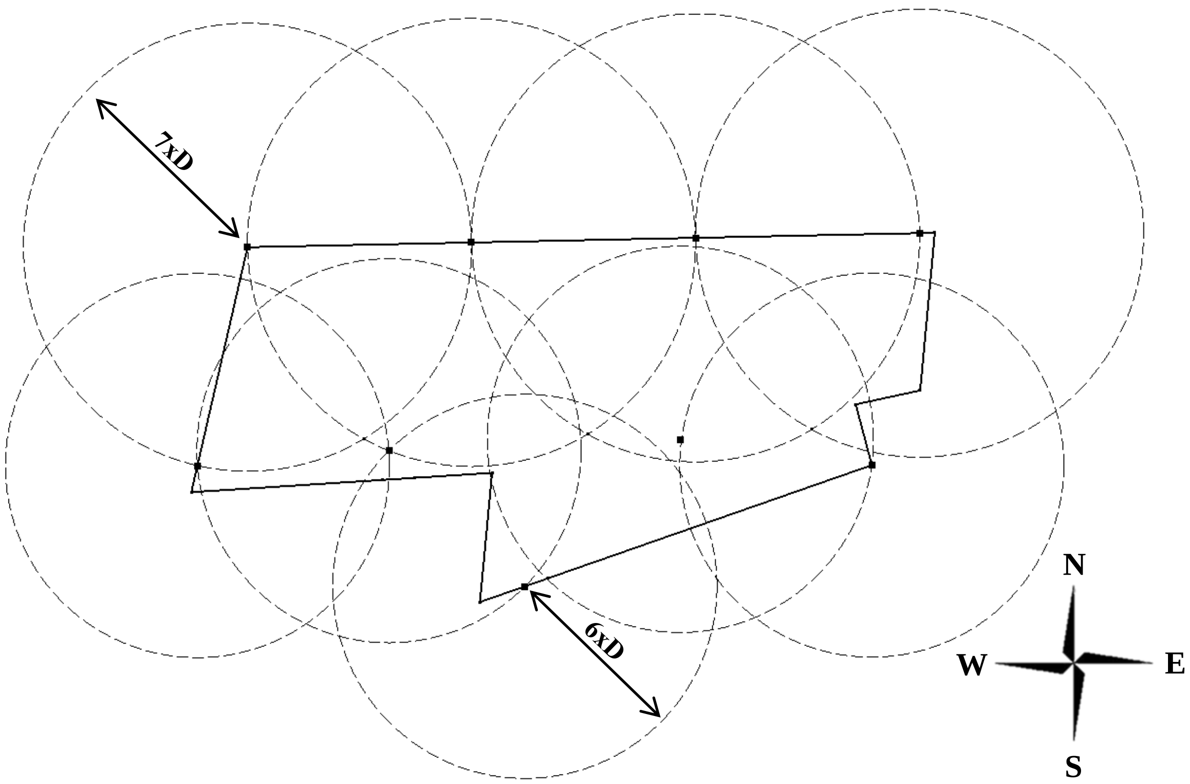


Figure 23. *Initial layout of the Vestas V164 on CATIA*

5.2.9.2 The wake effect

Different models with various complexities are available to model the wake effect. The WAsP engineering model is a program developed to estimate wind conditions in both complex and simple terrains and was launched in July 2001 at the European Wind Energy Conference and Exhibition in Copenhagen. This model was used to assess the losses in Middlegrund wind

farm and is chosen in the present study because it has the tendency to be slightly pessimistic (48).
Figure 24 is an illustration of the wake effect in which it can be noticed a decrease in speed after a certain distance X downstream the first turbine. This effect fades away when X increases but its width is however expanding, following a characteristic slope k (49).

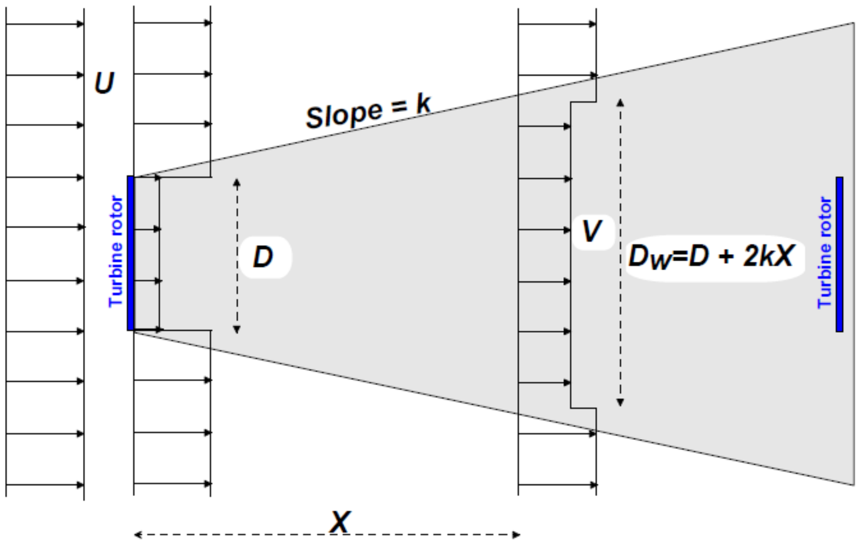


Figure 24. *Wake effect provoked by one turbine on another one located downstream (49)*

The following equation gives the actual value of the speed V for every distance X from the first turbine. This formula requires knowing the rotor diameter D, the characteristic slope k and the thrust coefficient C_T.

$$V = U.\left[1 - \left(1 - \sqrt{1 - C_t}\right).\left(\frac{D}{D + 2.k.X}\right)^2\right]$$

Equation 4. *WAsP modeling of the wind speed evolution downstream (49)*

The rotor diameter D of the Vestas V164 is 164 meters, the characteristic slope k used offshore is 5% and the thrust coefficient C_T, which is the change in momentum before and after the rotor, is not available for the Vestas V164 (49), (50).

The thrust coefficient depends on the wind speed and the effort applied on the rotor by the wind. As shown in *Figure 25*, the thrust coefficient decreases exponentially with the wind speed after 5 m/s, and is slightly lower for larger turbines. The evolution of the C_T before 5 m/s is rather marginal depending on the model and it was not judged useful to represent it here. The speed of 7.747 m/s accounts for the average modeled wind speed in 2012 for the Vestas V164 (i.e at 140 m height), which is the speed of interest for the following study.
In *Figure 25*, the thrust coefficient at 7.747 m/s seems to be independent from the turbine

model and will be assumed to be equal to 0.8 for the Vestas V164 as well.

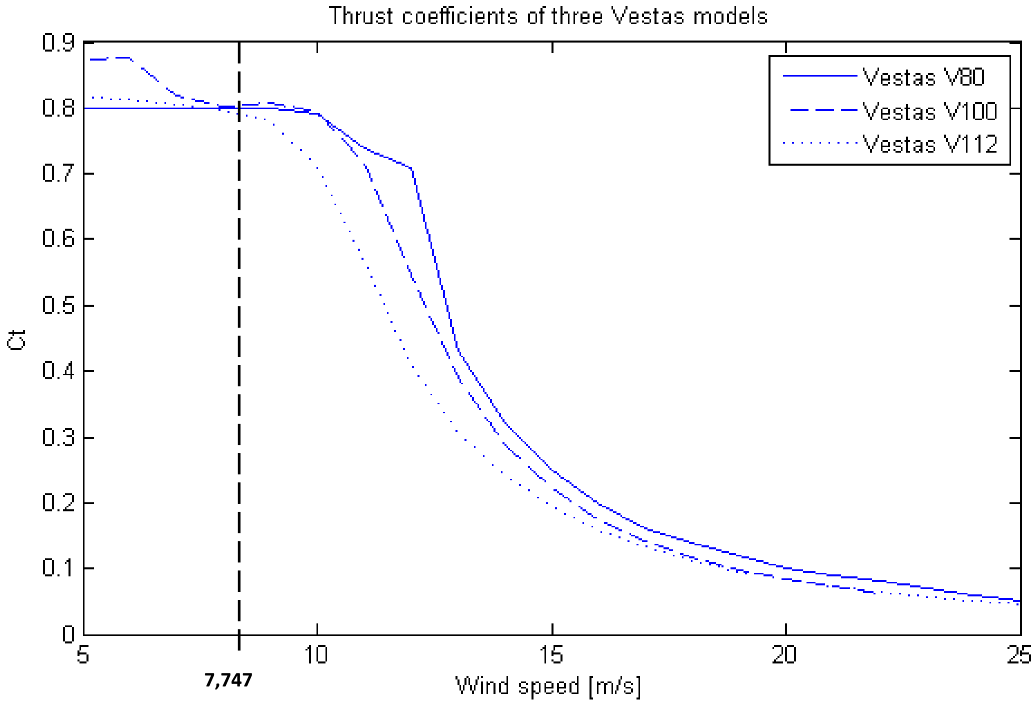


Figure 25. *Evolution of the thrust coefficient with the wind speed for different models*

As a conclusion, all the parameters required to implement the WAsP model for the Vestas V164 are now assessed and will be used further on.

5.2.9.3 Modeling with FLUENT

5.2.9.3.1 Introduction

In order to visualize the impact that each turbine has on the others, the computational fluid dynamic program FLUENT is used.

A 2D model of the turbine is used by associating the rotors with fixed stretched rectangular surfaces in order to enable the modeling of the whole wind farm on one computer. A 3D modeling with moving parts would be more accurate but extremely time consuming and resource demanding.

5.2.9.3.2 Method

A rectangular model of the Vestas V164 is hence built on CATIA and assembled on the initial layout seen in *Figure 23*. This assembly is exported scale 1:10 in FLUENT and is meshed with a satisfying resolution.

5.2.9.3.3 Results

Figure 26 below represents the meshing of one rotor with FLUENT, with the meshing appearing in blue and the white rectangle accounting for the rectangular surface of the rotor seen from above. The meshing includes in reality all the 9 turbines at a time on a large rectangular surface.

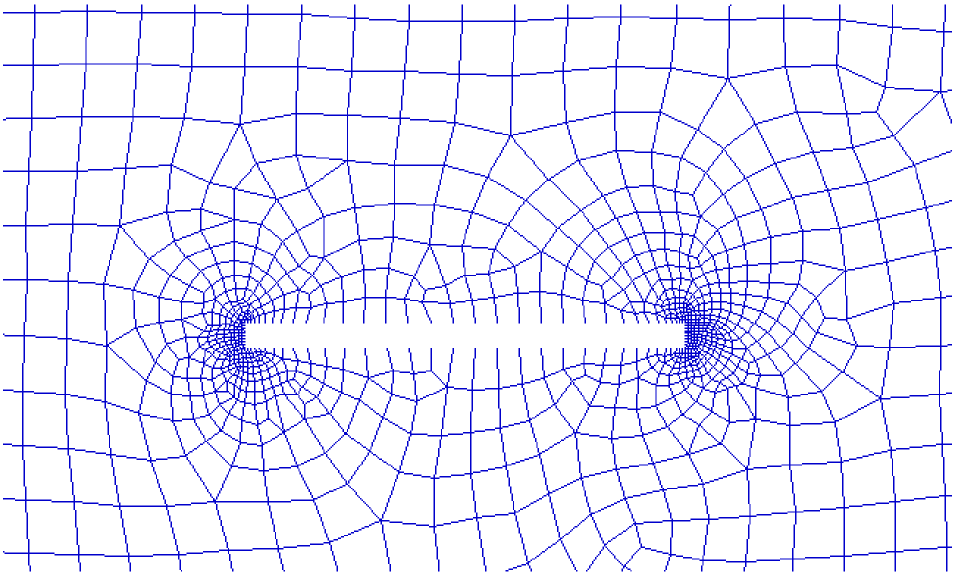


Figure 26. *Meshing of the Vestas V164 rotor*

This meshing is sent to FLUENT and the air flux is modeled with a viscous k-epsilon law. The walls of the rotors are transparent and the interiors are made of air with specific porosity and viscosity properties. The porosity is calculated by dividing the volume taken by the air with the total volume taken by a Vestas V164 rotor, which gives about 94%. The wind speed used at the inlet is constant and equal to 7.747 m/s oriented south-west, corresponding to the most common wind speed occurring in the most common direction.

The model is run and the wind speed is measured on a length of 1500 meters after an isolated turbine used as a reference. This reference will be used to adjust the parameters of the rotor viscosity in order to obtain a downstream evolution of the speed similar to what the WAsP model gives. A trial-and-error method gives the final set of parameters to use.

Figure 27 is the result of the simulation using FLUENT. The orange color surrounding the area corresponds to the 7.747 m/s wind speed at the inlet and the wake effect can be seen by the drag left after each unit. The speed drops down to 5 m/s which are slightly more pessimistic than the WAsP model but is still satisfying here. The outlined three turbines are forming a row and the simulation shows that the one in the middle could advantageously be displace aside to break this alignment and gain in productivity.

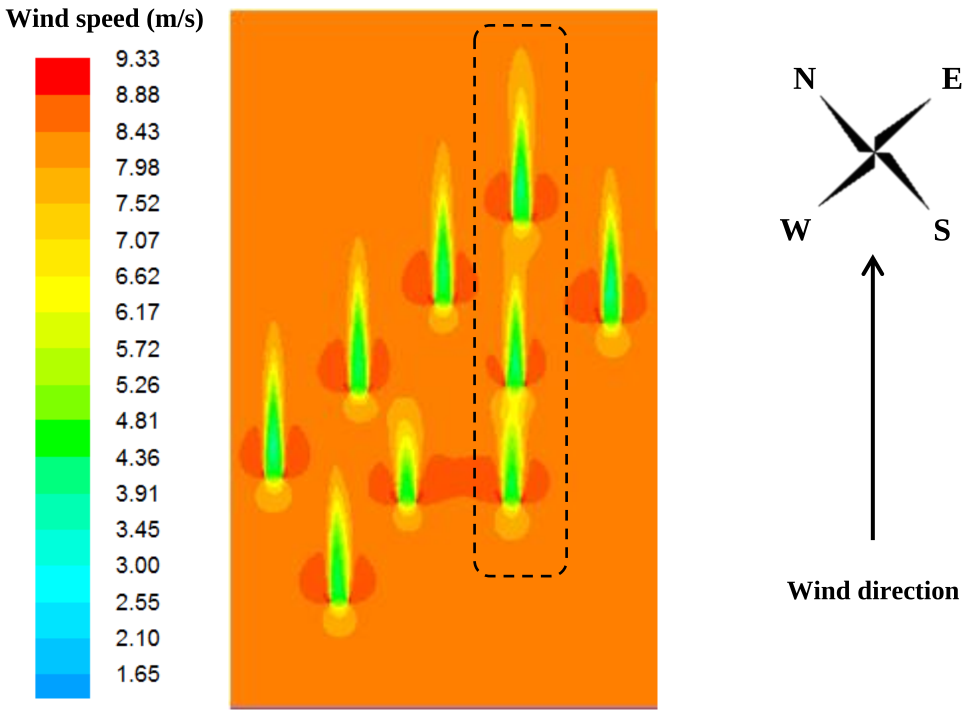


Figure 27. *Modeling of the Vestas V164 layout with a 7.747 m/s south-west wind*

As a conclusion, this might be recommended to perform an optimization of this initial layout in order to avoid these design mistakes.

5.2.9.4 Wind rose optimization

In order to keep a satisfying production rate, the layout needs to be optimized for each direction of the wind. The following gives an insight of the method used to do so.

The wind rose data, presented in the first module, was extracted and converted into a distance rose. The value of the average probability of the wind rose was multiplied by a coefficient to match 6 times the rotor diameter. This coefficient is then used to build the whole distance rose, by multiplying each probability to obtain a distance for every angle of the rose.

Once the distance rose is built, it can be inserted as a part on CATIA and assembled with the area of Hake Fjord.

Figure 28 below represents two distance roses, in blue and green, which have been inserted in the area, in black. The 9 circles dispatched in the area are the positions of the turbines. The circles representing the safety zone are here represented inside each distance rose.
By adding one by one the 9 distance roses on the 9 turbine positions, the probability of the wind blowing into a given direction clearly appears which enable to see into which extent the turbine can be advantageously moved and in which way.

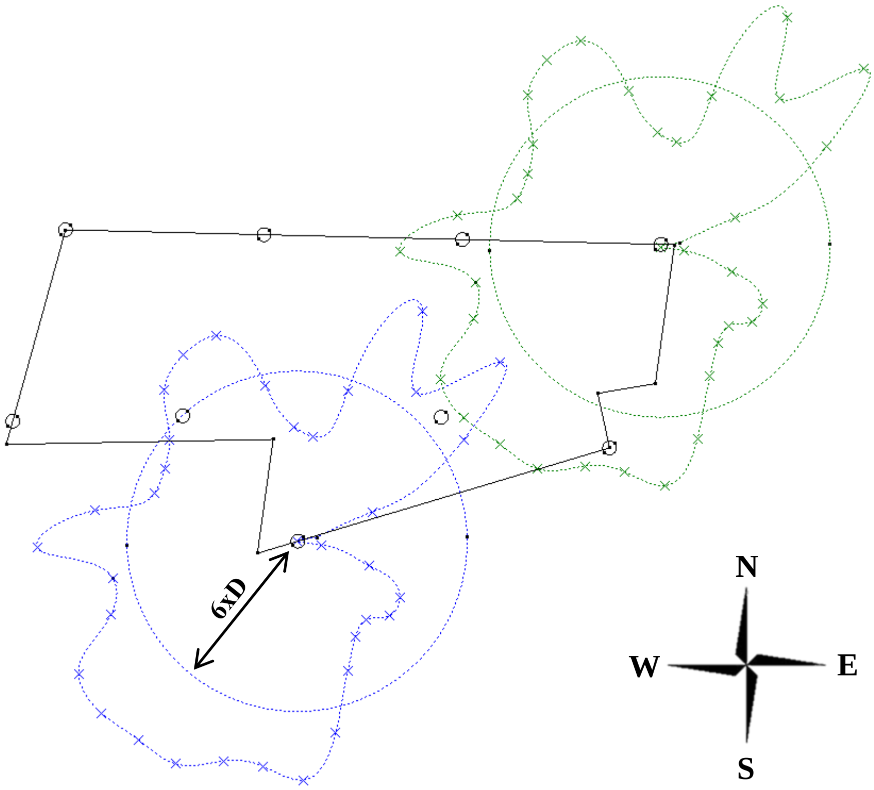


Figure 28. *Optimization of the layout with the distance rose*

5.2.9.5 Result of the optimization

After the wind rose optimization, the final layout is exported in FLUENT and meshed again. *Figure 29* below shows the result of the simulation, under the same conditions than above. It can be noticed that the alignment problem was partially fixed, which confer an improved power output to this configuration. The two lower turbines are still interfering but the wind rose optimization study shows that this is still the best alternative withstanding the fact that there is a minimal safety distance to respect between the units and that the dimensions of the Hake Fjord area are restricted.

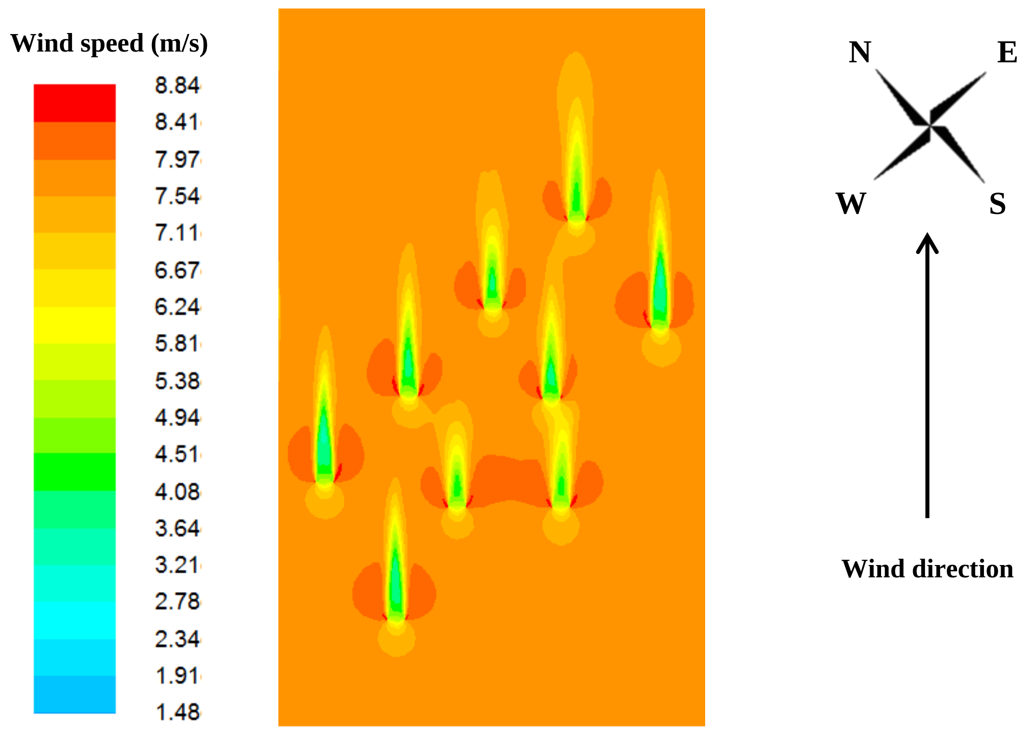


Figure 29. *Modeling of the Vestas V164 optimized layout with a 7.747 m/s south-west wind*

5.2.9.6 Final static wind farm model

5.2.9.6.1 Individual wake effect coefficients

From the FLUENT model the wake effect of the turbines is clearly seen. The wind speed after one turbine is presented in *Figure 30*.

From the simulation it is concluded that the recovery of the wind speed is good enough at a recovery factor of 95%, the wind power being hence assumed to be fully recovered at this point. This factor gives a distance surrounding each turbine and it is a fact that all turbines within this distance will have a wake effect on the evaluated turbine placed in the center of this drawn distance

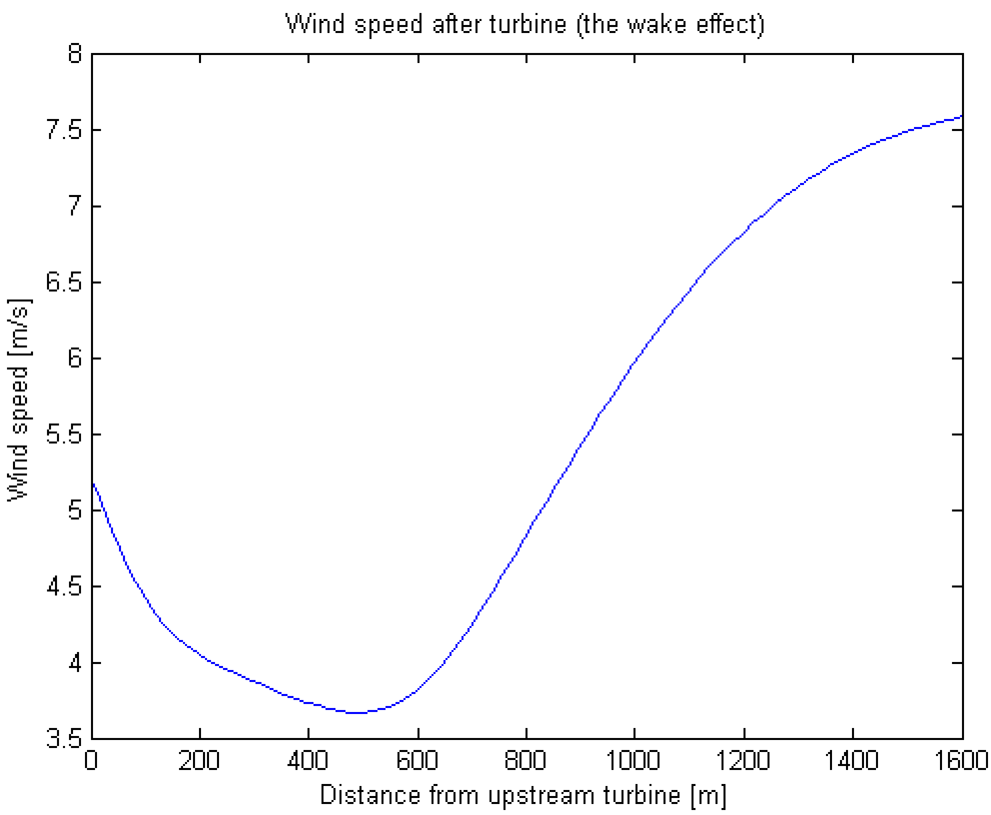


Figure 30. *Wind speed after turbine (FLUENT simulation)*

The method is shown in *Figure 31* where one of the turbines has an applied safety distance equal to 1400 m, corresponding to 95% of wind speed recovery. The other two turbines inside the circle in this figure will have a negative effect on the turbine placed in the center.

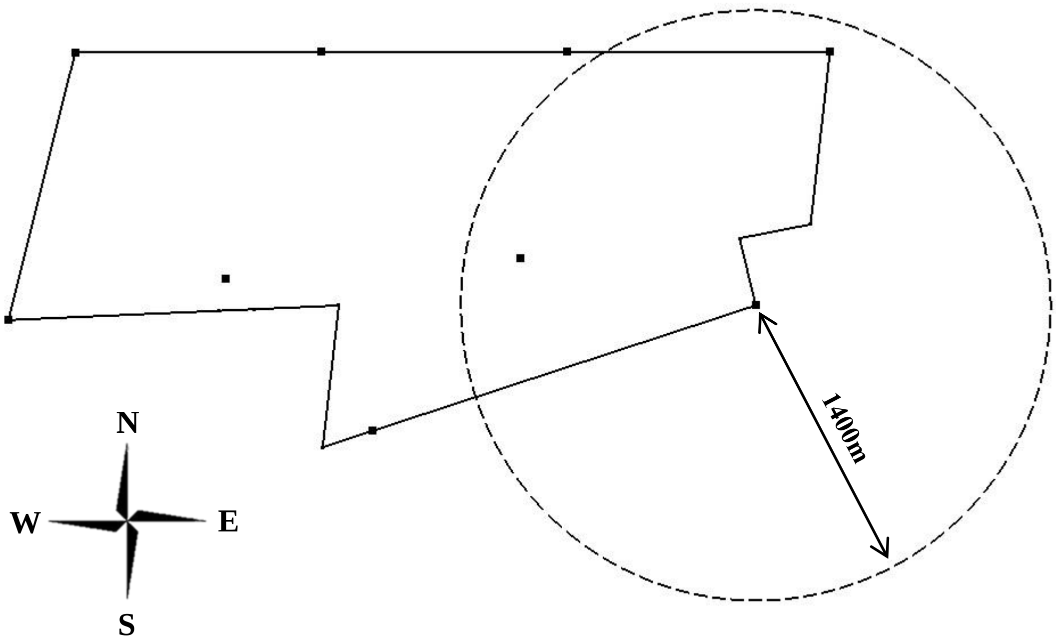


Figure 31. *Wake effect method*

This method was performed for all turbines and the result was 9 lists including in which direction each turbine will be affected and at what distance those neighboring turbines are located. From which directions the turbines affect each other is shown in *Figure 32*.

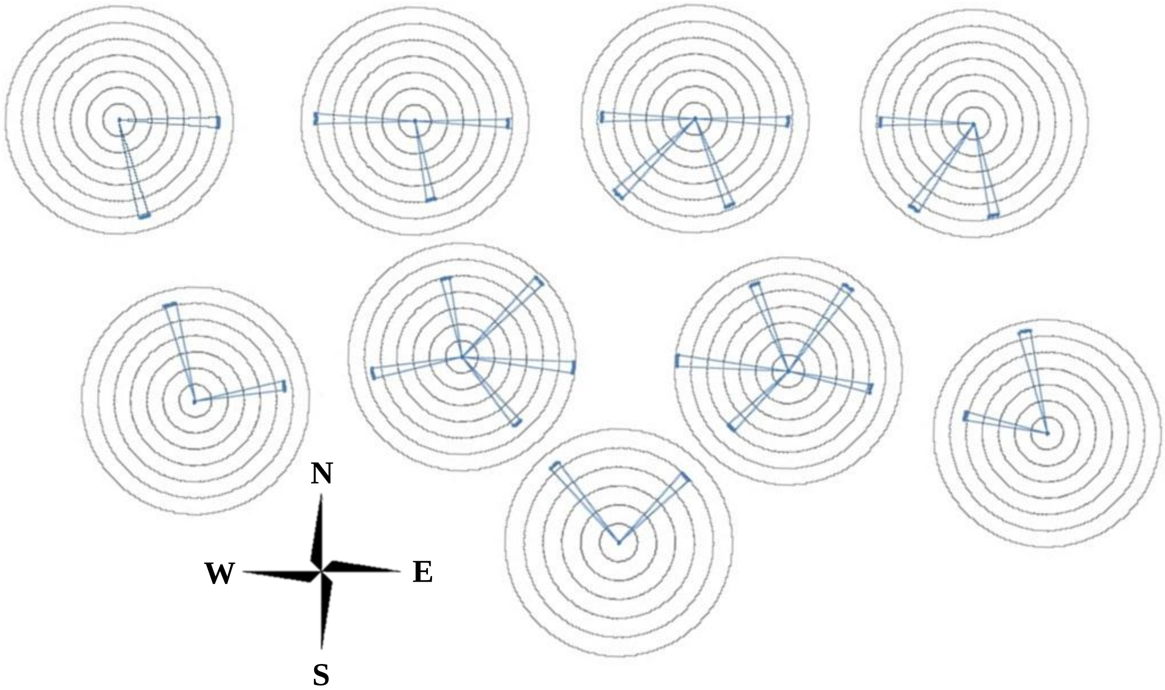


Figure 32. *Wake effect directions*

For each turbine a list for all 360 degrees is constructed, where each degree is assigned with a wind speed value. In all directions where the turbine is not affected by others the wind speed is set to the maximum, the average wind speed used in this case; 7.747 m/s. For the directions where neighboring turbines have an effect, the wind speed is taken from the simulated result in *Figure 30*, varying depending on the distance between them. This list of wind speeds from different directions was then multiplied by its corresponding probability, extracted from the previously constructed wind rose. The sum of the list was divided by the average wind speed, which is the maximum case if no wake effects, and the result is the wake effect coefficient for each turbine.

The wake effect coefficients for the turbines are all in the range 98.5 – 99.6%, concluding that the wind farm layout is relatively effective.

5.2.9.6.2 Performance of the final static wind farm model
All turbines are simulated individually in MATLAB. The wind speed for the modeled year 2012 is matched with the performance curve of the Vestas V164 and multiplied by each corresponding wake effect coefficient. The result is summed and the duration curve for the complete wind farm in Hake fjord is presented in *Figure 33*.

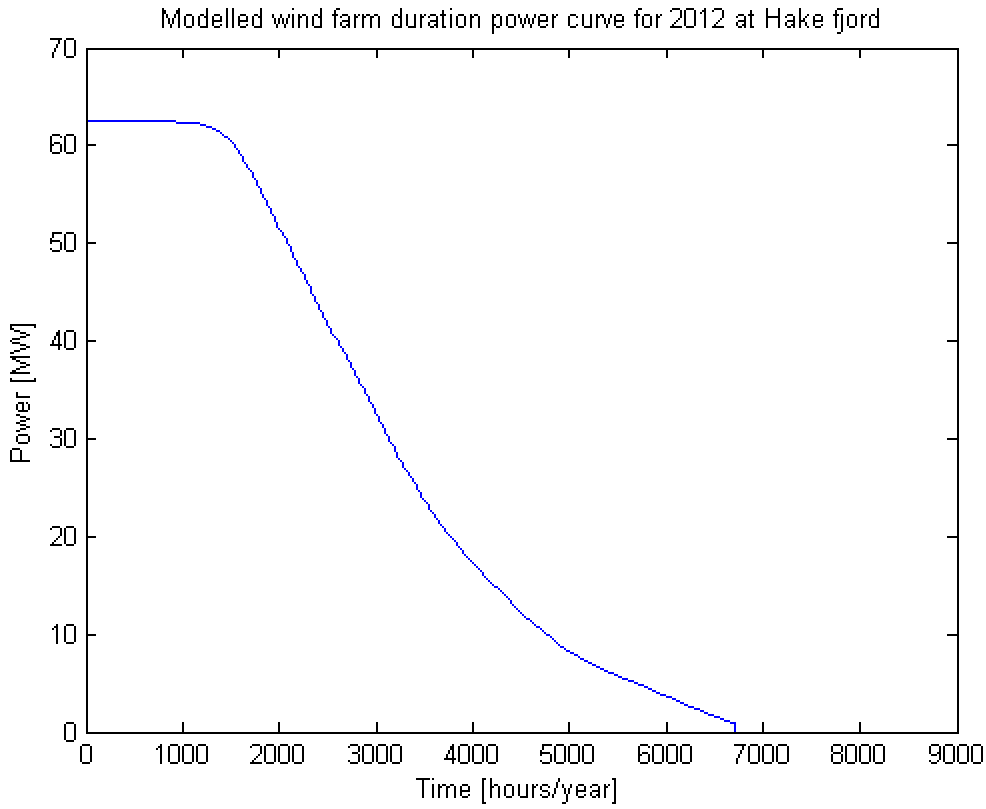


Figure 33. *Modeled duration power curve for the complete wind farm in Hake fjord*

The total amount of energy produced annually in the wind farm is maximum 207.7 GWh/year.

5.2.9.6.3 Downtime risks
However, some studies have shown that the downtime entailed by the failure of the different components composing a wind turbine could significantly affect the annual energy output. Up to 0.8 failures per year and per turbine have been observed in Sweden for example (51).

Figure 34 below shows the different types of possible failures occurring during the lifetime of a turbine. The red histogram represents the probability for each component to fail in one year, and the blue histogram accounts for the average downtime entailed by each failure in hours. The different failure downtimes were pondered by their respective probability of occurrence and summed up to obtain the average number of hours a turbine is out of order in one year. This downtime was multiplied by 9, corresponding to the number of units used in the final model, and this gives about 534 hours of downtime a year for the whole park. If the risk of failure is taken into account, the yearly production of the park is then reduced down to 195 GWh/year, slightly below the energy target of the project.

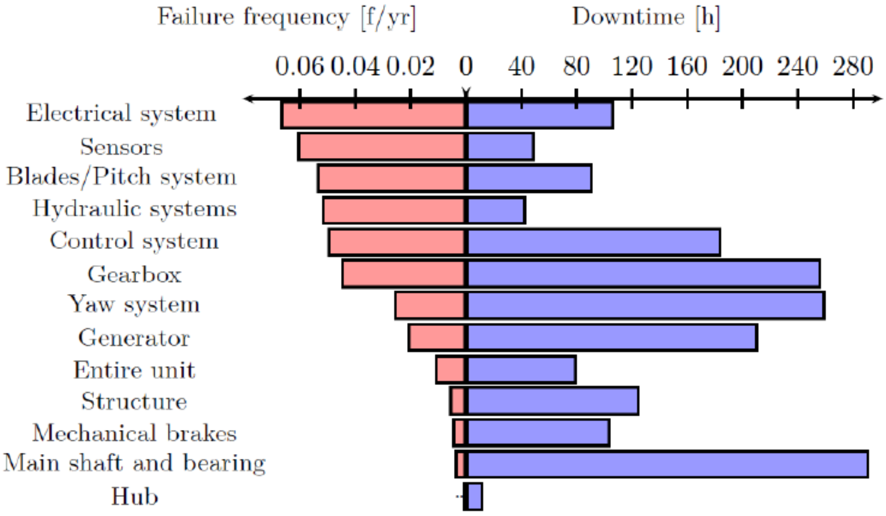


Figure 34. *Average failure frequency and downtime per component and per year (51)*

5.2.10 Conclusion

To conclude, the module 2 gives a proposition of wind turbine model associated with an optimized layout for Hake Fjord that respect the initial energy target fixed for Vindplats Göteborg:

- Different wind turbines were selected and compared from a space requirement and energetic output point of view.
- The costs associated with the number of turbines used were assessed as well as the revenues from the electricity produced.
- A final turbine model was adopted and the associated layout was optimized based on wake effect calculations.

The energy output was recalculated by taking into account the final layout and the potential production losses entailed.

5.3 Module 3 – Power fluctuations of the wind farm

5.3.1 Objective

The third module consists in studying the behavior of the power output from the wind farm under exceptional circumstances such as extreme wind conditions. Assessing how fast the power fluctuations are will enable to choose the relevant compensating back-up technology within the following modules.

5.3.2 Method

The method used in this module can be summarized by the following points:
- Study of the ramp rates from an existing offshore wind farm
- Extrapolation and adaptation of the results to the Hake Fjord case
- Confrontation of the results with the measurements of a nearby wind farm
- Conclusion on the ramp rates requirements for a potential back-up

5.3.3 Wind farm power ramp rates

The ramp rate is the variation of the power output in mean value from one instant n to the next instant n+1, as expressed in the *Equation 5* below.

$$\boldsymbol{P_{ramp}(n) = P_{mean}(n+1) - P_{mean}(n)}$$

Equation 5. *Power output ramp rate formula (52)*

The power output ramp rate of a wind farm depends on different factors such as the wind speed fluctuations, the power curve of the turbine used and the size of the farm considered.

5.3.3.1 The Horns Rev case

Horns Rev is a 160 MW offshore wind farm composed of 80 turbines and located in the North Sea, 14 kilometers away from Denmark (53). Commissioned in 2002, this park is still in operation and was used as a case study to investigate the fluctuations of the power output. *Figure 35* showed below represents the ramp rates measured from Horns Rev during 10 min. The initial mean power output is 0.8 p.u, and it must be noted that the ramp rates will be significantly dependent on this initial value: if a mean output close to the saturation is chosen, the ramp-rates measured will be relatively low (54). On this power curve, only the extreme values are interesting since these will be taken as a basis for designing a back-up.

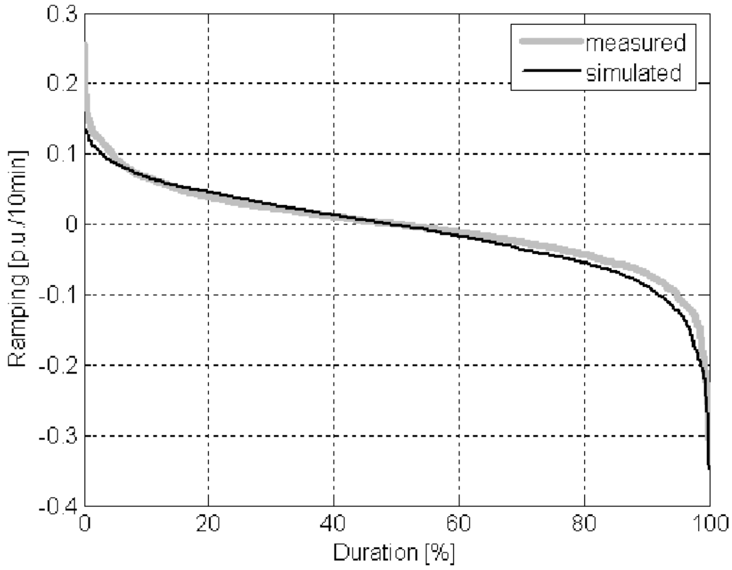


Figure 35. *Duration curves of 10 min ramp rates in the initial power range from 0.8 p.u (54)*

However, most of the wind farms can use a controller in order to limit the ramp up of the park, as illustrated in *Figure 36*. The dashed blue line represents the power harvestable from the wind conditions at that time and the red line is the path the power output is forced to choose by the controller.

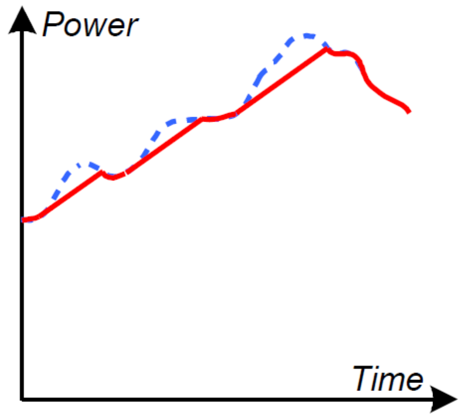


Figure 36. *Ramp up limitation mode (55)*

As a result, the power output ramp-up from the wind farm does not constitute a decisive factor when it comes to the design of a back-up since it can be lowered on demand. The study of the Horns Rev fluctuations, undertaken in the report "Power fluctuations from large wind farms" (26), is therefore focused on the last percentile (99%) of the duration curve that gives the extreme values for the ramp-down. *Figure 37* hereafter is presenting the extreme ramp-down measured for every initial power output value from 0 p.u to 1 p.u.

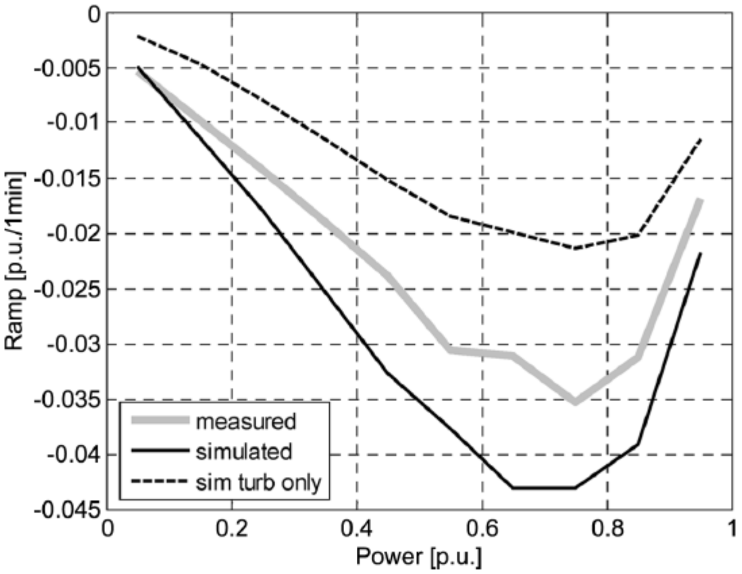


Figure 37. *The 99% percentiles of 1-min ramp rates in all power ranges (26)*

The maximal ramp-down detected corresponds to an initial value of 0.7 p.u and is equal to 0.035 p.u/min, which means 70 kW/s in this case.
As a conclusion, if a back-up technology had to be designed for this park, it should be able to start up at a rate of 70 kW/s. The present case study involves a considerably smaller park, both from a power output and a size perspective, and this should be taken into consideration to have a more accurate insight of the ramp-down.

5.3.3.2 The Hake Fjord case

5.3.3.2.1 Introduction

The same way the fluctuations of the wind are filtered and dampened by the turbine when the energy is transformed from wind to electricity, the power outputs from each turbine, once added up, give a smooth curve for the overall farm. This is due to the fact that the wind conditions are not homogeneous in the park and as a consequence all the turbines do not react synchronously. *Figure 38* shows an episode of strong wind in Horns Rev forcing one by one the turbines to shut down. It can be observed that the turbines do not shut down and restart simultaneously, entailing a reduction of the fluctuations of the total power.

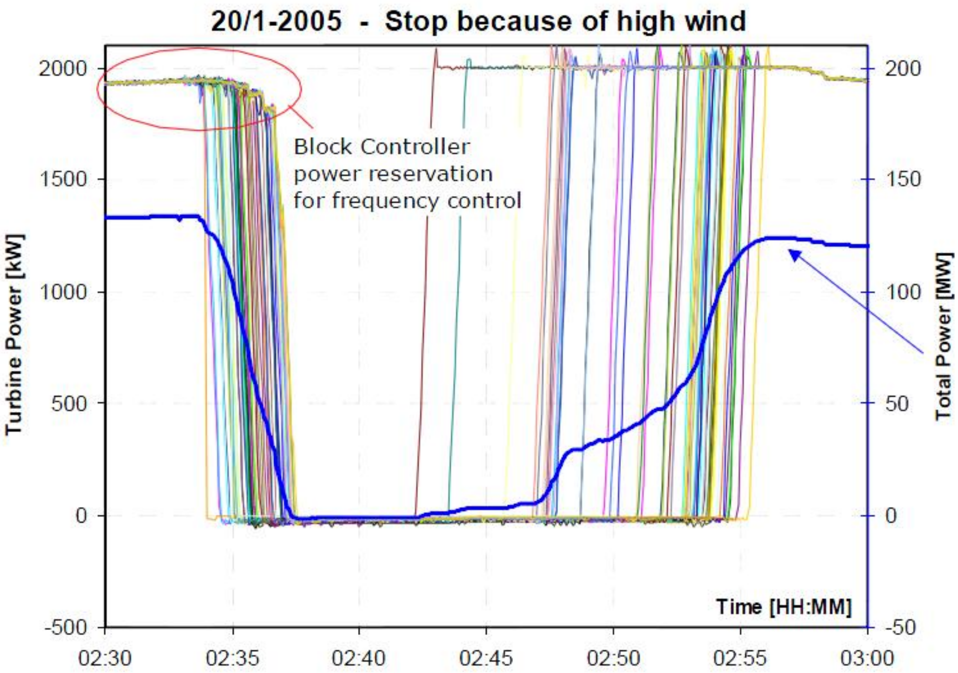


Figure 38. *Horns Rev power output when the wind exceeds 25 m/s for 20 min.*

This smoothing effect of the total output mainly depends on the number of turbines, the size of the layout and the power curves. A model taking into account all these factors was performed in the report "Power fluctuations from large wind farms" (26) and enabled to create the modeled duration curves mentioned above.
In order to assess the specific ramp-rates that can be expected at Hake Fjord, each of these factors will be reviewed and confronted with Horns Rev.

5.3.3.2.2 Influence of the number of turbines
In a study of the power fluctuations from different offshore wind farms carried out by Ervin Spahić and Gerd Balzer (56), it is reported that the power fluctuations are increasing when the size of the park is decreasing. In order to stress more accurately the dynamic filter behavior of the turbines, this survey splits the wind into two categories: large fluctuation winds (±35% around the mean) and low fluctuation winds (±10% around the mean), that are generally oscillating faster but with a lower amplitude. The tool used to measure the fluctuations is the standard deviation. *Equation 6* below is the explicit formula of this mathematical tool; with X being the power output of the farm in this case and n the number of samples.

$$\boldsymbol{std} = \sqrt{\frac{\boldsymbol{n}.\sum_{i=1}^{n}\boldsymbol{X}^2 - (\sum_{i=1}^{n}\boldsymbol{X})^2}{\boldsymbol{n}.(\boldsymbol{n}-\boldsymbol{1})}}$$

Equation 6. *Definition of the standard deviation (56)*

The two graphs below provide one of the main results of this study. *Figure 39* represents the standard deviation of the power output modeled for different sizes of farm and wind conditions under large fluctuations of wind. The general trend is the increase of the fluctuations when the size of the farm decreases. An extrapolation of the curve for an average wind speed of 7.747 m/s (mean wind speed at hub height in Hake Fjord) for 9 turbines gives a standard deviation 2.55 times higher than for the same wind with 80 turbines (Horns Rev).

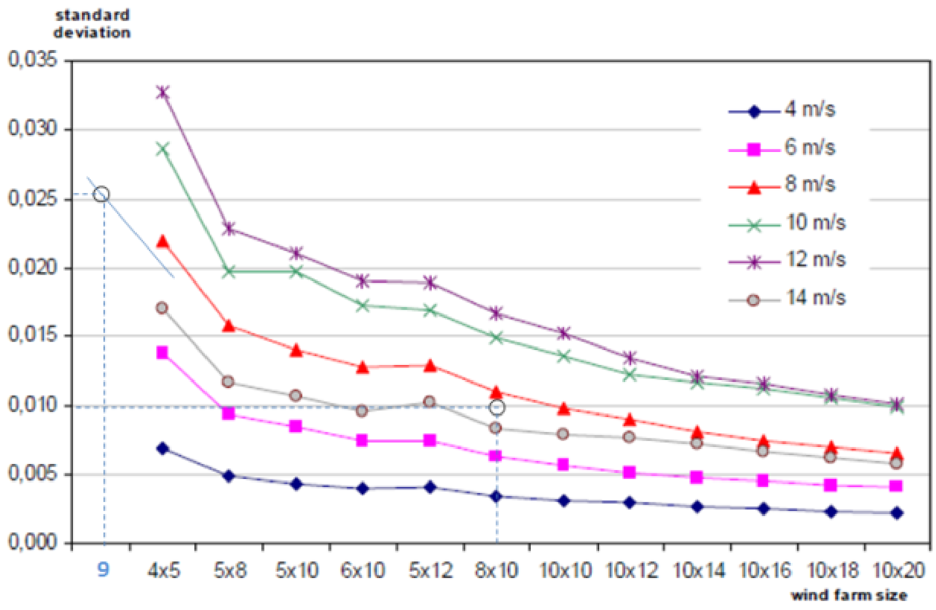


Figure 39. *Power fluctuations function of the wind farm size for large wind fluctuations (56)*

Figure 40 represents the standard deviation of the power output modeled for different sizes of farm and wind conditions under low fluctuations of wind. The general trend is also the increase of the fluctuations when the size of the farm decreases. An extrapolation of the curve for an average wind speed of 7.747 m/s for 9 turbines gives a standard deviation 2.88 times higher than for the same wind with 80 turbines.

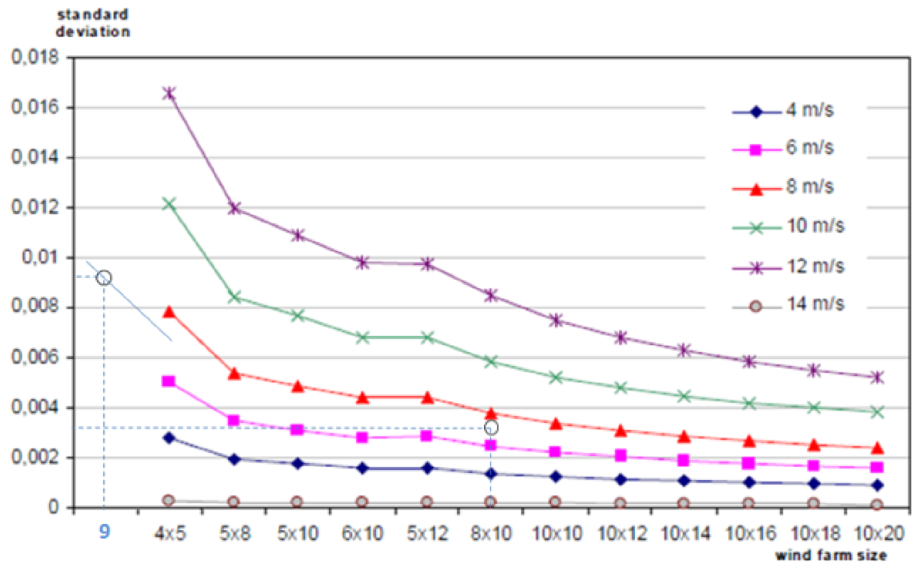


Figure 40. *Power fluctuations function of the wind farm size for low wind fluctuations (56)*

As a conclusion, the number of turbines seems to have a strong influence on the fluctuations of the power output, and the specifications proper to Hake Fjord might lead to 2.88 higher fluctuations than in Horns Rev for the worst case. However it should be noted that this survey was based on square patterns which is not exactly the case of layout chosen in Hake Fjord which might lead to slightly different results.

5.3.3.2.3 Influence of the size of the layout

As it takes time for a front wind to pass the first turbine of the park and reach the last one, the individual power fluctuations of the turbines do not occur simultaneously. By using a simple rule of thumb, it can be observed that if a given wind park is twice smaller than another one it will take half the time for the wind to pass through the smaller farm. *Figure 41* below represents the layout of Horns Rev that can be assimilated with a rectangle 5 km wide and 4 km high.

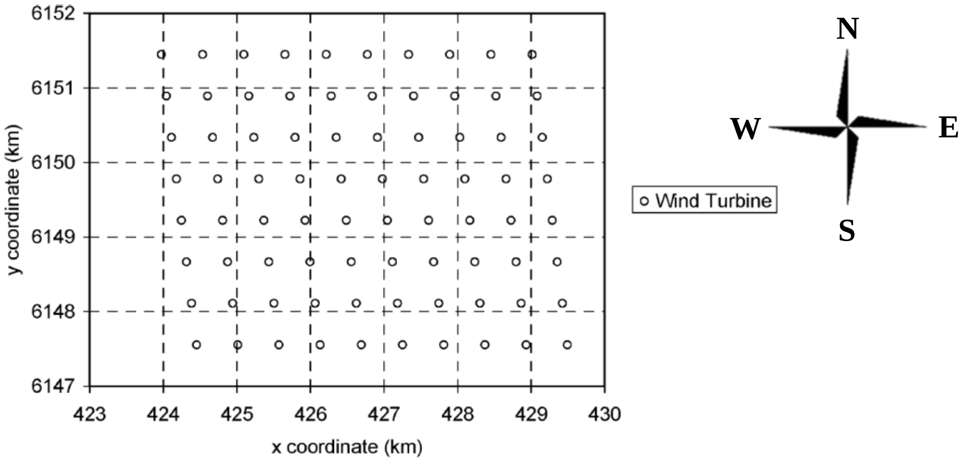


Figure 41. *Layout of Horns Rev (25)*

Figure 42 illustrates the layout of Hake Fjord, placed on the same scale than Horns Rev. Hake Fjord wind farm is only 3.5 km wide and 1.6 km high, if seen as a rectangle.
The wind would hence take 1.4 times more time to cross Horns Rev on the west/east axis than Hake Fjord, and 2.5 times more time if it is coming from the south/north axis.

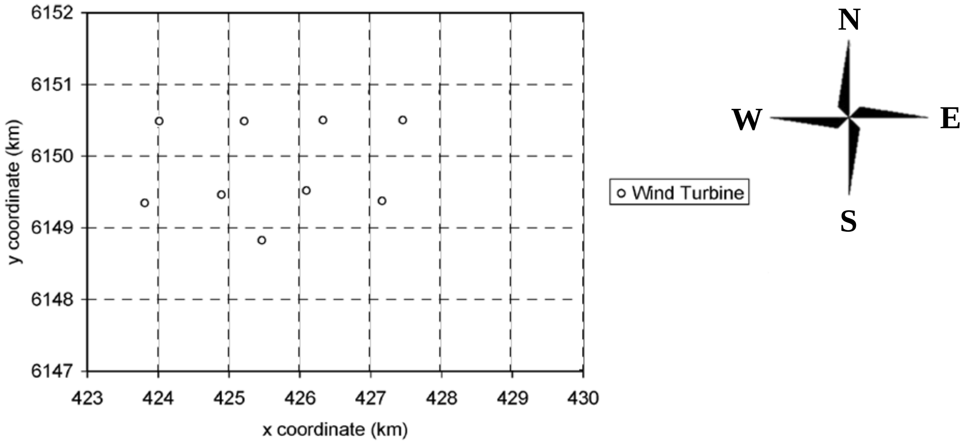


Figure 42. *Layout of Hake Fjord*

If the relation between the power output and the wind speed is considered to be linear, the ramp rate is directly affected by those ratios of distances (57). As a conclusion, the size of the layout seems to affect the fluctuations of the power output, and the specifications proper to Hake Fjord might lead to 2.5 higher fluctuations than in Horns Rev for the worst case.

5.3.3.2.4 Influence of the power curve

5.3.3.2.4.1 Under normal wind conditions

The power curve of the turbine used in a park associates for each wind speed a value of the power output that the turbine will deliver when exposed to the wind speed considered. This curve is one of the major performance factors of a wind turbine, and generally has the shape illustrated in *Figure 43.*

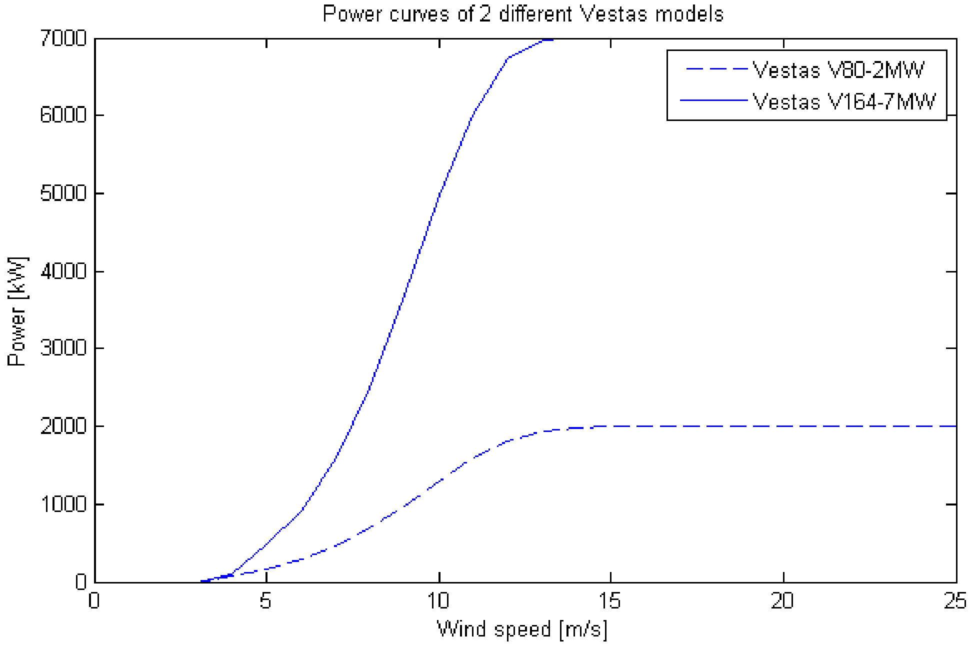


Figure 43. *Power curve of the Vestas V164*

Three zones naturally come out of this graph: between 0 m/s and about 4 m/s, the cut-in speed, the turbines do not produce electricity. Between 4 m/s and 13 m/s, the curves show the quasi-linear relation between the wind speed and the power output. Between 13 m/s and 25 m/s, the cut-out speed, the power output is maximal and the turbines productions are stable. The Vestas V164 is significantly more powerful than the one used in Horns Rev (Vestas V80), meaning that the slope of the linear part is much more important. As a result, the same variation of wind will entail a higher power increase per turbine in Hake Fjord. However, since this curve reflects the behavior of the turbine from a static point of view, it only gives the output for every wind speed but do not provide any information about how long it takes for the turbine to reach these different states.

Nonetheless, the survey on the fluctuations from Horns Rev reveals that the extreme ramp-down occur when the wind speed exceeds 25 m/s, the cut out-speed, which is why the behavior of a turbine under stormy conditions is studied hereafter.

5.3.3.2.4.2 Under harsh wind conditions

When the wind speed reaches a certain value, the wind turbine is usually disconnected from the network in order to keep the physical integrity of the unit. *Figure 44* shows the power curve of a typical wind turbine, starting to produce energy at the cut-in speed V_1, reaching the maximal power at V_2 and being disconnected at the cut-out speed V_3. Afterwards, the unit is reconnected at a lower speed V_4 in order to avoid successive reconnections when the wind speed is fluctuating around V_3.

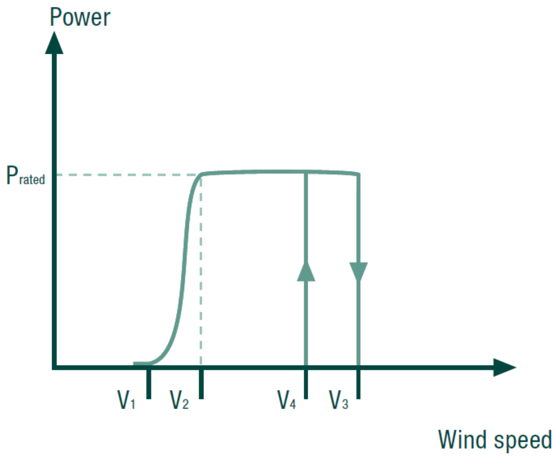


Figure 44. *Power curve with hysteresis behavior under storm conditions (58)*

This type of power curve is entailing sudden fluctuations in the park under stormy conditions, representing a risk of instability for the network and significantly lowering the energy harnessed. *Figure 45* hereafter shows an innovation from Enercon GmBH enabling a smoother ramp-down in case of strong winds. The unit is starting to produce energy at the cut-in speed V_1, reaching the maximal power at V_2 and progressively lowers its power output if the wind speed exceeds V_{storm}.

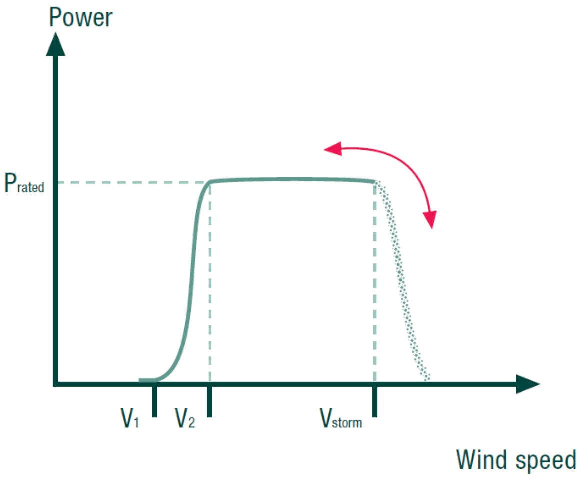


Figure 45. *Power curve of a turbine equipped with a Soft Storm Transition (SST) system (58)*

As a conclusion, the power output fluctuations will be influenced by the type of power curve the turbines have been designed to follow.

5.3.3.2.5 Conclusion

The fluctuations of the power output from Horns Rev have been studied in detail in a precedent survey and the confrontation of the different factors affecting these fluctuations with the Hake Fjord case indicates that the maximal ramp-down of 0.035 p.u/min observed in Horns Rev will be 2.88 times higher in Hake Fjord. In order to keep a security margin, a ramp-down of 0.105 p.u/min will be chosen, hence corresponding to a value three times higher than in Horns Rev.

5.3.3.3 Model confrontation with wind farm measurements

5.3.3.3.1 Introduction

In order to confirm that the Hake Fjord farm is expected to generate power fluctuations three times higher than in Horns Rev, the power output evolution of an existing farm nearby is studied. This wind farm, composed of 5 turbines similar to the Vestas V44 – 600 kW, is located in Risholmen, about 2 km away from the focus area of Hake Fjord.

5.3.3.3.2 Results of the measurements

Figure 46 below shows the wind speed reigning in Risholmen during a period of harsh climatic conditions, from the 07/12/2011 to the 13/12/2011. This period was specifically chosen because it contains both conditions exceeding the cut-in speed (25 m/s) and wind speeds below the cut-in speed (4 m/s) of the park.

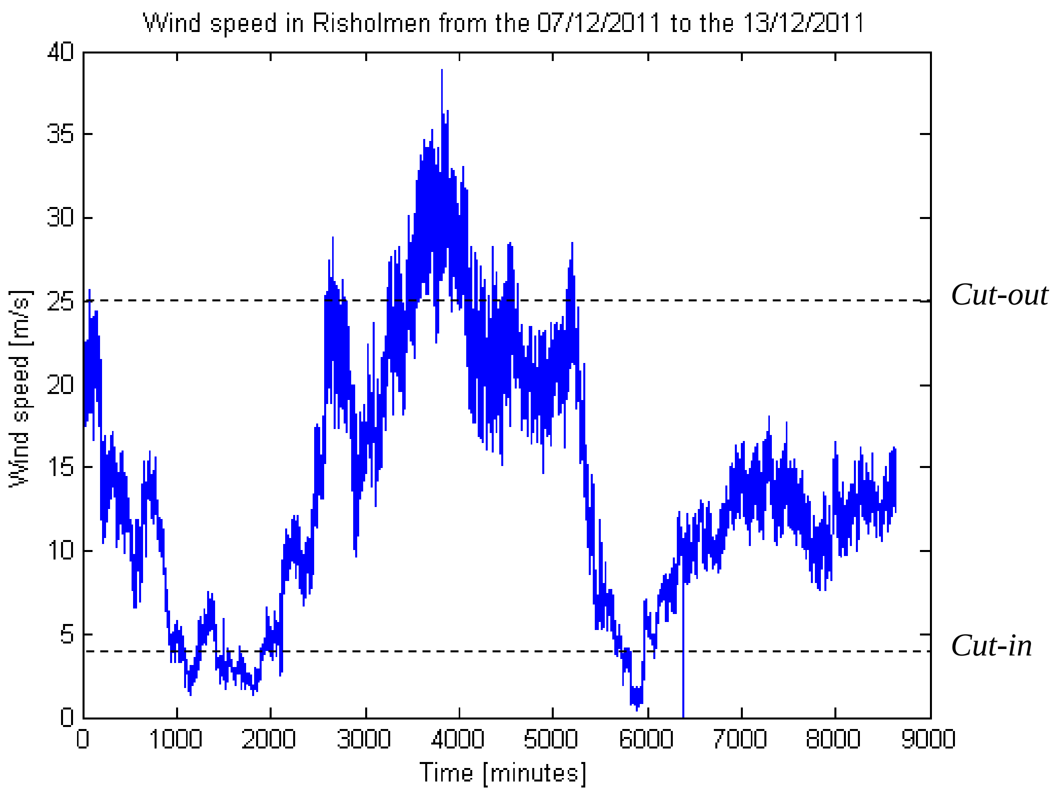


Figure 46. *Wind speed measured from a 40 m mast at Risholmen during a particularly rough day*

Figure 47 hereafter is the corresponding power output from the park of Risholmen. As a whole the power output follows the same pattern than the wind speed. It can be seen though that the power is suddenly dropping when the wind speed reaches 25 m/s and is stable on 0 p.u when the speed is reduced below 4 m/s. The reason why the output is not null in case of high wind speed is because the different turbines are experiencing slightly different conditions at a given time, resulting in some of them starting up while others are still shutting down.

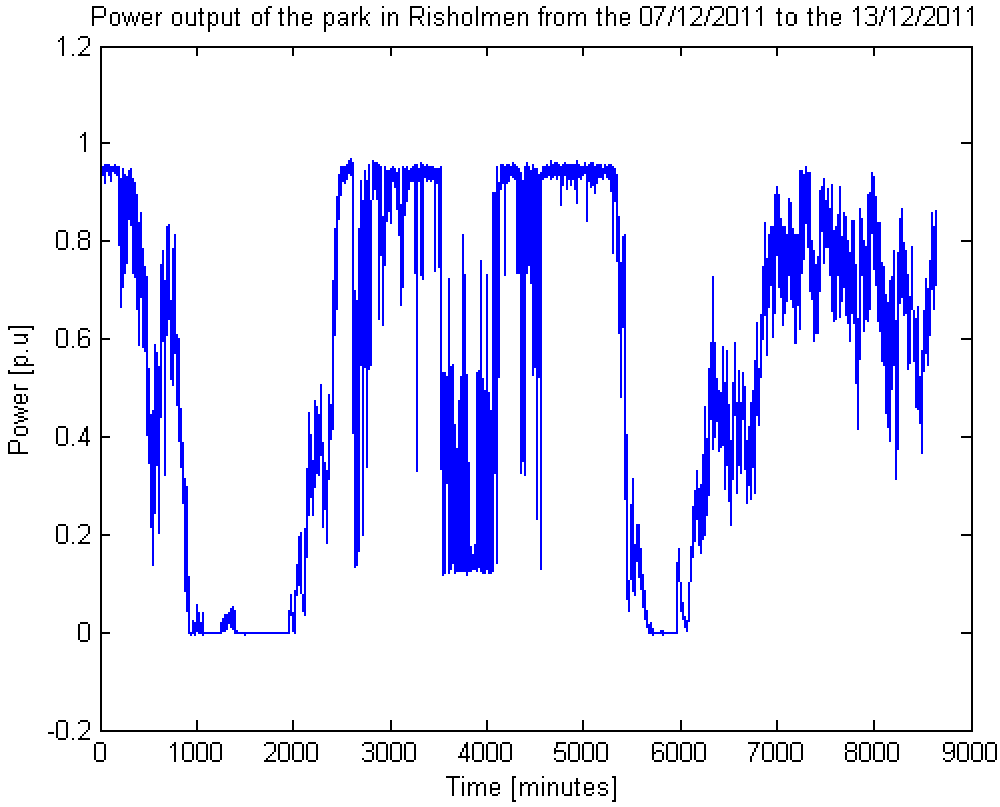


Figure 47. *Power output of the park of Risholmen measured during the same period*

Finally, *Figure 48* is displaying the ramp rates of the overall park during these exceptional conditions. Most of the values are below 0.1 p.u/min which is in accordance with the extrapolation from Horns Rev. However the back-up technology should provide a constant support, even during these extreme scenarios, which is why the maximum should be here considered: the value corresponding to the maximum ramp-down is 0.368 p.u/min (observable at around 3600 min in *Figure 48*), ten times more than in Horns Rev.

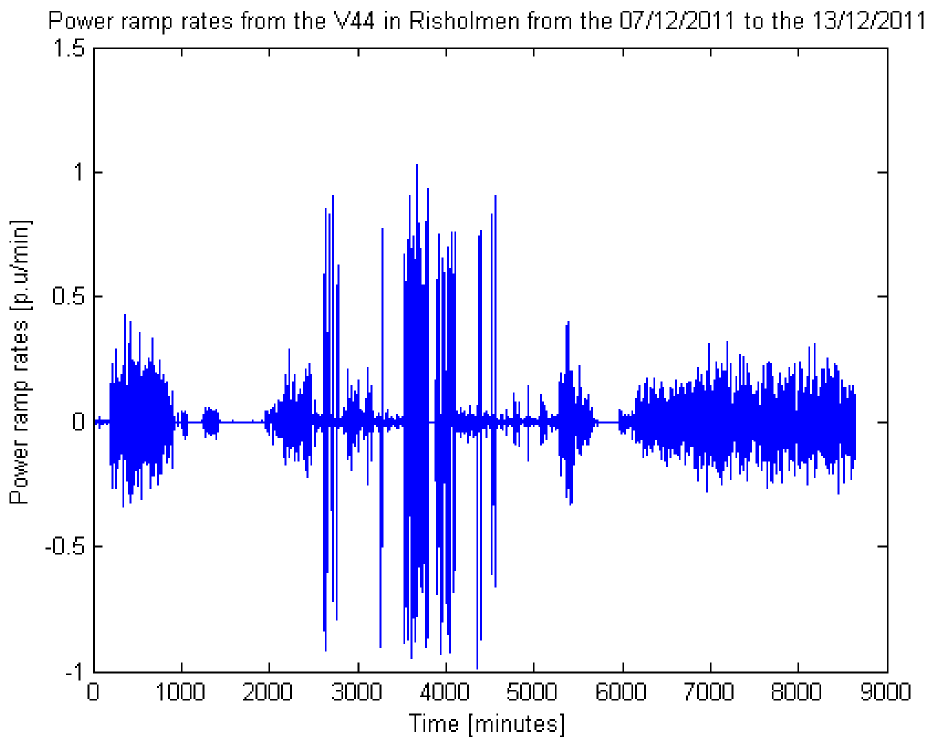


Figure 48. *Power ramp rates of the park of Risholmen measured during the same period*

5.3.3.3.3 Conclusions

The study of the large offshore wind farm Horns Rev might lead to an underestimation of the ramp-down from Hake Fjord. It should be stressed however that the park of Risholmen only involves 5 turbines against 9 in the present case, and those turbines are significantly smaller and consequently more sensitive to wind fluctuations. As a result, the investigation of the local park of Risholmen reveals that the dynamic of Hake Fjord could actually reach close to 0.3 p.u/min, which accounts for 20 MW/min in the case of Hake Fjord.

5.3.4 Requirements of the back-up technology

The Hake Fjord wind farm produces annually 200 GWh of electricity, considering an optimistic downtime due to maintenance. This production corresponds to a 23 MW utility producing with 100% availability throughout the year and with no fluctuations.

To conclude, if the goal is to reach a 200 GWh energy output without fluctuations, the back-up technology in charge of ensuring a stable power supply will have to ramp-up at a rate of 20 MW/min and should have at least a capacity of 23 MW in case of prolonged power outage from the park.

The technology considered will endure a significant amount of ramp-up and ramp-down cycles throughout the day and should be designed to resist to this extensive operation mode. Some effects on the efficiency and the lifespan are hence expected if compared with a classic (relatively constant) operation mode.

5.3.5 Conclusion

- The Horns Rev wind farm ramp-rate was studied and then extrapolated and adapted to fit the Hake fjord case.
- The result was compared with a study of a nearby small wind farm at Risholmen.
- The worst case ramp-rate predicted to occur at the Hake fjord wind farm is 20 MW/min. This ramp-rate is then required to back-up the Vindplats Göteborg wind farm to achieve a 23 MW capacity energy system steadily available throughout the year.

5.4 Module 4 – Power demand and power supply production mix in Göteborg

5.4.1 Objective

This module is performed due to a few main reasons. The power demand needs to be investigated to be able to conclude on how much power that is consumed over the year and how fast the fluctuations in demand are. The production mix is examined to see what difference the introduction of the wind farm, Vindplats Göteborg, will do regarding CO_2-emissions, import capacity and the amount of electricity required as import.

5.4.2 Power demand and its dynamics

5.4.2.1 Method

To study the power demand, data of the power consumption from the past ten years in Göteborg was acquired with an hourly time resolution from Göteborg Energi AB. A model of the power consumption was made for 2012 by using the measurements of 2011 and then adjusting that dataset so that its average equals the average of the consumption of the past few years. This modeled 2012 was used to conclude on the average annual electricity consumption and as an input when later studying the production mix. The total annual energy consumed for the modeled 2012 was found by integrating the dataset containing the day-to-day capacity consumed.

For the dynamic study one week of high resolution data was acquired. This data was collected in December of 2011 with a rate of 1 sample/second. The dataset was minute averaged and then a differentiate function was applied to find the maximum ramp rates of the power demand. The maximum and minimum of this result were extracted as they represent the maximum ramp rates for increase and decrease in power demand.

5.4.2.2 Results

In *Figure 49* the power consumption of the years 2002-2011 is displayed. A pattern is here clearly seen, which shows that the consumption is higher during winters than during summers.

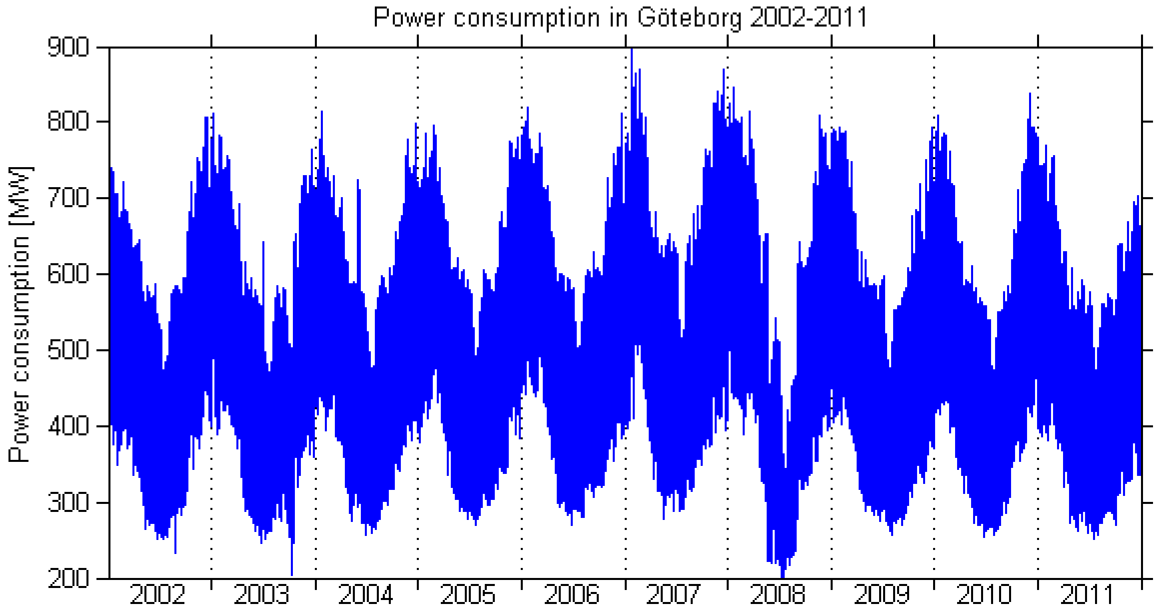


Figure 49. *Power consumption in Göteborg during 2002-2011*

The model of 2012 is displayed in *Figure 50*. It is based on the data for 2011 and since no trend was detected it is adjusted to match the average of 2009-2011. In this figure two patterns can be spotted. First, as in *Figure 49*, the difference between winter and summer consumption is clear, but a weekly pattern also appears, showing the difference in consumption between weekdays and weekends.

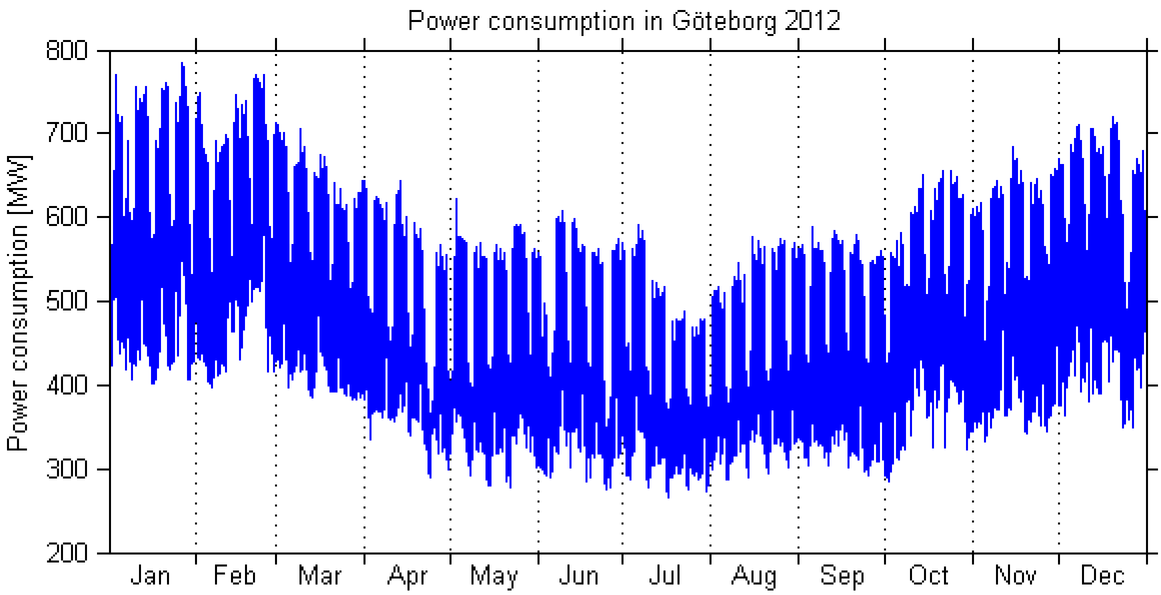


Figure 50. *Power consumption in Göteborg during modeled year 2012*

The total amount of electricity consumed in the 2012 model of Göteborg is 4 247 GWh and the maximum power capacity required is 784 MW.

Figure 51 shows the high resolution power consumption data of one week in December 2011. In this figure the weekly pattern becomes obvious, with lower consumption during the weekend.

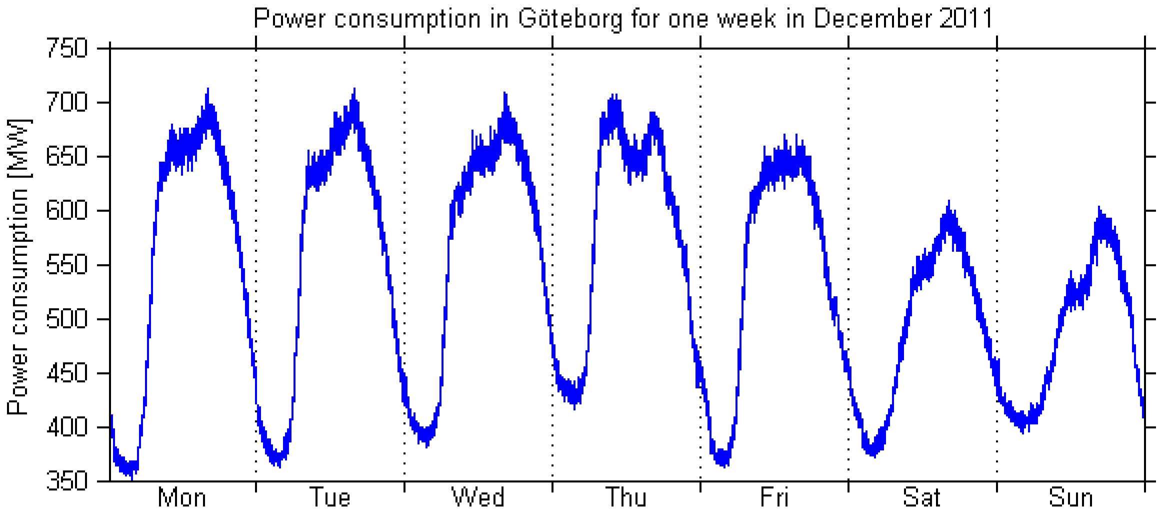


***Figure 51.** Power consumption in Göteborg during one week in December 2011*

Applying a differentiate function on the high resolution data resulted in ramp rates for the week considered, displayed in *Figure 52*. Displaying the result in such a graph enables to stress that the fluctuations are of a greater magnitude during daytime compared to nighttime.

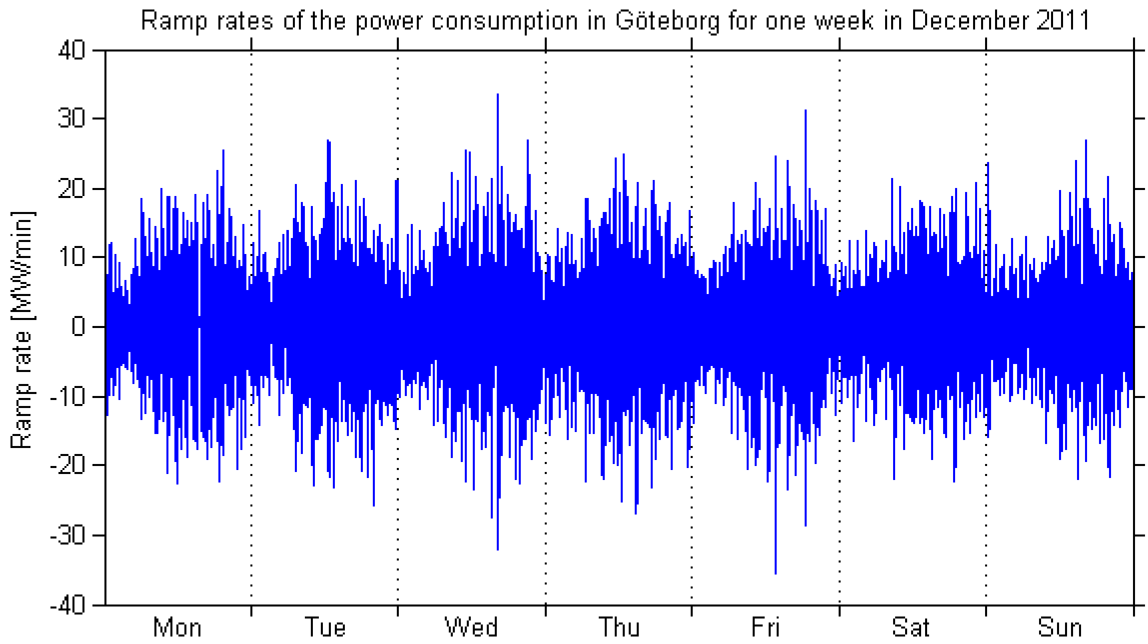


***Figure 52.** Ramp rates of power consumption during one week in December 2011*

The maximum and minimum values of the rates during this specific week represent the maximum ramp rates for both increase and decrease in power demand. The values are presented in *Table 8*.

Table 8. *Maximum ramp rates in power demand*

Ramp	Increase [MW/min]	Decrease [MW/min]
Rate	33.4	35.5

5.4.2.3 Discussion

In *Figure 49* it is clearly seen that something out of the ordinary happened with the electricity consumption during 2008. The drop in consumption during the summer period was much deeper that year than during the others. The reason for this was that a rapid increase in the electricity price occurred, which happened due to a strong increase in fossil fuel prices together with a price increase for emissions (41), (59), (60). The year 2008, breaking the pattern, confirmed that the modeled 2012 should be based on the average of the following years.

For the dynamic study a week in December was chosen. This decision was made out of the fact that the electricity consumption is higher during the winter period compared to the summer period. The chosen week would then provide ramp rates close to the worst case fluctuations, which is desired.

5.4.2.4 Conclusions

- The annual electricity demand of Göteborg is 4 247 GWh
- The maximum required power capacity of Göteborg is 784 MW
- The ramp-rates for the electricity consumption is 33.4 MW/min for increase and 35.5 MW/min for decrease

5.4.3 Production mix in Göteborg

5.4.3.1 Introduction

In Göteborg the main electricity producer is Göteborg Energi AB. There is also a minor producer called Renova. The already existing wind power in the system is run by Göteborg Energi AB and a cooperative in the Arendal area. All facilities and their approximate electricity production capacities are listed below.

- Göteborg Energi AB – Rya CHP plant (256 MW) (61)
- Göteborg Energi AB – Rosenlundsverket (36 MW) (61)
- Göteborg Energi AB – Högsbo Kraftvärmeverk (13 MW) (61)
- Göteborg Energi AB – Sävenäsverket (13 MW) (61)
- Göteborg Energi AB and Arendal cooperative – Wind power (11 MW) (62)
- Renova – Sävenäs Waste Incineration (36 MW) (63)

The gap with the existing power demand is then imported into Göteborg from producers outside the city. These other producers could be located close by or in other market areas of Sweden as well as abroad. Göteborg is located in the market area of Sweden called SE3, in *Figure 53* a map of the Nordic power market areas and connections between them are presented.

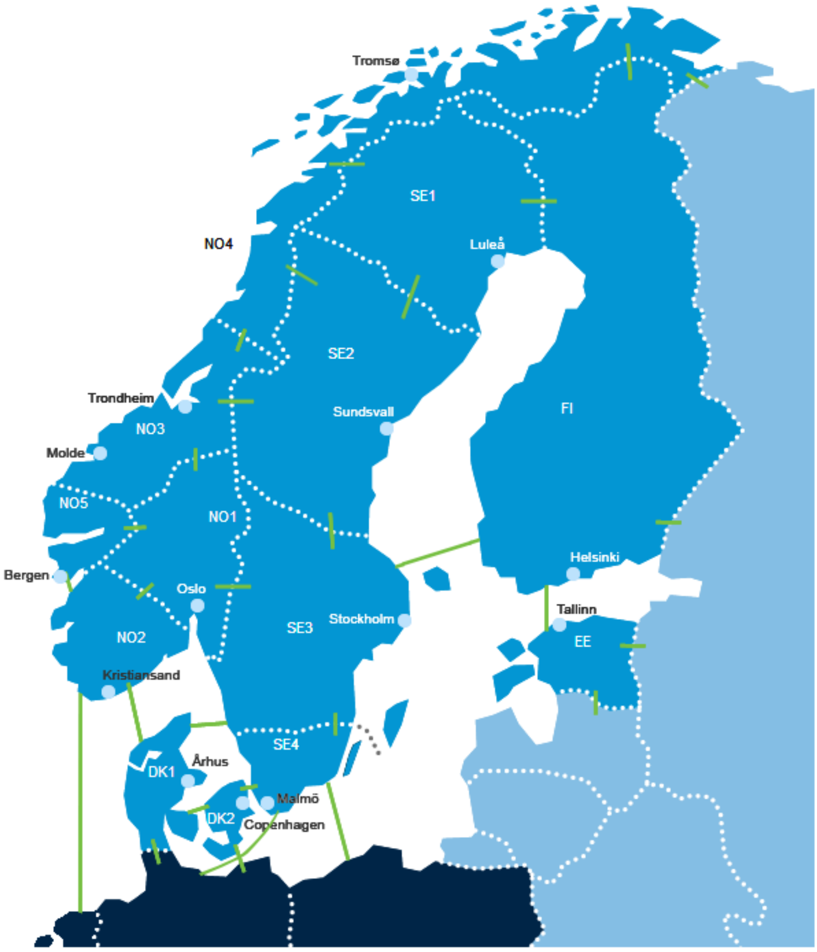


Figure 53. *The Nordic power market areas and its interconnections (64)*

5.4.3.2 Method

Data from Göteborg Energi AB regarding power production of all their facilities was acquired for 2011 with an hourly time resolution. Renova supplied the total amount of energy produced during that year, which then was divided over the hours of the year to approximate an hourly output. For each hour all the production capacities were summed and then subtracted from the demand of that hour, resulting in hourly import capacity requirement. The demand scenario used was the modeled scenario called 2012, presented in the previous section. The production mix was visualized by the help of an area plot including the different production facilities and the import.

The modeled Vindplats Göteborg scenario for 2012 was added to the production mix and hereby the potential decrease in required import capacity could be found.

To be able to calculate the potential CO_2-savings for Vindplats Göteborg it was necessary to determine which electricity producing technology was on the margin. In other words, which technology would lower its production once Vindplats Göteborg is in place. Sweden is transporting power over the national borders in both directions, dependent on season and location in the country. The standpoint was adopted in the project that when Sweden in total is exporting power, the margin technology can be found within the Swedish borders. At the times when Sweden is in a lack of energy, and hence requires imports of power, the margin technology is located abroad. To determine at what times of the year Sweden is importing or exporting energy, data was analyzed concerning electricity transmission within the Nordic system, data collected at Nord Pool Spot (65). Some filtering had to be done to simplify the situation and to have the possibility to draw conclusions. The filter was applied at a few irregularities, e.g. when a long time period of pure import includes one day of export in the middle, that day of export was transformed.

In Sweden the base production of electricity is mainly composed of nuclear and hydro power. Hydro power is also the resource for regulating power, implying that it is the technology on the margin when power export is occurring. Hydro power is associated with zero emissions which entails that no CO_2 will be saved by sparing Hydro power. This viewpoint is specific to this project but many other ways to consider this issue are possible. In the discussion section of this module this subject is further expanded and another way to regard the potential CO_2-savings in this case is presented and discussed. (66)

To be able to analyze what is on the margin when Sweden is importing power; data was collected from Nord Pool Spot regarding power transmission over the borders of the SE3 price area. The data consisted of daily averages for the five different transmission lines connected to the SE3 area, for the whole period Sweden is importing power as a whole. For each transmission line and over the whole time period all transferred power was summed up, for both directions, to determine if the line considered was in total exporting or importing power. The lines resulting in total export, even though Sweden in total imports power, were concluded as not being connected to the region containing the margin production technology, and by that excluded from further analysis. For the power lines resulting in total import, the transmission capacity usage was calculated for every day and an average over the whole time period was thereafter calculated. A conclusion was drawn that the transmission line that was the least used, compared to its full capacity, was connected to the region where the margin technology could be found. Finally in order to find the specific margin technology in that region, data was analyzed from the local energy associations.

5.4.3.3 Results

5.4.3.3.1 Production mix

The current electricity production mix of Göteborg is shown in *Figure 54*.

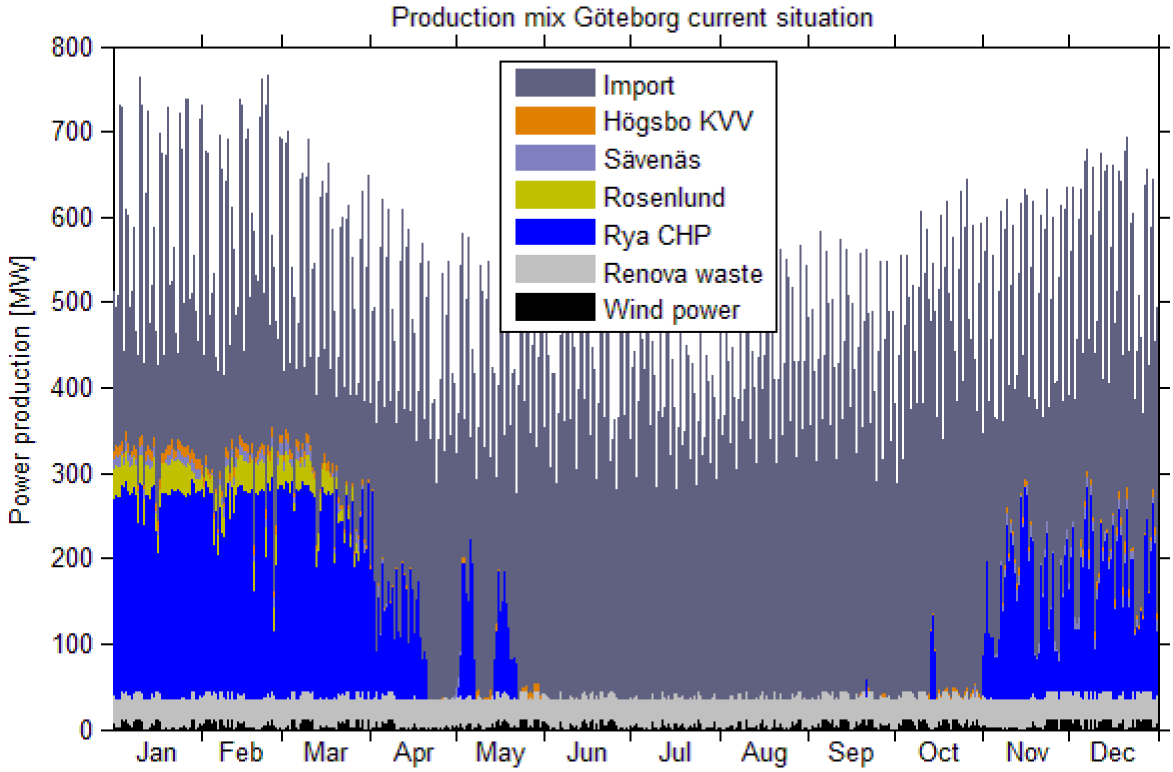


Figure 54. *Current electricity production mix in Göteborg*

It can be clearly seen in *Figure 54* that the majority of the local electricity production stops when the winter is over. Only the wind power and the waste incineration continue over the full year.

The result when adding Vindplats Göteborg to the production mix is visualized in *Figure 55*.

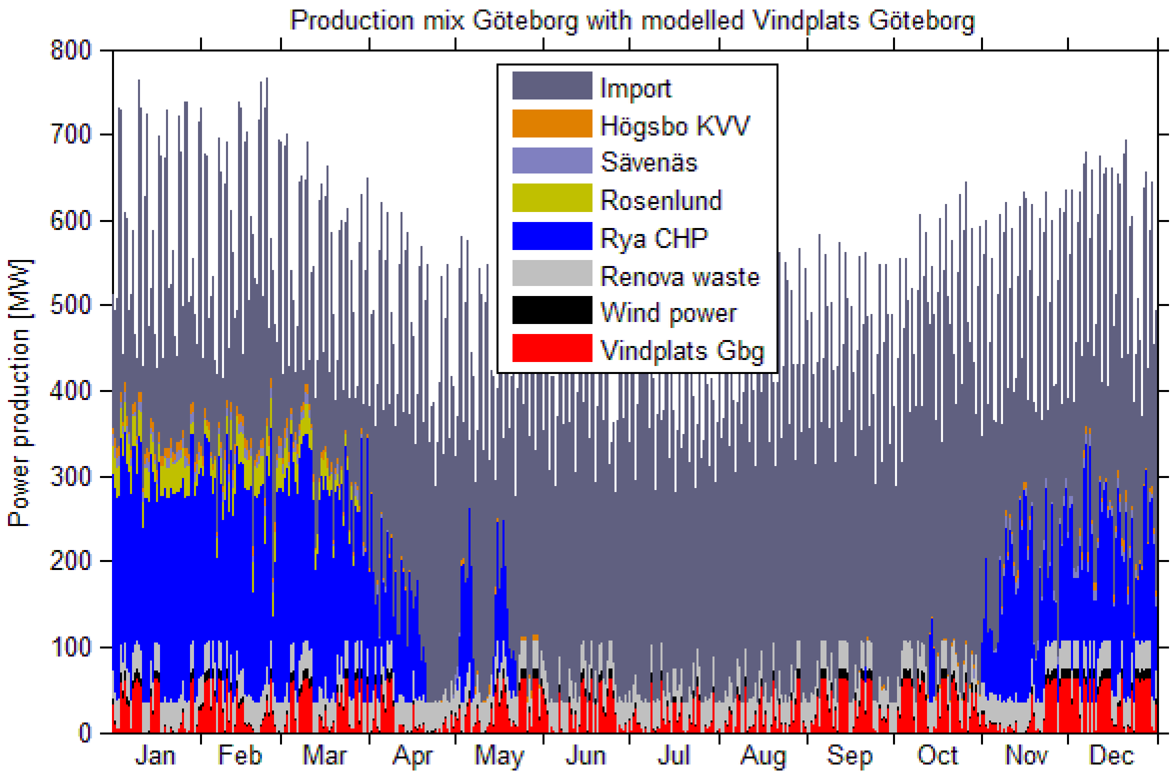


Figure 55. *Electricity production mix in Göteborg with modelled Vindplats Göteborg*

The fluctuating power output of the wind farm become very evident when visualized in the production mix. It also appears that these variations induce larger fluctuations for the power import to fulfill the demand.

The maximum required import capacity for the current case and the case with the added Vindplats Göteborg is presented in *Table 9* with the two respective amounts of energy imported over the year.

Table 9. *Required electricity import*

	Import capacity [MW]	**Energy imported [GWh]**
Current	616	3026
Vindplats Göteborg	611	2818
Difference	***5***	***208***

5.4.3.3.2 Tracing the margin production

In *Figure 56* the import and export pattern of electricity for Sweden over a typical year is presented.

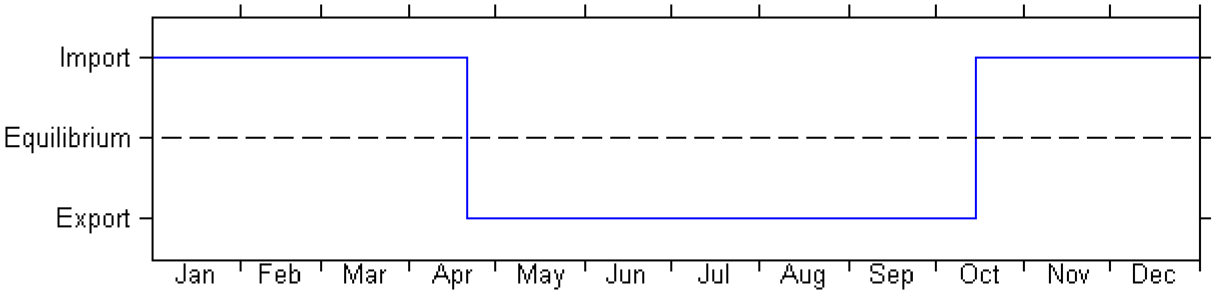


Figure 56. *Electricity import and export in total for Sweden a typical year*

The period of import is hereon called winter and the period of export called summer. In *Table 10* the amount of energy produced by Vindplats Göteborg, and by that not imported and produced from the margin source, is presented for the summer and the winter period respectively.

Table 10. *Seasonally produced electricity from Vindplats Göteborg*

	Winter	**Summer**
Produced electricity [GWh]	117	91

As stated in the method section, the electricity produced at Vindplats Göteborg during summer will not imply any savings in CO_2-emissions since it is only replacing Swedish hydro power. However, during the winter period the production will be replacing a margin source which has to be traced to see whether it is carbon neutral or not.

The sum of the electricity transferred over the transmission lines connected to the SE3 area during the winter period is presented in *Table 11*. Exports are represented with negative numbers, implying that the result will not show the total amount of energy transferred over the lines in both directions but rather if a particular line is dominated by import or export.

Table 11. *Electricity transfer in and out of the SE3 area during winter*

	SE3-SE2	**SE3-SE4**	**SE3-FI**	**SE3-NO1**	**SE3-DK1**
Energy transfer [GWh]	14 391	-9 888	-468	1 597	438
Domination	Import	Export	Export	Import	Import

The connections from SE3 to SE4 and to Finland were by this ruled out as not connected to the margin source, since they have been used mainly for export during the winter. For the other three connections the average transmission capacity usage was calculated for the winter and presented in *Table 12*.

Table 12. *Average transmission capacity usage during winter*

	SE3-SE2	SE3-NO1	SE3-DK1
Maximum transmission capacity [MW]	7300	2145	740
Average usage [%]	63.7	34.4	20.6

As a result the Danish connection seems to be the least preferable to use for SE3 and therefore the margin technology should be found within the Danish electricity production system.

Data was achieved from the Danish Energy Association concerning the electricity production and used fuels (67). The electricity in Denmark is produced primarily by wind power, local Combined Heat and Power plants (CHPs) and Condensing Coal power plants. The wind power produces as long as the wind blows and the local CHPs are an important part of the heating system during the winter. None of these technologies could then be considered as marginal electricity producers. The Condensing Coal power plants are however more easily regulated and by that the conclusion was drawn that marginal electricity producing technology during winters in this project comes from Danish Condensing Coal power plants.

5.4.3.3.3 Potential CO_2-savings

Coefficients used for the calculations:

- Danish coal power plant efficiency (68) = 35%
- Energy content in coal (68) = 32 MJ/kg
- Carbon content in coal (68) = 80%
- Mole mass carbon = 12 g/mol
- Mole mass carbon dioxide = 44 g/mol
- Vindplats Göteborg electricity production during winter (*Table 10*) = 117 GWh

Potential CO2-emissions from coal usage:

$$0.8\left[\frac{kg_C}{kg_{Coal}}\right]\cdot\frac{44}{12}\left[\frac{g_{CO_2}}{g_C}\right]=2.93\,\frac{kg_{CO_2}}{kg_{Coal}}$$

Energy produced per mass of coal, plant efficiency included:

$$0.35[\eta]\ \cdot\ \frac{32\left[\frac{MJ}{kg_{Coal}}\right]}{3.6\left[\frac{MJ}{kWh}\right]} = 3.11\,\frac{kWh}{kg_{Coal}}$$

Potential CO_2-emissions from the Danish coal power:

$$\frac{2.93\left[\frac{kg_{CO_2}}{kg_{Coal}}\right]}{3.11\left[\frac{kWh}{kg_{Coal}}\right]} = 0.94\,\frac{kg_{CO_2}}{kWh}$$

Annual CO2-savings due to Vindplats Göteborg:

$$117[GWh]\ \cdot 10^6 \cdot 0.94\left[\frac{kg_{CO_2}}{kWh}\right] \cdot 10^{-3} = 109\ 980\,\frac{ton_{CO_2}}{year}$$

5.4.3.4 Discussion

On the current production mix situation presented in *Figure 54*, the summer period is clearly characterized by a trough. This phenomenon can be explained by the extensive use of combined heat and power technologies in Göteborg. Rya CHP plant is the largest electricity production facility in Göteborg. It is a combined heat and power plant where heat is the primary energy product. The electricity production in this facility is regarded as a bonus to make the heat production more profitable. It is not running during summers due to the fact that there is no significant heat demand in Göteborg in this period of the year. Running the Rya facility during summers in condensing mode is not profitable, neither out of the economic aspect nor for the local environment. This due to the much lower total efficiency compared to combined heat and power mode. The same argument is applicable for the other thermal facilities in Göteborg.

The result of the electricity import calculations, presented in *Table 9*, deserves a short explanation. The required import capacity of the Vindplats Göteborg scenario is in the model calculated to a 5 MW difference compared to the original scenario. This difference could have been zero as well as up to the whole wind farm capacity, 63 MW. The difference calculated is just a coincidence, dependent on how much the wind is blowing in the model at the time of the maximum peak in the demand. When adding a wind farm of this size to a production mix scenario the change in required import capacity should be regarded as null. It was clear from previous modules that every time this wind farm will be standing still, due to lack of wind, the wind farm will suddenly become invisible in the production mix. This implies that one cannot count on any changes in the required import capacity even after the introduction of Vindplats Göteborg in the energy system. However, the change in the amount of energy imported, calculated to 208 GWh, is reliable since it is calculated on an annual basis.

The electricity import and export pattern of Sweden, i.e. the shape of *Figure 56*, is partly based on spotted trends over the past years. It is very hard to make an average in this aspect and the fact that Sweden exports power during summers and imports power during winters is a generalization. The pattern is in fact very dependent on the weather conditions, e.g. how cold the winter is and how much water is refilled in the hydro power reservoirs. A cold winter implies higher domestic electricity consumption and a low rate of water refill gives a decreased ability to produce electricity by the hydro power. (66)

The CO_2-savings calculated are based on the assumption that when hydro power is on the margin, no CO_2 is saved by decreasing the production at that source. Some people could argue that this should actually entail some CO_2-savings even when hydro power is on the margin. The argument is based on the fact that when the hydro power is decreased during the summer, for instance due to the energy produced from Vindplats Göteborg, water will be saved in the reservoirs. This water can then be used during winters instead, when Danish coal power is on the margin, hence saving CO_2 thanks to the hydro power savings achieved in summer. This fact though, cannot be isolated from other facts regarding the overall characteristic moisture of the year considered and how large the flows have been to the reservoirs. The argument seems legitimate but a calculation based on it would require further investigations.

5.4.4 Conclusion

- The annual electricity demand of Göteborg is 4 247 GWh
- The maximum required power capacity of Göteborg is 784 MW
- The ramp-rates for the electricity consumption is 33.4 MW/min for increase and 35.5 MW/min for decrease
- Current electricity production in Göteborg during summers only consists of wind power and waste incineration at Renova
- With Vindplats Göteborg in place the electricity import will decrease by 208 GWh annually, the import capacity will though remain the same
- Sweden exports electricity during the summer period (6 months) and imports during the winter (6 months)
- The margin technology during summers is Swedish hydro power and Danish coal power during winters
- Annual potential CO_2-savings with Vindplats Göteborg are estimated to approximately 110 000 tons.

5.5 Module 5 – Vehicle to Grid as a back up technology

5.5.1 Objective

The fifth module is an investigation of the Vehicle to Grid (V2G) alternative to compensate the power fluctuations from Hake Fjord. The V2G concept refers to the action of transferring electricity between electric vehicles and the grid. This system requires an extended network offering many possibilities for the drivers to plug their car and an intelligent metering system able to determine the needs and the available capacity in real time (69).

5.5.2 Method

In order to assess the potential of the power compensations offered by the V2G technology, the following plan of study is followed:

- Study of the electric vehicles (EV) available on the market soon
- Investigations on the use of cars in Göteborg
- Assessment of the potential from EVs as energy storage
- Conclusions regarding the feasibility of the implementation of V2G in Göteborg to back-up the Hake Fjord wind farm

5.5.3 EV

Numerous specifications can differ from one model to the other such as the motorization, the type of battery or the converter technology. The current study will however be limited to the specifications that are vital to dimension and evaluate the potential of the whole car fleet to compensate the power fluctuations. The technical details more specifically linked with the car performance, safety or comfort will be left aside.

5.5.3.1 The battery

Among the last models of EV commercially available by the end of 2012, the majority has adopted the lithium-ion (Li-ion) battery. The different points below will try to stress the reasons lying under this choice and explaining the basics on the Li-ion batteries (70).

5.5.3.1.1 Li-ion: the solution for EVs

Figure 57 below is the illustration of the different types of battery compared to each other from a power and an energy density point of view.

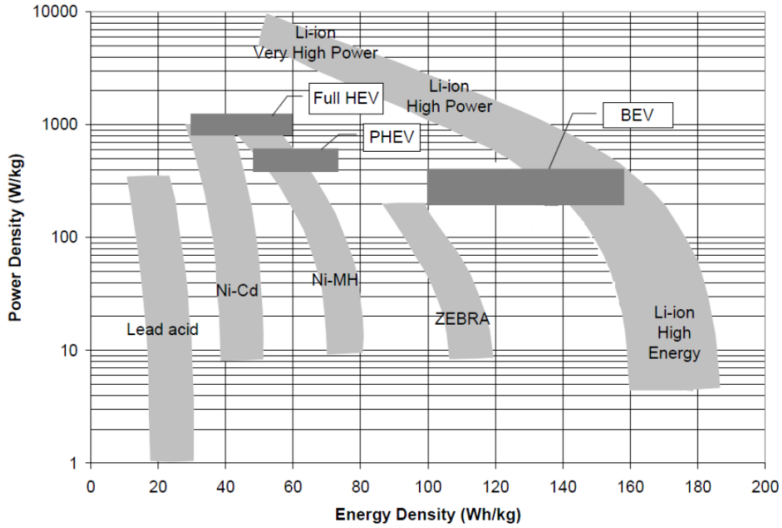


Figure 57. *Comparison of the power and energy densities of different types of battery (71)*

The superiority of Li-ion technology can be observed both in terms of power and energy content. It can be noticed that the hybrid vehicles (HEV) were previously relying on the Nickel technology, but the future fleet of EV (referred to as BEV on the picture) is most likely to adopt the Li-ion battery, because of the extreme dependence of EVs on energy from an autonomy perspective.

Another strength of the Li-ion technology is that it does not suffer from the so called "memory effect" which is in fact a voltage depression entailed by a chemical change creating an additional internal resistance (72). In addition to that, it has been observed that the Li-ion battery is suffering much less from self-discharge than the Nickel or Lead-acid based technologies. The self-discharge is due to internal electro-chemical reactions that can be compared to small loads and entails a 2% discharge per month in a Li-ion battery depending on the temperature (73). As a conclusion, the Li-ion battery requires less maintenance than the other technologies.

Finally the Li-ion battery does not need any formatting, which is the optimization of the capacity by an adequate cycling of charge and discharge following the manufacturing process. This usually occurs during the early utilization phase, the maximal capacity being reached after 50 cycles for Nickel-based batteries. The Li-ion batteries are on the contrary fully operational from the first charge (74).

As a conclusion, the Li-ion based batteries seem to be the adequate choice for EVs, supplying a relatively large amount of power and avoiding any extra maintenance or conditioning during the use phase. This technology however has some improvements to perform concerning the safety of operation and the aging related issues (74).

5.5.3.1.2 A limited number of cycles

The Li-ion battery has a lot of advantages for the EV application but it does suffer from aging problems. There are two different types of aging process: the cycling aging and the aging at rest. The aging at rest is related to the instability of the negative electrode and occurs even when the battery is unused which is why it will not be considered in the present study, being part of the natural life phase of a battery. The cycling aging is however specifically observed when repetitively charging and discharging the battery, meaning that the compensation of wind power will represent an extra duty and will hence have an impact on the battery lifespan (75).

Figure 58 below illustrates the loss of capacity after a certain amount of cycles. It can be observed that this loss of capacity is due to the development of a parasitic internal resistance.

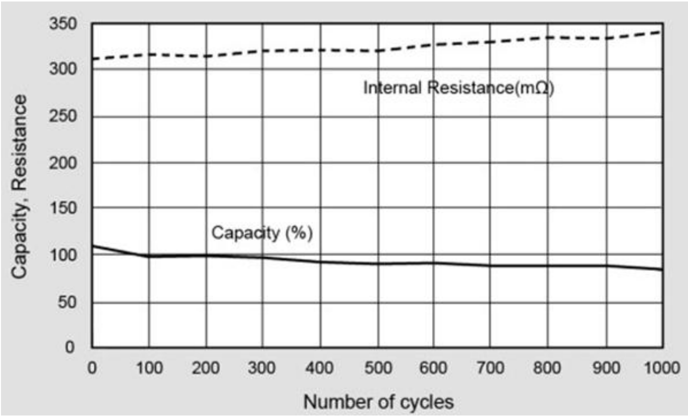


Figure 58. *Cycling aging of a Li-ion battery (76)*

It has been reported that the capacity reduction rate is decreasing with time and enter a stable phase when the Solid/Electrolyte interface is so thick that the electrode corrosion is prevented. Some studies however show that an accelerated capacity fade can occur instead, in case of poor design and improper choice of materials (75).

As a conclusion the Li-ion battery lifetime is dependent on the number of cycles and this issue should be addressed when relying on EVs to compensate wind power fluctuations.

5.5.3.1.3 A sensibility to the charge/discharge current

Another crucial factor to be considered when charging and discharging an EV is the inrush current. Many car manufacturers are underlining the possibility to operate a “fast-charge” of their EV by applying a relatively high current. This has the effect of significantly reducing the amount of time for charging/discharging but has for drawback a negative impact on the battery lifetime. *Figure 59* shows the decreasing number of cycles when applying a stronger current to the battery.

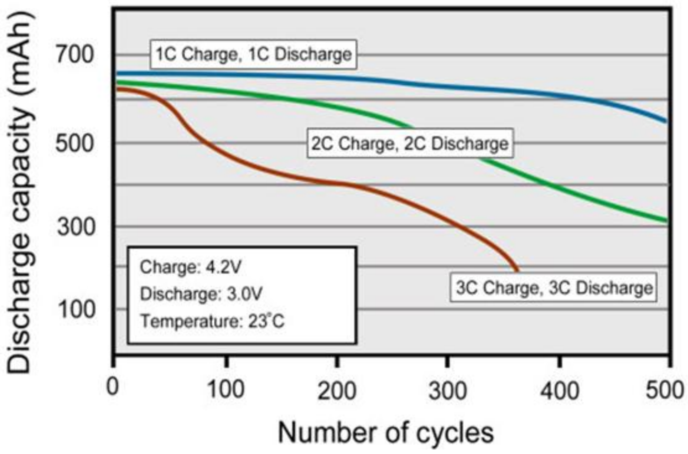


Figure 59. *Influence of the current on the cycling aging for Li-ion batteries (77)*

The term "1C" used here signifies charging or discharging a battery at its rated capacity, meaning 1 A for a 1000 mAh battery, "2C" corresponding to 2 A for the same battery. The charge/discharge of Li-ion battery above 1C should be avoided in order to benefit from the full service life of the device. As a consequence the type of charger considered to connect the EV to the grid for energy storage purposes will use a slow rate (0.1C), the driver still having the choice to fast-charge on his way if needed.

5.5.3.1.4 A strong dependence on the Depth of Discharge

Finally the largest factor dramatically lowering the lifetime of a Li-ion battery is the depth of discharge (DOD), which is the percentage of capacity consumed for one cycle. The larger the DOD and the higher the mechanical stresses are during the charge. The average number of possible full charge/discharge cycles is estimated to 500 whereas more than 4000 cycles could be performed by using only 10% of the battery capacity (78).

The depth of discharge will hence be kept at maximum 50% in the present study in order to preserve the EVs used for energy storage. In other words, this means that the battery of the EVs will be used only from 100% down to 50% of their capacity by the energy utilities.

5.5.3.1.5 The temperature can play a role

Several surveys reveal that the extreme temperatures have a strong influence on the behavior of the Li-ion batteries. When the use of Li-ion batteries was still limited to multimedia applications such as mobile phones or laptops this factor was not of first importance but since this technology is now being considered within the transport area, it might face extreme conditions, especially in Scandinavia.

Because the conductivity of the electrolyte is temperature dependent, the battery starts seeing its maximal capacity reduced under -10ºC, which can be improved by using a proper mix of different electrolytes (79). In the present study, the EVs will be considered to be parked indoor for a certain amount of time already when transferring power to the grid, so that no reduction of capacity due to extreme temperatures is considered.

5.5.3.2 The autonomy

The autonomy plays a key role within the EV industry because it does not only affect the driver habits but also the development of the entire infrastructure to reload the battery. *Table 13* gives the main specifications of the incoming EVs from the largest car manufacturers in Europe.

Table 13. *Autonomy specifications of the coming EVs in Europe (80)*

EV model	Volkswagen Golf blue-e-motion	Renault Zoe ZE	Peugeot ion	Volvo C30 Electric
Consumption [Wh/km]	177	138	125	160
Battery capacity [kWh]	26,5	22	16	24
Range [km]	150	160	130	150

In order to simplify the study, one average EV will be considered to be used in the whole city, consuming 150 Wh/km, equipped with a 25 kWh Li-ion battery and being able to travel 150 km on one charge.
However, according to the Edison survey, a Danish project on electric vehicles in a distributed and integrated market using sustainable energy and open networks, the efficiency of the different components between the EV battery and the network should be taken into consideration. As a consequence a coefficient of 90% efficiency, corresponding to the average charger efficiency, will be considered when calculating the available energy stored into the car fleet. The efficiencies of the battery, the inverter and the motor are here specific to the car performance (81).

5.5.3.3 The ramp rates

The ramp rate capacity is a critical parameter when considering the compensation of wind power. It has been assessed in the module 3 that the wind farm could reach a 0.3 p.u/min ramp-down that needs to be compensated. If the EVs are equipped with Li-ion batteries, a response time of few milliseconds only is needed to deliver the full power (82). Assuming the transmission delay between the EV and the grid is negligible, this signifies that the response time of the batteries is considerably higher than the wind power fluctuations. The ability to back-up Hake Fjord is then determined by the total storage capacity available in Göteborg, the velocity side of the system being compliant already.

5.5.4 Use of cars: Göteborg case study

This chapter helps to assess the situation of the use of cars in the Göteborg area. The long term objective is to calculate the amount of cars needed to back-up Hake Fjord. The different aspects hereafter will help to assess how large the potential of energy storage is in Göteborg.

5.5.4.1 Car fleet in Göteborg

The number of cars in the commune of Göteborg has been gradually increasing for the last decade, reaching 178 448 personal cars in 2011 (83). *Figure 60* reveals the steady rise in the number of cars since 1994.

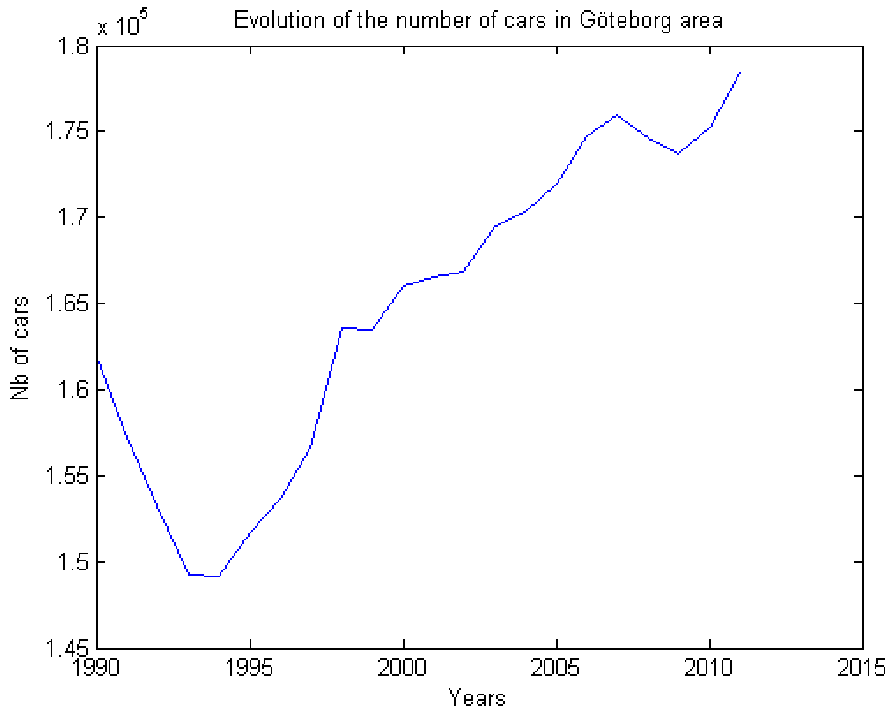


Figure 60. *Increasing number of cars in Göteborg (84)*

The severe drop in the early 1990s may account for the harsh period of recession occurring in Sweden at that time.
As a conclusion the future market of cars in Göteborg is promising and the transport sector seems to benefit from a positive dynamic which is perfectly suitable for the security of supply required by a large energy storage system.

5.5.4.2 Car availability

The car availability is of interest because this accounts for the number of hours a car can be plugged into the grid and be used as an energy storage system. This is hence closely linked with the amount of energy the utilities can dispose of to compensate the fluctuations from Hake Fjord wind farm.
There are different methods to assess the availability of a car. The Edison project (85) relies for example on the Danish national transport data and takes into account the starting and ending time of parking for one car during a day. The car is hence considered to be unavailable when not parked. The result is a minimum availability of 89% of the car every day, which means that the car is most of the time unused.

In the present survey a slightly different approach was adopted in order to be more specific to the region of Göteborg and to have another perspective of the problem. Using the statistics from the city of Göteborg (7), the traffic intensity was assessed in order to obtain the share of cars in motion every hour of the day. *Figure 61* below gives the number of cars passing on the main bridges of the city on a daily basis. It can be observed that two main peaks of activity occur during a day, corresponding to the travel to work at 8a.m and the return to home around 5p.m. As expected the traffic is relatively calm at night, and a minimum activity is maintained during the day. By adding the traffic on the four bridges, a minimum availability of 89% is reached, based on the total number of cars present in Göteborg commune in 2009.

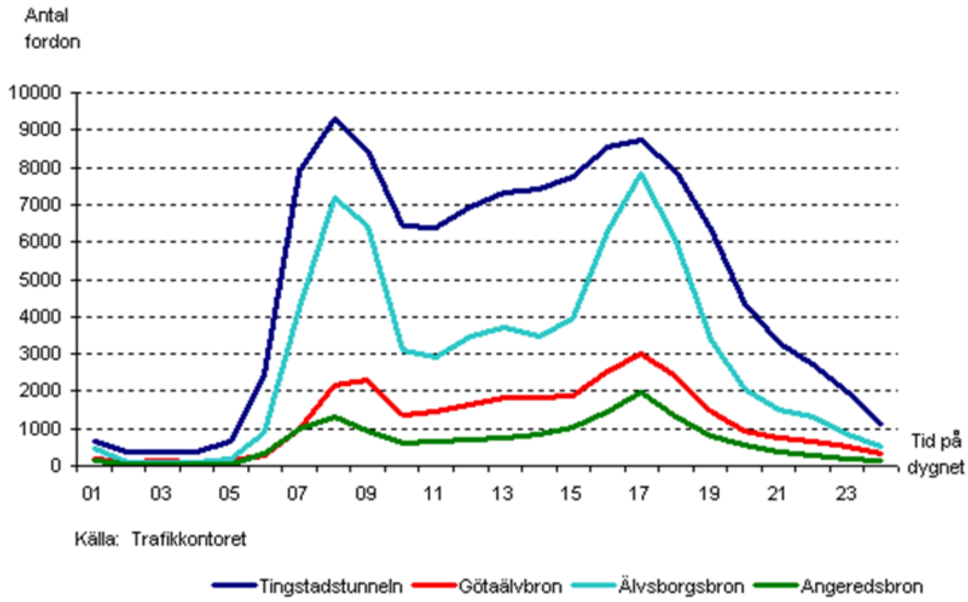


Figure 61. *Daily variation of the traffic over Göta Älv in 2009*

However, this graph is counting all the vehicles passing the different bridges, including public transports, which tends to underestimate the availability of the personal cars. Nonetheless, it does not report the activity occurring in the rest of the city, relatively far from the bridges, which on the contrary gives a more optimistic availability than in reality.

As a conclusion, this approach gives the same car availability as the study carried out in Denmark, and this availability of 89% will be adopted for the rest of the present survey.

5.5.4.3 Daily covered distance

This part has the objective to unveil the average distance driven in Göteborg by the average car. This factor is crucial when assessing the minimal battery load to save for the customers in order to enable them to drive back home every day. Knowing the distance covered by each car in the morning is also a mean to assess the average state of charge (SOC) of the EV when arriving at the office.

According to a recent survey, the average distance between the place of residence and the office was 19km on average in the whole Västra Götaland, meaning 38 km to drive daily during the weekdays (86). With the help of the data from the statistics central office of Sweden, the average distance per year for one car was assessed and corresponds to 36 km per day in Göteborg (87). The difference could be explained by a lower activity during the week-ends or a higher density of population in Göteborg, living closer to their work place. In the present study, the final distance adopted will be the most pessimistic: 38 km/day.

5.5.4.4 Average car lifespan expected

As the use of EV to damper the wind power fluctuations might have a significant impact on the integrity of its batteries, this is important to evaluate the amount of years the driver is expecting to use his car.

The age of the cars in operation in Sweden gives a relatively good idea of how long the drivers expect their car to last. The data from the statistics central office of Sweden enable to determine that the average car model in 2000 was 12 years old (88). The same organization reveals in a more recent survey (89), dated from 2008, that this number was reduced to 8 years. The trend seems to shift towards a faster change of car, which could be explained by a change in the way of consuming or by a strategy from the car manufacturers to reduce the lifespan of their components.
In the following, an average car lifetime of 10 years will be considered. As a consequence, the calculation of the energy available to compensate the wind power fluctuations will take into account this additional limitation in the use of the battery.

5.5.5 Energy storage assessment

This chapter corresponds to the calculation part of this module. It is based on the assumptions made in the previous sections and follows the method used by the Edison project (85).

5.5.5.1 Loading of the EV

During the day, the average EV will face different cycles of charge and discharge either by being used as a car or as energy storage. It is here assumed that every EV will be used up to 50% maximum and will then be charged at home at the end of each day.

5.5.5.1.1 Capacity to load

As mentioned previously, the discharge of batteries below 50% of the capacity might represent a threat for the integrity of the device on the long run, which is why the EV as energy storage will be used only between 100% and 50% of their maximal charge level, the battery level being supposed to be at 50% on average when it is ready to be charged.

5.5.5.1.2 Charging time

Considering a 25 kWh battery capacity, the daily consumption per EV is hence corresponding to 12.5 kWh. The strategy used to load the cars is to use the basic socket present in most of the houses in Göteborg, 230 V and 10 A. The reason of this choice is first the respect of the slow-charging by using a relatively low current and secondly because the infrastructure required to fast-charge the EVs signifies a long process of public acceptance and installation of specific high-current stations in all the houses of EV owners, which is not envisaged in the early stages of the EV penetration.
As a conclusion, 12.5 kWh to be charged with a 2.3 kW socket will take about 5 hours.

5.5.5.1.3 Influence of the electricity prices

The electricity price within the Göteborg area, belonging to the SE3 bidding zone in the Nordpool market, keeps fluctuating throughout the day. *Figure 62* hereafter illustrates these variations for 3 days. The price can reach 50 €/MWh when the consumption is at its maximum in the morning, and almost falls to 30 €/MWh during the night. The average price is reaching about 40 €/MWh.

It is hence expected that the EV owners are likely to charge their vehicle when the lowest prices are available, that is to say at night between midnight and 5a.m.

Nonetheless after calculation, it turns out that the opportunist drivers loading at night will pay 137 € per year for their electricity consumption against 183 € for those who choose to charge their car randomly. This difference of 46 € might not be significant enough to encourage customers to charge by night, especially if it is compared with the annual 1 750 € they used to pay to fuel their conventional diesel vehicle (8 L/100km, 38 km/day and 1.57 €/L).

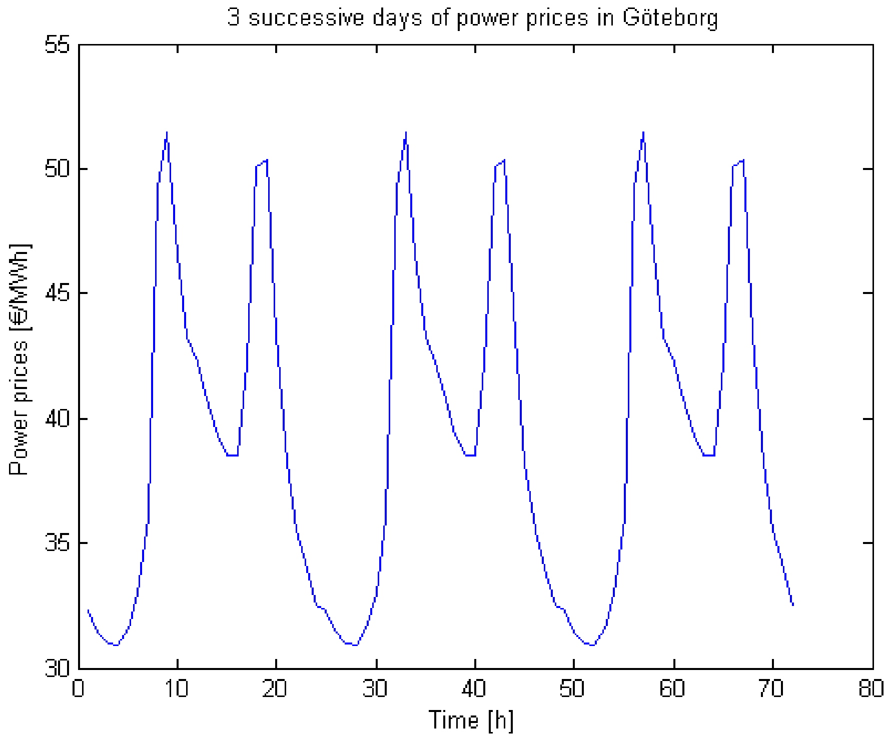


Figure 62. *2011 averaged electricity prices in SE3 for 3 days*

The price of electricity is though expected to rise overtime and depending on the regulation frame imposed for the EV charging at home, the consumption pattern may follow this trend of charging by night. The direct benefit of this consumption pattern is the smoothing of the consumption load, absorbing the peak of activity in the morning by supplying power to the grid, and reloading the capacity when the consumption is low.

5.5.5.2 Impact on the consumption

The electricity consumption of Göteborg also follows a fairly well known pattern, illustrated in *Figure 63*.

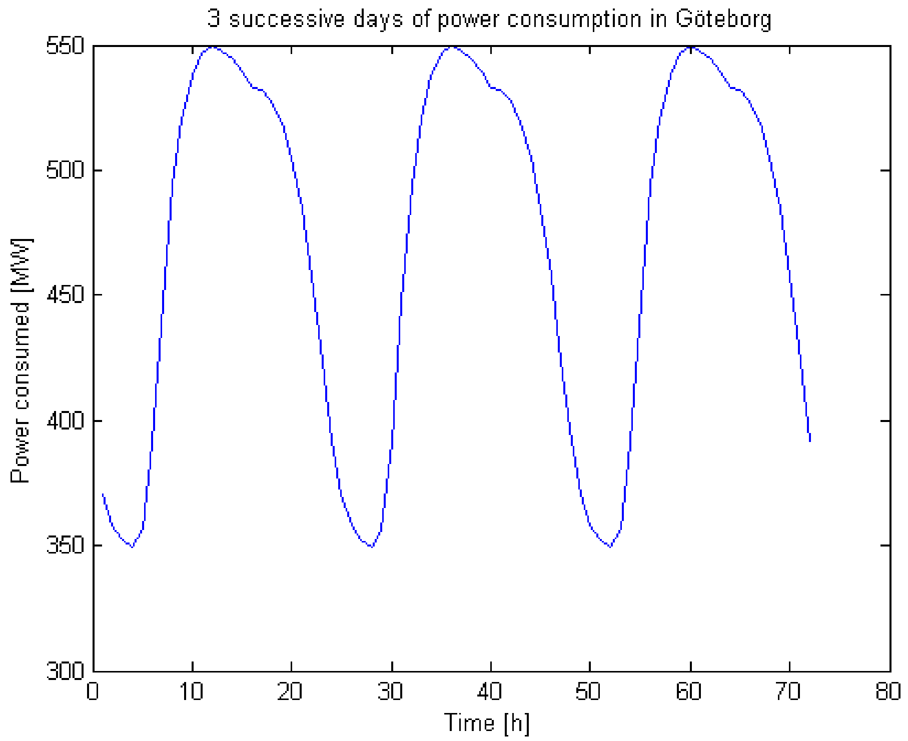


Figure 63. *2011 averaged electricity consumption in Göteborg for 3 days*

The consumption is closely linked with the electricity prices since the periods of high electricity demand entail an increase in prices of electricity, the morning and the evening being the two highest peaks demand of the day. Figure 63 was built by calculating the average consumption day based on the whole year 2011. As a result it does not necessary reflect a typical day because of the dampening of the peaks but it does indicate the general trend of the high peaks demand in terms of hour of occurrence and average amplitude.

Figure 64 below shows how the introduction of EVs will affect the current consumption pattern of Göteborg. The black line represents the original consumption in Göteborg for 3 days as seen above, the blue dashed line is the additional load entailed by charging EVs at night and the red dashed line shows how the consumption would raise in case of charging in the morning.

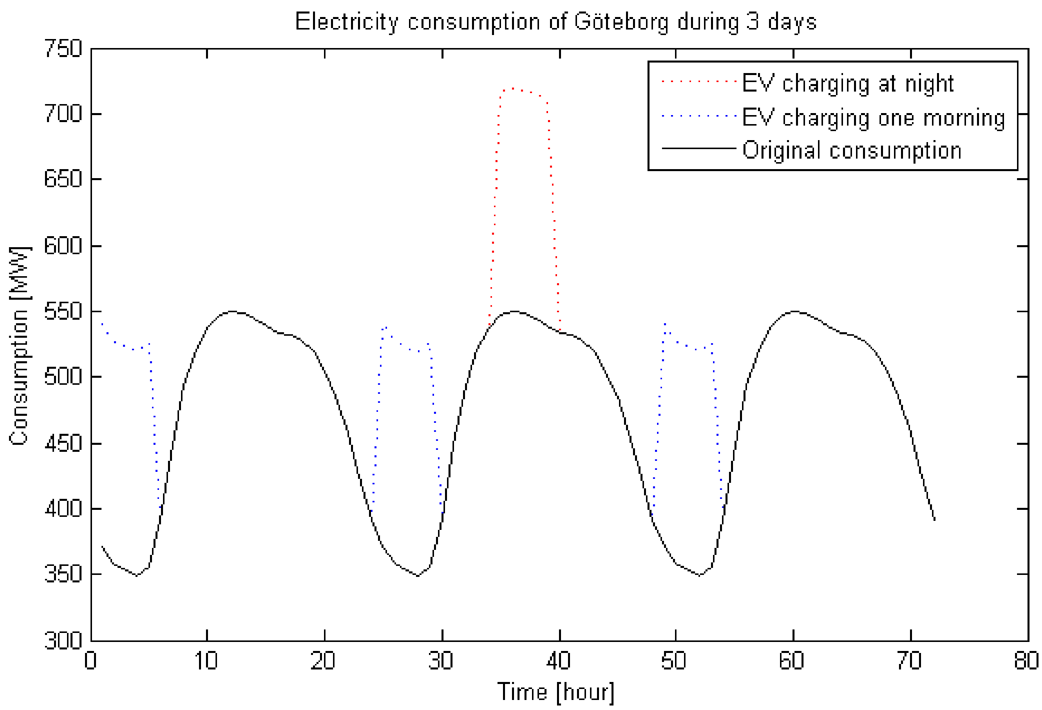


Figure 64. *Introduction of EV in the consumption pattern of Göteborg*

In the hypothesis all cars are being charged at night, 170 MW is the maximum capacity allowed from EVs in order not to exceed the current daily average consumption peak. Adding this capacity of EV will hence raise the consumption at night without exceeding the daily average 550 MW peak.

After further investigations, a maximum electricity consumption of 784 MW peak was recorded in Göteborg area in 2011 (see Module 4), which is 234 MW higher than the daily average consumption peak. As a result, even if all the drivers decide to charge their car in the morning, the total consumption will not reach the current limit of 784 MW.
In order to respect the current transfer capacity limit of Göteborg, the threshold of 170 MW of EV penetration will hence be observed. However, if all the EVs are charged in the morning during a very high demand winter day, the transfer capacity might fail to face the new peak demand even if the total EV fleet only accounts for 170 MW, since the consumption rate would already be maximal and equal to 784 MW. Nonetheless, the probability of all the EVs charging simultaneously is very low, 89% of them being idle, and the coincidence with a very cold morning makes it even less frequent.
To conclude, a total capacity of 170 MW of EVs can be added to the system without any major change in the transfer capacity in the extent that an appropriate regulatory framework can encourage the charge of cars by night. This capacity enables to back-up the entire Hake Fjord production power of 63 MW from an instantaneous point of view. The following section will try to determine how long the EVs can provide an energy back-up to the network before facing an energy outage.

5.5.5.4 Energy reserve from the EVs

The V2G system is a mean to store the energy when the consumption is low and restitute it when the demand is high. Compensating the fluctuations of wind power through the use of V2G implies depending on the wind conditions; if the wind stops blowing for a prolonged period of time, the energy available in the batteries might not be enough to compensate the power outage. In other words, an energy storage system cannot supply energy indefinitely like an energy production system would do, which raises the following questions: how long can the 170 MW of EVs back-up Hake Fjord in case of adverse wind conditions? Is sufficient to last until the next EV charging at night?

5.5.5.4.1 Method

In order to assess how long the 170 MW EVs can back-up Hake Fjord, the wind farm annual production is considered in order to dimension an equivalent energy system which would have 100% availability, which is theoretically the case when implementing an energy storage system.

A model of the Hake Fjord wind farm equipped with 9 Vestas V164 was implemented with Simulink. The input is the wind speed at hub height and the output is the power fluctuation from the whole park. The model was first tested and approved based on the data available from the Vestas V44 at Risholmen. It was then upgraded to the present situation in Hake Fjord, with larger turbines and very low wind conditions to simulate the power outage.

5.5.5.4.2 Results

According to Module 3, it is assumed that the overall energy system composed of Hake Fjord wind farm and V2G system is a 23 MW utility producing with 100% availability throughout the year. Providing 23 MW steadily throughout the year implies that if the wind suddenly stops blowing, the EV batteries are taking over.

A wind episode starting from 20 m/s and ending up below 1 m/s for 1 day was sent into the model. *Figure 65* below shows the decrease in power output from Hake Fjord starting from 63 MW and falling to 0 MW when the wind progressively slows down to less than 1 m/s. The energy system combining Hake Fjord wind farm and V2G in Göteborg has a constant output equal to 23 MW, meaning that the gap between the 23 MW dashed line and the Hake Fjord blue line has to be filled by the energy storage. If power exceeding 23 MW is available, it can be used to balance the load or the frequency of the grid.
A simple integration indicates that 440 MWh of energy storage are required in this specific scenario in order to compensate this low wind episode, and 552 MWh in case of no wind the whole day. Considering the 170 MW of EVs available, this would mean about 74000 vehicles (base on a 2.3 kW socket assumption) representing about 1 285 MWh of energy storage, (counting on 25 kWh per EV, 50% of the daily distance already driven and the other 50% to be available before reaching the 50% SOC and 90% of battery efficiency).

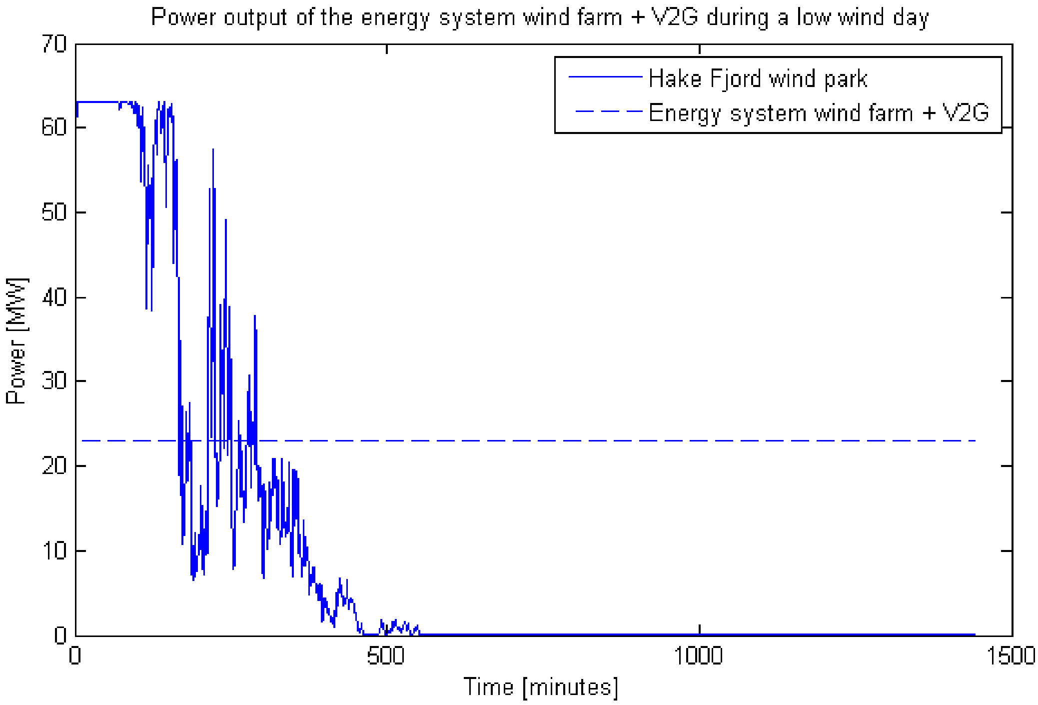


Figure 65. *Low wind speed impact on the energy system wind farm + V2G*

As a conclusion, the present scenario requires 34% of the total energy storage available and 43% in case of 24 hours without wind. This complies with the utilization of the fleet with a maximum 50% DOD. This illustrates the fact that the 170 MW EVs can back-up Hake Fjord on the basis of a 23 MW constant supply energy system during a whole day. It is then assumed that the overall fleet is recharged at night and is ready to face another power outage 5 hours later.

5.5.5.4.3 Discussion

An investigation on the probability of having adverse wind conditions was led. *Figure 66* gives the probability of facing successive hours of extreme winds, either below the cut-in speed of 4 m/s or above the cut-out speed of 25 m/s.

The histogram stresses the scarcity of extreme wind conditions episodes that would involve a shut-down of the wind farm for few hours. It appears that more than 24 successive hours power outage has a very low probability.

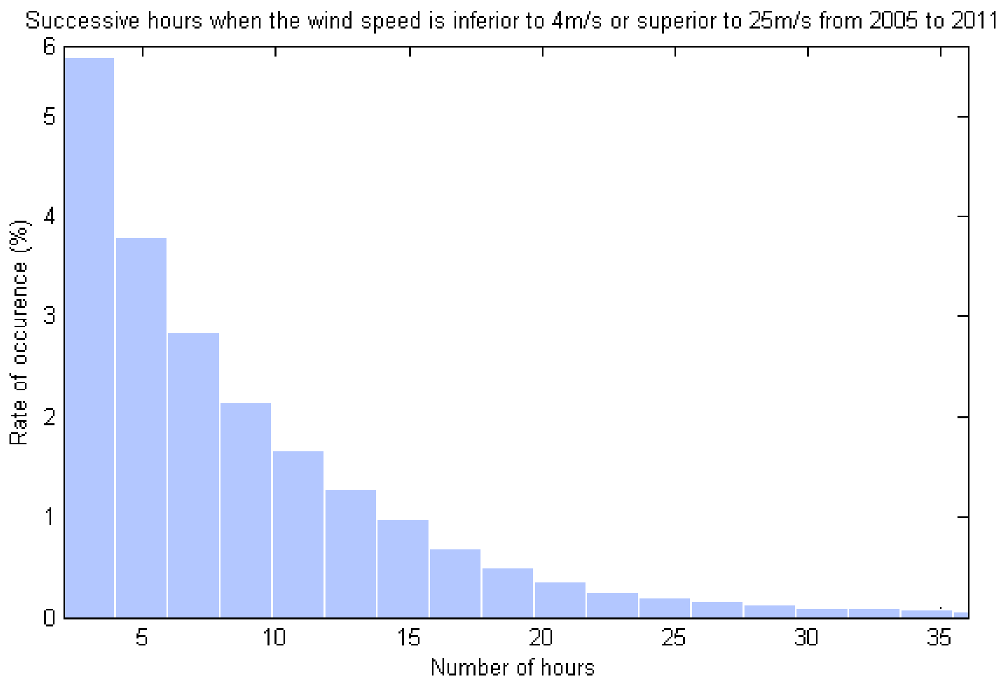


Figure 66. *Probability of having successive hours of extreme wind conditions in Hake Fjord*

However, the extreme conditions are not the only one requiring energy storage. As the wind farm starts producing 23 MW only from 8 m/s, this means that all the periods characterized by lower wind speeds than 8 m/s should be studied. The analysis of the Risholmen data shows that the number of 24-hour episodes where wind speeds below 8 m/s are observed is slightly higher and may justify the need of an auxiliary production system able to back-up the combined wind farm and V2G systems.

5.5.6 Conclusion

The V2G system benefits from a very fast response and a high availability. Introducing 170 MW into the system could back-up a power outage for 24 hours, which is not occurring frequently. The constant power supply of 23 MW would be ensured while respecting the integrity of the batteries and the autonomy of the drivers.

In order to provide 170 MW through the V2G system, about 84 000 vehicles are needed taking the car availability into account, which corresponds to 47% of the current car fleet of Göteborg today. This penetration rate is relatively high withstanding the fact that 23MW represents only 5% of the average electricity consumption. However, the assumptions made concerning the reasonable DOD are very pessimistic and future breakthroughs within the field of Li-ion batteries would considerably increase the potential from V2G.

The V2G is an energy storage system and cannot compensate the power outage indefinitely. Depending on the future wind power capacity expected in Göteborg area, a need for a production back-up facility might be necessary, and would try to follow the wind power fluctuations at a lower rate. Moreover, the larger the wind power capacity and the lower the fluctuations, which indicates that the requirements of fast-response for this additional production back-up will not necessary be as high as for the battery, especially since the EVs could be handle the gap when needed. The introduction of an additional production system would hence decrease the very large amount of cars required for a stand-alone V2G system and could even benefit from this fast-response reserve to follow the wind fluctuations.

Finally the lifetime of the EVs was assumed to be 10 years and this should be compatible with a 50% use of the battery. However, deeper investigations are required if a V2G system is likely to be designed in Göteborg. The amplitude and the number of the charge/discharge cycles, having a negative impact on the lifetime, are expected to decrease with the rise of the EV and the wind penetration. Moreover, the improvement of the durability of the batteries is today being challenged in the industry and might lead to significant improvements to decrease the relative need for EVs to compensate the power fluctuations.

5.6 Module 6 – Rya CHP plant as a back-up technology

5.6.1 Objective

In Göteborg today the largest electricity producing facility is Rya CHP plant, owned by Göteborg Energi AB. Rya entered into operation in 2006 and is a natural gas combined cycle with combined heat and power production (NGCC CHP) (90). In this module the Rya CHP plant is examined to conclude on the possibilities to use this facility as a balancing technology for the fluctuating power output of Vindplats Göteborg. Investigations have been performed in the annual running pattern of the facility to see if there is any available capacity over the year. Another important parameter investigated is the ramp-rate; is it possible to change the power output fast enough to match the changes in the wind power and how are other parameters, e.g. turbine lifetime, affected by this fast ramping?

5.6.2 Method

Technical specifications and running data have been achieved from Göteborg Energi AB. This information combined with a study visit and the meeting with the process engineers at the Rya facility constitute the basis of this module (91).

5.6.3 Technical specification

Rya CHP plant runs on natural gas, delivered by pipeline from Denmark and Germany, and it consists of three gas turbines, three heat recovery steam generators (HRSG) with supplementary firing and one steam turbine. The natural gas is combusted with compressed air in the gas turbines. The flue gases are then passing through the HRSG, where the heat is used to boil water that further ahead is running the steam turbine. Heat exchange to the incoming cold district heating water is done at the end of the HRSG and after the steam turbine as well to condensate the feedwater (90). Additional details on the plant specifications and operation are available in Appendix B. Output specifications are presented hereafter:

- Gas turbine model: Siemens SGT-800 (90)
  Minimum individual output: 20 MW_{el}
  Maximum individual output: 42 MW_{el}
- Steam turbine model: Siemens SST-900 (90)
  Minimum output: 8 MW_{el}
  Maximum output: 130 MW_{el}
- Total Rya minimum electricity output: 20 MW_{el}
  Total Rya maximum electricity output: 256 MW_{el}
- Total Rya maximum heat output: 290 MW_{heat} (90)

The facility operates mainly at high levels of both electricity and heat output, with a power-to-heat ratio of around 0.9. The electrical efficiency is 43.5% while the total efficiency is 92.5%. (90)

5.6.4 Available capacity

Rya CHP plant is primarily seen by Göteborg Energi AB as a heat producing facility where the electricity production is regarded as a bonus product that will make the heat production more profitable. Rya is one of many heat production facilities in the Göteborg Energi AB district heating grid, implying that the operation of Rya is linked to how these other facilities are running. At Göteborg Energi AB a special team called Ekonomiskt Kontrollrum plans the heat production at least 7 days ahead. The heat demand is forecasted by this team as well as a wide range of other parameters such as prices for biomass, oil, natural gas and electricity. This forecast makes a hierarchy of all the heat production facilities within Göteborg, ranging from the cheapest to the most expensive technology, and the heat demand will determine which of them, and at what level they will be running. By this it stands clear that Rya will be used to its maximum at times of low natural gas price and high electricity price, in relation with the fuel prices of the other facilities. The operation of Rya CHP plant during 2011 is visualized in *Figure 67* (92).

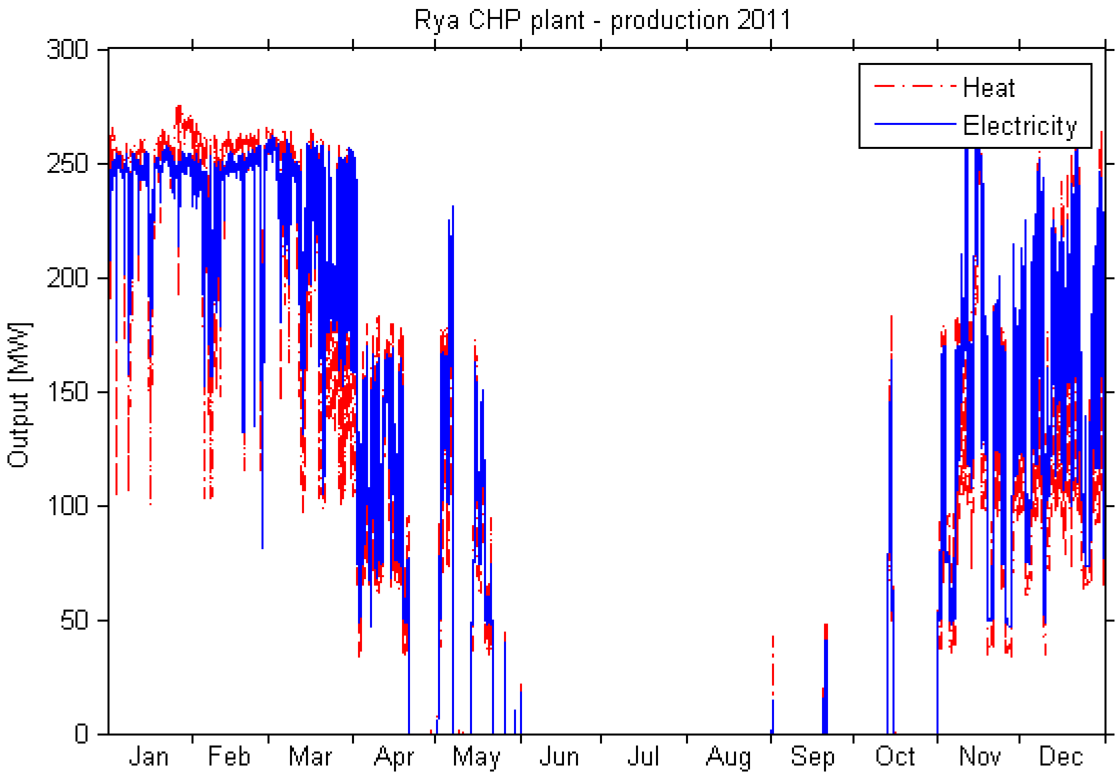


Figure 67. *Rya CHP plant heat and power production during 2011*

With *Figure 67* it becomes clear that Rya CHP plant is not in operation during summers. There is not enough heat demand in Göteborg to keep the facility running. At the end of March the facility gradually stops, first by taking the steam turbine out of operation and then occasionally the gas turbines. During the summer maintenance and eventual upgrades are performed and the production then generally starts up again in November, in relation to a colder climate and by that increasing heat demand (91).

If instead of having the heat demand as the determining factor of the operation, the electricity demand is used, i.e. the fluctuating power output of Vindplats Göteborg, the annual operation pattern would then look different. As it is now, there is no available electrical capacity at Rya during winter. The capacity of the energy system composed of Vindplats Göteborg and its back-up is 23 MW_{el}, implying that the maximum usage of Rya has to be decreased by that amount so that the facility has this capacity available in case of sudden low wind. To do such an operation would then cause problems for the heat production planners.

One strategy to solve the problem would be to invest in a heat accumulation tank. The required capacity should be 26 MW_{heat}, this due to that the electrical decrease is 23 MW_{el} and the power-to-heat ratio 0.9. This strategy is comparable to the 90 MSEK investments done by Borås Energi in a heat accumulator (93). That price tag gave a tank that fits 1700 MWh_{heat}, which is slightly higher than a 26 MW_{heat} delivery during 65 hours (94).

Another strategy to make electrical capacity available during winters at Rya would be, instead of lowering the used capacity, to construct more capacity. In the Rya facility there is available space to fit in a fourth gas turbine line. Such an investment would then make both more electricity and heat available and it would be possible to manage it aside from the steam cycle (91).

The problem still stands during the summer though. The heat demand is not sufficient to run the facility at all. Operating in cogeneration mode is not an option, which gets clear when looking at the 43.5% electrical efficiency. Rya CHP plant is designed to produce both heat and electricity with a power-to-heat ratio of 0.9, which then gives a satisfying total efficiency.

5.6.5 Ramp-rate

The ramp-rate of Rya CHP plant depends on what parts of the facility are in operation, which in its turn depends on the desired level of electrical output. Rya can be operated in many different combinations; 1, 2 or 3 gas turbines together or without the steam turbine, the supplementary firing also being optional after each gas turbine. Each turbine has a fixed maximum value for ramping, determined by the manufacturer Siemens. When that limit is kept, no problems should occur regarding eventual impacts on lifetime, increase of emissions or other operational depending parameters (90).

- Ramp-rate gas turbine: 3 MW_{el}/min
- Ramp-rate steam turbine: 1 MW_{el}/min

In order to have a simplified visualization of the full facility ramp-rate, *Figure 68* displays four different operation modes on a chart. From the left to the right the boxes represent the cases of 1, 2 and 3 gas turbines in operation. The fourth box is the case of three gas turbines in operation combined with the steam turbine.

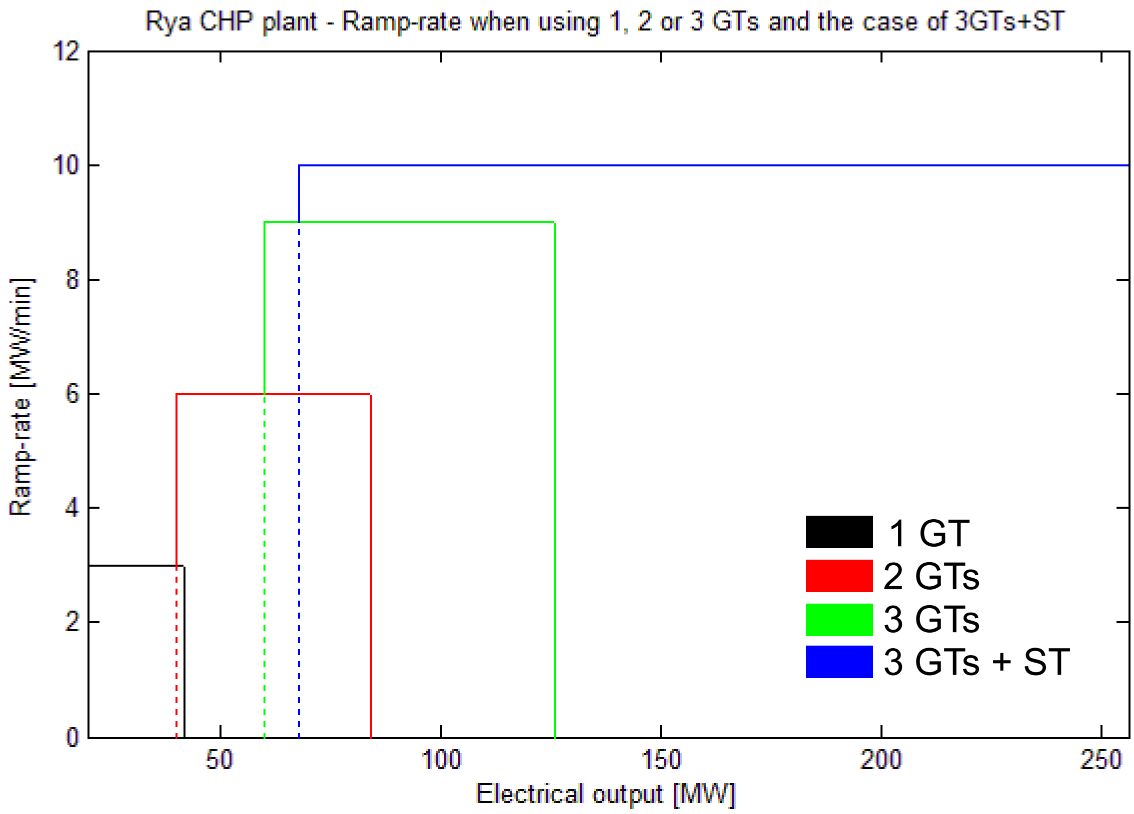


Figure 68. *Rya CHP plant ramp-rate when using 1, 2 or 3 GT's and the case of 3 GT's+ST*

As previously mentioned, the most common case for Rya is high output operation. This implies that all three gas turbines are in operation and combined with the steam turbine. This mode gives a ramp-rate for the facility of 10 MW/min within lower limit of 68 MW_{el} output to upper limit of 256 MW_{el}. The supplementary firing units go into operation when the gas turbines individually exceed a 35 MW_{el} output (91). This will not affect the ramp-rate and is performed to keep a proper heat supply to the steam boiler.

The presented ramp-rate of 10 MW/min will not be enough to cover the demand from Vindplats Göteborg, determined to be 20 MW/min in the worst cases. What could be done at Rya would be to investigate the possibilities of modifying the existing gas turbines. Gain in ramp-rate could be achieved by adding by-pass dampers between the gas turbines and the HRSG's (91). The other possibility is to invest in this previously mentioned fourth gas turbine line, which would be designed for high ramp-rate operations. The three gas-turbines in place now are specially designed for stable high output operation and they do not have enough ability to ramp-up fast.

5.6.6 Discussion

As Rya CHP plant is operating now, it is not a candidate for being a back-up technology in service for Vindplats Göteborg, both regarding ramp-rate and available capacity. The main problem is that the operation plan for Rya is determined by the heat demand and how to fulfill that demand in the most cost efficient way. Unless the electricity demand, i.e. the power fluctuations from Vindplats Göteborg, becomes more important Rya CHP plant will never work well as a back-up technology for wind power.

The technology of the combi-cycle, combining gas turbines with steam turbines, is though a very efficient technique. Rya CHP plant was optimized for heat production and was built to have a total efficiency as high as possible, one of the greatest in the world when the facility came into operation. Research and development in the area of the combi-cycle is progressing and one interesting example is the FlexEfficiency Combi-Cycle by General Electrics. This facility is developed for the modern market that sets requirements on both efficiency and ramp-rates. The FlexEfficiency Combi-Cycle has an electrical efficiency of 61% and can still ramp 50 MW/min (95). Rya CHP plant will never perform in that division, but with investments in reconstruction the numbers have the potential to improve.

5.6.7 Conclusion

- Electrical capacity is not available at Rya CHP plant to serve as a back-up for Vindplats Göteborg
- Capacity could be created by investing in the retrofit of Rya, but the problem would still stand during the summers regarding the profitability of running the facility at all during this period
- The ramp-rate is determined to be 10 MW/min in the interval 68 - 256 MW_{el}
- The ramp-rate is not enough to cover the worst case scenario at Vindplats Göteborg, but could here as well significantly be improved

6 Conclusion

- To locate the Vindplats Göteborg project in Hake fjord seems to be a good choice. With the layout produced in this thesis project the annual production target of 200 GWh will be reached by 9 Vestas V164 wind turbines.
- Using a Vehicle-to-Grid system as a back-up for the fluctuating wind power could work in theory regarding the ability to charge and discharge fast enough. However in order to reach the needed capacity to compensate only Vindplats Göteborg wind farm, up to 84000 electric vehicles are required.
- Rya NGCC is not well suited as a back-up for the wind power fluctuations. The available capacity is not sufficient but could be improved by investing. The ramp-rate is sufficient for the standard fluctuations but not the extreme peaks. As it is operated today, it is not profitable to run the facility during summers because of the lack of heat demand.

7 Discussion

As it is shown in this report, Hake fjord is a good location for a wind farm. The most profitable investment would be to use a few large capacity turbines in comparison with a larger amount of smaller capacity turbines. This could though cause problems with the public acceptance since the turbines will be spotted from a larger distance due to the height. On the other hand this kind of farm will allow for a much wider distance in between the turbines. The area in Hake fjord is used a lot for boat tourism and professional sailing and the fact regarding the distance between turbines would be positive in this aspect.

None of the proposed back-up systems are about to become reality in the near future. The V2G system requires too many electric vehicles in Göteborg, a penetration level of around 50%, and the Rya CHP plant system requires too much investment to increase both capacity and ramp-rate. However, there is a possibility for these two technologies to work together in a combined system, a system that would not be too far away in the future due to lower investment required. The strength of the V2G system is that it has a very fast response time, which can quickly reply to the extreme ramp-downs occurring at the wind farm. To make electrical capacity available at Rya CHP plant investments are required, but not as large as if the ramp-rate had to be improved too. The investments would be made to secure the heat supply at Rya, while making electrical capacity available as back-up for the wind farm. In practice when the wind farm is ramping down fast, the V2G system would back-up for a few minutes and then the Rya CHP plant system would be ready and serve as back-up instead. This combined system implies that much less electrical vehicles would be required at the same time as no investments to increase the ramp-rate at Rya CHP plant is required.

As an example, if the wind power outage simulated in module 5 is considered (see *Figure 65*), and a 50% use of the EV batteries is assumed, this means that 72 000 cars are needed (making all the restricting assumptions from module 5) to back-up this outage if the energy system only encompasses Vindplats Göteborg and the V2G system. The Rya CHP plant is now introduced in the system (in Simulink) with a ramp-rate of 1.6 MW/min, which is 60 times less than the maximum possibility of the plant and also corresponds to the variation daily experienced at Rya CHP plant today. *Figure 69* below shows the same decrease in wind power from Vindplats Göteborg as in *Figure 65* but also displays in red Rya CHP plant backing up the system when Vindplats Göteborg production is under 23 MW. After integration of the difference between the wind farm combined with Rya and the 23 MW line, it appears that only 7.7 MWh of storage are now needed instead of 440 MWh without Rya presented in module 5. This 7.7 MWh corresponds to 1 414 EVs only, meaning 8% of the current Göteborg car fleet.

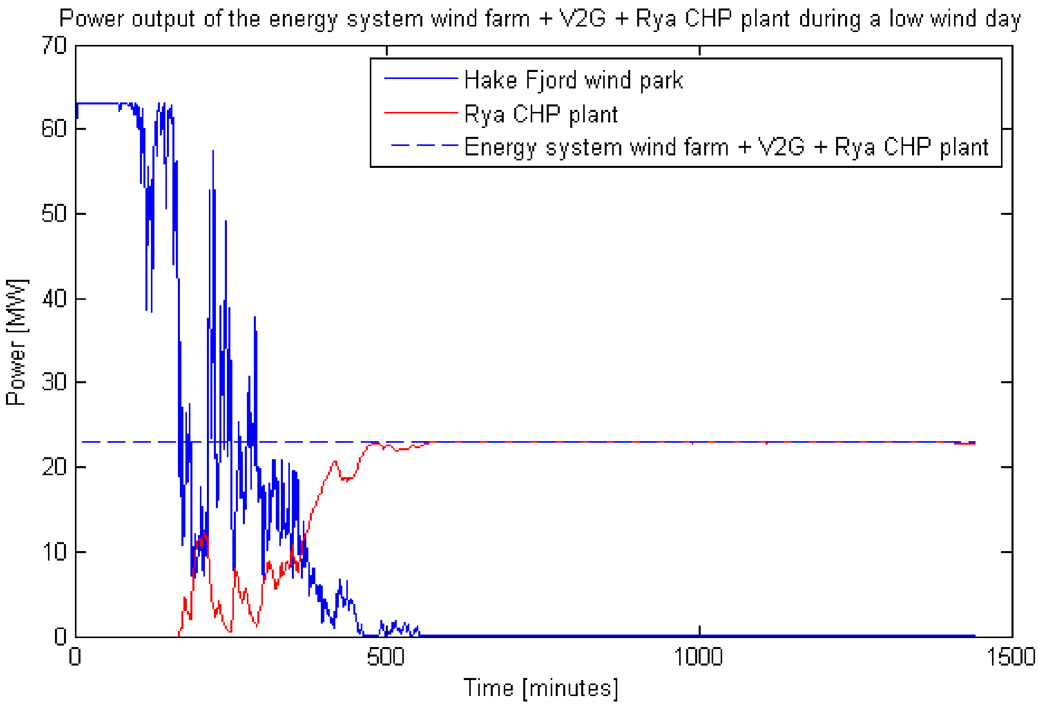


Figure 69. *Low wind speed impact on the energy system wind farm + V2G + Rya CHP plant*

As a result, this example illustrates the potential of combining the two back-up technologies considered in this study to compensate the fluctuations from Vindplats Göteborg. Considering the further expansion of wind power and EVs in Göteborg, the compensation of the city consumption fluctuations could even be envisioned, all the more that the use of V2G system already gives a smoother consumption pattern.

With the future wind power capacity expected in Europe, the need for energy storage to ensure the quality and safety of supply is increasing and the combination of thermal power plants and energy storage might be a promising transition technology to shift towards a more flexible electric network.

References

1. Göteborg Energi AB. Nu laddar vi Göteborg för elfordon. [retrieved: 2012-05-07]. Accessible at: http://www.goteborgenergi.se/Privat/Projekt_och_etableringar/Smarta_elnat/Laddning_for_eldrivna_fordon.

2. Kjaer C, Zervos A. Pure Power, wind energy targets for 2020 and 2030. 2011 [retrieved: 2012-05-08]. Accessible at: http://www.ewea.org/fileadmin/ewea_documents/documents/publications/reports/Pure_Power_III.pdf.

3. Market observatory for energy. Europe's energy position markets and supply. 2009 [retrieved: 2012-05-09]. Accessible at: http://www.energy.eu/publications/KOAE09001_002.pdf.

4. EWEA. Wind Energy and the Grid. [retrieved: 2012-05-09]. Accessible at: http://www.ewea.org/index.php?id=196.

5. Statens energimyndighet. Energy in Sweden 2011. 2011 [retrieved: 2012-05-10]. Accessible at: http://www.energimyndigheten.se/en/Press/News/New-publication-Energy-in-Sweden-2011/.

6. Svenska Kraftnät. Annual report 2010. 2010 [retrieved: 2012-05-10]. Accessible at: http://www.svk.se/PageFiles/44158/uppslag_SvK%20Annual%20report%202010.pdf.

7. Göteborgs stad. Statistik årsbok Göteborg 2012. 2012 [retrieved: 2012-04-25]. Accessible at: http://www4.goteborg.se/prod/sk/statistik/statistikR5.nsf.

8. Railbookers. Holidays in Sweden. [retrieved: 2012-05-14]. Accessible at: http://www.railbookers.com/holidays/europe/sweden.

9. Göteborg Energi AB. Naturlig el. [retrieved: 2012-05-14]. Accessible at: http://www.goteborgenergi.se/Foretag/Projekt_och_etableringar/Fornyelsebar_energi/Vindkraft.

10. Göteborg Energi AB. Vindplats Göteborg, en del av ett hållbart Göteborg samrådsunderlag enligt miljöbalken. 2012 [retrieved: 2012-05-15]. Accessible at: http://www.vindplatsgoteborg.se/doc/SAMRADSUNDERLAG_2012.pdf.

11. Eniro. Sjökort. [retrieved: 2012-05-15]. Accessible at: http://kartor.eniro.se/query?what=maps&search_word=&geo_area=g%C3%B6teborg&from=.

12. SMHI. Vad gör SMHI? 2011 [retrieved: 2012-03-08]. Accessible at: http://www.smhi.se/omsmhi/Om-SMHI/vad-gor-smhi-1.8125.

13. MathWorks. MATLAB The Language of Technical Computing. 2012 [retrieved: 2012-03-08]. Accessible at: http://www.mathworks.se/products/matlab/.

14. SMHI. Vind – Varför blåser det? 2011 [retrieved: 2012-02-17]. Accessible at: http://www.smhi.se/kunskapsbanken/meteorologi/vind-varfor-blaser-det-1.362.

15. Argyriadis K, Germanischer L. Wind conditions for offshore wind turbine design RECOFF, comparison of standards and regulations. [retrieved: 2012-02-24]. Accessible at: Accessible at: http://www.risoe.dk/vea/recoff/Documents/Sec_7/RECOFFdoc032.pdf.

16. MathWorks. Product documentation. [retrieved: 2012-02-28]. Accessible at: http://www.mathworks.se/help/toolbox/stats/brn2ivz-158.html.

17. Bhattacharya P. A study on Weibull distribution for estimating the parameters. [retrieved: 2012-02-28]. Accessible at: http://jaqm.ro/issues/volume-5,issue-2/pdfs/bhattacharya.pdf.

18. Zheng R, Zhong J. Generation Adequacy Assessment for Power. IEEE PES Innovative Smart Grid Technologies Conference; 2010.

19. Bayar T. World Wind Market: Record Installations, But Growth Rates Still Falling. 2011 [retrieved: 2012-02-15]. Accessible at: http://www.renewableenergyworld.com/rea/news/article/2011/08/world-wind-market-record-installations-but-growth-rates-still-falling?cmpid=rss.

20. Vestas Wind Systems A/S. V112-3.0 MW Offshore. 2010 [retrieved: 2012-02-15]. Accessible at: http://www.vestas.com/en/media/brochures.aspx.

21. Vestas Wind Systems A/S. V164 7.0 MW. 2011 [retrieved: 2012-02-15]. Accessible at: http://www.vestas.com/en/media/brochures.aspx.

22. Repower. Bewährte Technologie in neuen Dimensionen. [retrieved: 2012-02-15]. Accessible at: http://www.repower.de/fileadmin/download/produkte/RE_PP_5M_de.pdf.

23. Enercon GmBH. Wind energy converters, product overview. 2010 [retrieved: 2012-02-15]. Accessible at: http://www.enercon.de/p/downloads/EN_Productoverview_0710.pdf.

24. Vattenfall Vindkraft 2009. Lillgrund vindkraftpark, ett svensk pilotprojekt inom havsbaserad vindkraft. Fälth & Hässler; 2009.

25. Sørensen P, Cutululis N.A, Vigueras-Rodríguez A, Madsen H, Pinson P, Jensen L.E, Hjerrild J, Donovan M. Modelling of Power Fluctuations from Large Offshore Wind Farms. 2007 [retrieved: 2012-02-28]. Accessible at: http://onlinelibrary.wiley.com/doi/10.1002/we.246/abstract.

26. Sørensen P, Cutululis N.A, Vigueras-Rodríguez A, Madsen H, Pinson P, Jensen L.E, Hjerrild J, Donovan M. Power Fluctuations From Large Wind Farms. IEEE Transactions on Power Systems; 2007.

27. Morthorst P.E, Auer H., Garrad A., Blanco I. The Economics of Wind Power. 2009 [retrieved: 2012-02-21]. Accessible at: http://www.wind-energy-the-facts.org/documents/download/Chapter3.pdf.

28. Middelgrundens Vindmöllelaug. About Middelgrunden Wind Cooperative. [retrieved: 2012-02-21]. Accessible at: http://www.middelgrunden.dk/middelgrunden/?q=en/node/35.

29. E.ON Climate & Renewables. Factbook E.ON sur l'éolien offshore. 2011 [retrieved: 2012-02-16]. Accessible at: http://www.eon-france.com/pages/efr_fr/Activits/Les_nergies_renouvelables/.

30. Hammar L, Andersson S, Rosenberg R. Adapting offshore wind power foundations to local environment. 2010 [retrieved: 2012-02-16]. Accessible at: http://www.naturvardsverket.se/Start/Om-Naturvardsverket/Vara-publikationer/ISBN1/6300/978-91-620-6367-2/.

31. Kaiser M.J, Snyder B. Offshore Wind Energy Installation and Decommissioning Cost Estimation in the U.S. Outer Continental Shelf. 2010 [retrieved: 2012-02-16]. Accessible at: http://www.boemre.gov/tarprojects/648/aa.pdf.

32. The International Association of Engineering Insurers. Engineering Insurance of Offshore Wind Turbines. 2006 [retrieved: 2012-02-16]. Accessible at: http://www.imia.com/downloads/imia_papers/wgp45_2006.pdf.

33. Vølund P. Concrete is the future for offshore foundations. [retrieved: 2012-02-16]. Accessible at: http://wind.nrel.gov/public/SeaCon/Proceedings/Copenhagen.Offshore.Wind.2005/documents/papers/Low_cost_foundations/P.Voelund_Concrete_isthefutureforoffshorefoundations.pdf.

34. Elkinton C.N, Manwell J.F, Mcgowan J.G. Offshore Wind Farm Layout Optimization (OWFLO) project: an introduction. [retrieved: 2012-02-16]. Accessible at: http://wind.nrel.gov/public/SeaCon/Proceedings/Copenhagen.Offshore.Wind.2005/documents/papers/Poster/C.Elkinton_Offshore_WindFarmLayoutOptimization_OWFLO.pd

f.

35. Nielsen P. Offshore Wind Energy Projects – Feasibility Study Guidelines – Seawind. 2003 [retrieved: 2012-02-21]. Accessible at: http://www.emd.dk/Projects/Projekter/Seawind/OTHER%20RELEVANT%20DOCUMENTS/Feasibility%20Study%20Guidelines.pdf.

36. Middelgrundens Vindmöllelaug. The Location of the Middelgrunden Shoal. [retrieved: 2012-02-21]. Accessible at: http://www.middelgrunden.dk/middelgrunden/sites/default/files/public/file/Location.pdf.

37. Van Bussel G.J.W, Zaaijer M.B. Reliability, Availability and Maintenance aspects of large-scale offshore wind farms, a concepts study. [retrieved: 2012-02-27]. Accessible at: http://www.tudelft.nl/live/binaries/3dcbe092-4334-4d47-9f82-dff9ed15ab5e/doc/MAREC_O&M.pdf.

38. Morthorst P.E. Wind Power, Volume 2, Costs & prices. [retrieved: 2012-02-27]. Accessible at: http://www.ewea.org/fileadmin/ewea_documents/documents/publications/WETF/Facts_Volume_2.pdf.

39. Obdam T, Rademakers L, Braam H, Eecen P. Estimating Costs of Operation & Maintenance for Offshore Wind Farms. 2007 [retrieved: 2012-02-27]. Accessible at: ftp://130.112.2.45/pub/www/library/report/2007/m07045.pdf.

40. Nord Pool Spot. The power market - how does it work. [retrieved: 2012-03-08]. Accessible at: http://www.nordpoolspot.com/How-does-it-work/.

41. Nord Pool Spot. Elspot prices. 2012 [retrieved: 2012-01-31]. Accessible at: http://www.nordpoolspot.com/Market-data1/Elspot/Area-Prices/ALL1/Hourly/.

42. Svensk Kraftmäkling. Elcertifikat. [retrieved: 2012-03-08]. Accessible at: http://www.skm.se/elcert.php.

43. Svensk Kraftmäkling. El-certificate price history. 2012 [retrieved: 2012-02-02]. Accessible at: http://www.skm.se/priceinfo/history/.

44. Energimyndigheten. Elcertifikatsystemet 2011. 2011 [retrieved: 2012-01-31]. Accessible at: http://energimyndigheten.se/sv/Press/Nyheter/Ny-publikation-Elcertifikatsystemet-2011/.

45. Jørgensen H.E, Nielsen M, Barthelmie R.J, Mortensen N.G. Modelling offshore wind resources and wind conditions. [retrieved: 2012-05-30]. Accessible at:. http://citeseerx.ist.psu.edu/search?q=J%C3%B8rgensen+H.E%2C+Nielsen+M%2C+Ba

rthelmie+R.J%2C+Mortensen+N.G.+Modelling+offshore+wind+resources+and+wind+conditions&sort=rlv&t=doc.

46. Lange B, Larsen S, Højstrup J, Barthelmie R, Focken U. Modelling the vertical wind speed and turbulence intensity profiles at prospective offshore wind farm sites. [retrieved: 2012-02-27]. Accessible at: http://citeseerx.ist.psu.edu/viewdoc/summary?doi=10.1.1.59.8489.

47. Hauge Madsen P. Introduction to the IEC 61400-1 standard. 2008 [retrieved: 2012-02-27]. Accessible at: http://www.windpower.org/download/461/Introduction_to_the_IEC.pdf.

48. Jørgensen H.E, Frandsen S, Vølund P. Wake Effects on Middelgrund Windfarm. 2003 [retrieved: 2012-02-29]. Accessible at: http://130.226.56.153/rispubl/vea/veapdf/ris-r-1415.pdf.

49. Rathmann O. Wind farm Wake-effect model in WAsP8. [retrieved: 2012-02-29]. Accessible at: http://www.risoe.dk/vea/storpark/presentations/WAsP8%20Wake-effect%20model.pdf.

50. Zaaijer M. Introduction to wind energy, relevant to offshore wind farm design. 2007 [retrieved: 2012-02-29]. Accessible at: http://ocw.tudelft.nl/fileadmin/ocw/opener/introductionwindenergyhfd1.pdf.

51. Besnard F, Fischer K, Bertling L. Reliability - Centred Asset Maintenance – A step towards enhanced reliability, availability, and profitability of wind power plants. Proceedings of the IEEE PES Conference on Innovative Smart Grid Technologies; 2010.

52. Cutululis N.A, Zeni L, Sørensen P. Reliability indexes for offshore wind power production under extreme wind conditions. [retrieved: 2012.03.21]. Accessible at: http://ewec2010proceedings.info/proceedings/index2test.php?page=info2&id=27&id2=251&ordre=21&tr=&searchin=0&what=2&searchtext=DTU&day=&top=&fil1=&fil2=&fil2&ord1=&sess=.

53. Vattenfall. Vattenfall´s power plants. [retrieved: 2012.03.21]. Accessible at: http://powerplants.vattenfall.com/#/sort/viewed.

54. Sørensen P, Pinson P, Cutululis N.A, Madsen H Jensen L.E, Hjerrild J, Donovan M.H, Kristoffersen J.R, Vigueras-Rodríguez A. Power fluctuations from large wind farms - Final report. 2009 [retrieved: 2012.03.21]. Accessible at: http://www.risoe.dtu.dk/rispubl/reports/ris-r-1711.pdf.

55. ECPE Seminar. Wind farm control. 2006 [retrieved: 2012.03.21]. Accessible at: http://www.univ-lehavre.fr/recherche/greah/documents/ecpe/sorensen.pdf.

56. Spahić E, Balzer G. Power fluctuation from a large wind farm. International Conference on Future Power Systems; 2005.

57. Gleditsch M. Utilization of hydro power for balancing wind power with relation to establishment of 1000 MW offshore wind power in Norway. 2008 [retrieved: 2012-03-22]. Accessible at: http://www.dtu.dk/upload/centre/cet/studentprojects/08/mg_sc.pdf.

58. Enercon GmBH. Wind energy converters, technology and service. 2010 [retrieved: 2012-03-21]. Accessible at: http://www.enercon.de/p/downloads/EN_Eng_TandS_0710.pdf.

59. New York Stock Exchange. Crude Oil Price History. 2012 [retrieved: 2012-03-22]. Accessible at: http://www.nyse.tv/crude-oil-price-history.htm.

60. European Environment Agency. EU ETS future contract prices 2005-2009. 2009 [retrieved: 2012-03-22]. Accessible at: http://www.eea.europa.eu/data-and-maps/figures/eu-ets-future-contract-prices-200520132009.

61. Göteborg Energi AB. Miljörapporter. 2011 [retrieved: 2012-03-22]. Accessible at: http://www.goteborgenergi.se/Privat/Kundservice/Informationsmaterial/Miljorapporter.

62. Göteborg Energi AB. Vindkraft – I drift. 2012 [retrieved: 2012-03-22]. Accessible at: http://www.goteborgenergi.se/Privat/Projekt_och_etableringar/Fornyelsebar_energi/Vindkraft/I_drift.

63. Renova. Från avfall till ren energi. 2011 [retrieved: 2012-03-22]. Accessible at: http://www.renova.se/Global/pdf/Fran_avfall_till_ren_energi_full_web.pdf.

64. Nord Pool Spot. Power system overview. 2012 [retrieved: 2012-04-23]. Accessible at: http://www.nordpoolspot.com/Market-data1/Maps/Power-System-Overview/Power-System-Map/.

65. Nord Pool Spot. Elspot flow. 2012 [retrieved: 2012-03-22]. Accessible at: http://www.nordpoolspot.com/Market-data1/Elspot/Flow1/Flow/KEY/Norway1/.

66. Svensk Energi. Elproduktion. 2011 [retrieved: 2012-03-22]. Accessible at: http://www.svenskenergi.se/sv/Om-el/Elproduktion/.

67. Danish Energy Association. Danish Electricity Supply ‘09. 2010 [retrieved: 2012-03-22]. Accessible at: www.danishenergyassociation.com/~/media/Energi_i_tal/Statistik_09_UK.ppt.ashx.

68. Azar C. Sustainable Energy Futures. Course compendium, Chalmers University of Technology; 2010.

69. Letendre E, Kepton W. The V2G concept: A new model for power? 2002 [retrieved: 2012-04-23]. Accessible at: http://www.udel.edu/V2G/docs/V2G-PUF-LetendKemp2002.pdf.

70. Anderson D.L, Patiño-Echeverri D. An evaluation of current and future costs for lithium-ion batteries for use in electrified vehicle powertrains. 2009 [retrieved: 2012-04-24]. Accessible at: http://dukespace.lib.duke.edu/dspace/bitstream/handle/10161/1007/Li-Ion_Battery_costs_-_MP_Final.pdf?sequence=1.

71. Element Energy. Cost and performance of EV batteries. 2012 [retrieved: 2012-04-24]. Accessible at: http://hmccc.s3.amazonaws.com/IA&S/CCC%20battery%20cost_%20Element%20Energy%20report_March2012_Public.pdf.

72. Nishimura K.A. Some ramblings about NiCd batteries. [retrieved: 2012-04-24]. Accessible at: http://www.resrchintl.com/memory_effects.html.

73. Roberge P.R. Self-discharge of batteries. [retrieved: 2012-04-24]. Accessible at: http://corrosion-doctors.org/Batteries/self-compare.htm.

74. Battery University. How to prime batteries. [retrieved: 2012-04-24]. Accessible at: http://batteryuniversity.com/learn/article/how_to_prime_batteries.

75. Broussely M, Biensan B, Bonhomme F, Blanchard B, Herreyre S, Nechev K, Staniewicz R.J. Main aging mechanisms in Li ion batteries. 2005 [retrieved: 2012-04-26]. Accessible at: http://www.sciencedirect.com/science/article/pii/S0378775305005082.

76. Battery University. Cycle Performance. [retrieved: 2012-04-26]. Accessible at: http://batteryuniversity.com/learn/article/battery_performance_as_a_function_of_cycling.

77. Battery University. All about Chargers. [retrieved: 2012-04-26]. Accessible at: http://batteryuniversity.com/learn/article/all_about_chargers.

78. Battery University. How to prolong lithium-based batteries. [retrieved: 2012-04-26]. Accessible at: http://batteryuniversity.com/learn/article/how_to_prolong_lithium_based_batteries.

79. Mark Salomon M, Lin H.P, Plichta E.J, Hendrickson M. Temperature Effects on Li-Ion Cell Performance. 2002 [retrieved: 2012-04-27]. Accessible at: http://www.springerlink.com/content/hv377v08kg37322j/.

80. New electric cars. Available Electric Cars. [retrieved: 2012-04-25]. Accessible at:

http://newelectriccars.wordpress.com/.

81. Foosnas A.H. Report: wp1.1 electric vehicle technology. 2010 [retrieved: 2012-04-25]. Accessible at: http://www.edison-net.dk/Dissemination/Reports.aspx.

82. Kintner-Meyer M, Elizondo M, Balducci P, Viswanathan V, Jin C, Guo X, Nguyen T, Tuffner F. Energy Storage for power systems applications: a regional assessment for the Northwest Power Pool (NWPP). 2010 [retrieved: 2012-04-27]. Accessible at: http://energyenvironment.pnnl.gov/ei/pdf/NWPP%20report.pdf.

83. Trafikanalys. Fordon i län och kommuner 2011. 2011 [retrieved: 2012-04-25]. Accessible at: http://www.trafa.se/Press/Pressmeddelanden/2012-02-09-11-procent-av-de-svenska-bilarna-ar-miljobilar/.

84. Trafikanalys. Bilar, lastbilar, bussar och motorcyklar 1990-2010. 2010 [retrieved: 2012-04-25]. Accessible at: http://www4.goteborg.se/prod%5Csk%5Cstatistik%5Cstatistikr5.nsf/0/DAAEB2DE2B5EFD52C1256D1600262C1B/$File/7.15.pdf.

85. Wu Q, Nielsen A.H, Østergaard J. Potential analysis for electric vehicle (EV) grid integration. 2011 [retrieved: 2012-04-25]. Accessible at: http://www.edison-net.dk/Dissemination/Reports.aspx.

86. Pyddoke R. Empiriska analyser av bilanvändning och bilägande i Sverige. 2009 [retrieved: 2012-04-25]. Accessible at: http://www.vti.se/sv/publikationer/pdf/empiriska-analyser-av-bilanvandning-och-bilagande-i-sverige.pdf.

87. Statistika centralbyrån. Körsträcka (mil) per bil och per invånare för åren 1999, 2000, 2005,2008 , 2009 och år 2010. 2010 [retrieved: 2012-04-25]. Accessible at: http://www.scb.se/Pages/Standard____313065.aspx.

88. Tångdahl S. Körsträckedatabas, en databas med koppling till Fordonsregistret för beräkning av körsträckor. [retrieved: 2012-04-25]. Accessible at: http://www.trafa.se/Global/Documents/Statistik/K%C3%B6rstr%C3%A4ckor/K%C3%B6rstr%C3%A4ckedatabas%20%E2%80%93%20en%20databas%20med%20koppling%20till%20Fordonsregistret%20f%C3%B6r%20ber%C3%A4kningar%20av%20k%C3%B6rstr%C3%A4ckor.pdf.

89. Statens institut för kommunikationsanalys, sika. Fordon 2008, Tema yrkestrafik. 2008 [retrieved: 2012-04-25]. Accessible at: http://www.scb.se/Statistik/TK/TK1001/Fordon_2008.pdf.

90. Göteborg Energi AB. Teknisk information om Rya. 2005 [retrieved: 2012-01-17]. Accessible at:

http://www.goteborgenergi.se/Files/dok/Informationsmaterial/Broschyrer/Teknisk%20information%20om%20Rya.pdf.

91. Rokka M (Process Engineer at Rya, Göteborg Energi AB). Interviewed by the authors 2012-04-04.

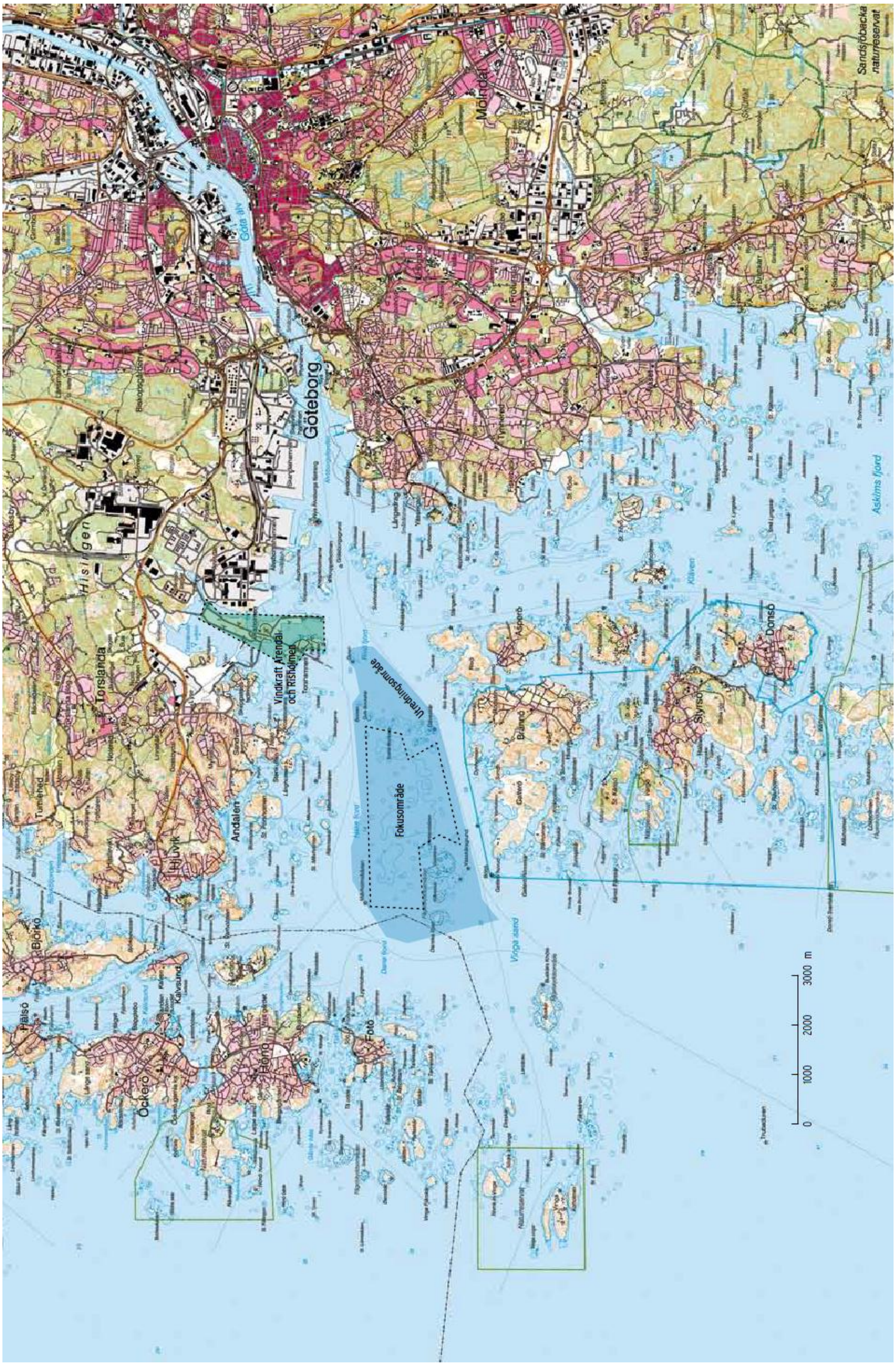
92. Leinberg P (Ekonomiskt Kontrollrum, Göteborg Energi AB). Interviewed by the authors 2012-04-02.

93. Borås Stad Kommunfullmäktige. Reviderad investeringskalkyl för ackumulatortank. 2007 [retrieved: 2012-05-09]. Accessible at: http://www.boras.se/download/18.63fbc1fa126f45b1ad78000633/h-2007-12-13.pdf.

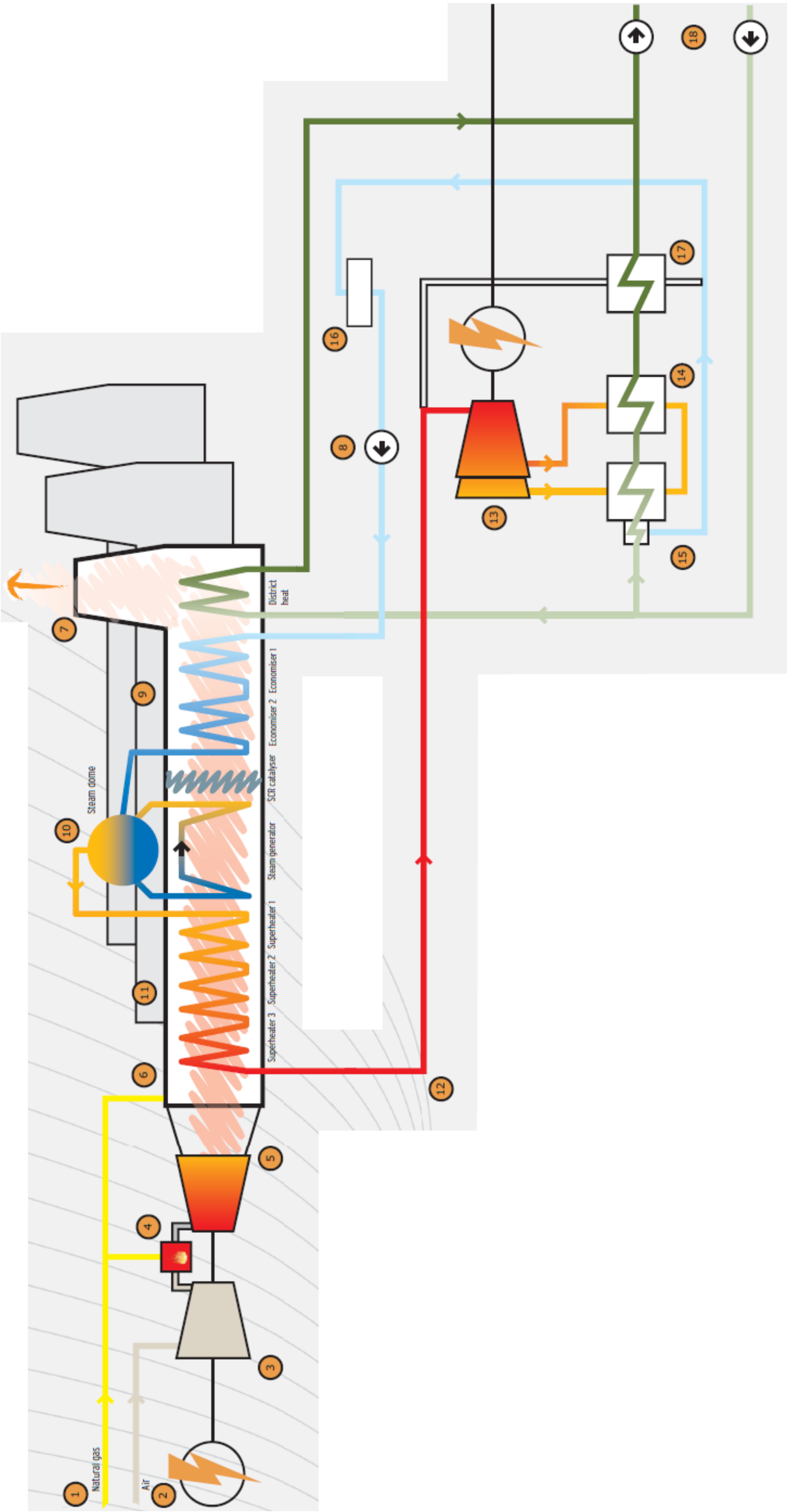
94. Borås Energi & Miljö. Miljötanken som räknas. 2011 [retrieved: 2012-05-09]. Accessible at: http://www.kretsloppsbloggen.se/miljotanken-som-raknas.

95. General Electrics Energy. FlexEfficiency 50 Combined Cycle Power Plant. 2012 [retrieved: 2012-05-09]. Accessible at: http://www.ge-flexibility.com/solutions/flexefficiency-50-combined-cycle-power-plant/index.html.

Appendix A: Map of Göteborg (10)



Appendix B: Rya CHP Plant



Rya CHP plant heat and power production process (90)

1. The gas is supplied by pipeline from Denmark and Germany, approximately 600 MW. When it arrives at the Rya CHP plant, its pressure, 26-28 bar, is suitable for the gas turbines with no need for a pressure increase.
2. The air enters via air intakes on the roof of each gas turbine. To ensure high efficiency and prevent ice formation in the air intakes, these are furnished with heat exchangers to preheat the air. The air preheating uses waste heat from the lubricating oil system for the purposes of good economy and to raise the overall level of plant efficiency.
3. The gas turbine compressor increases the pressure of the incoming air in 15 stages. The temperature is increased to 400°C.
4. In the combustion chamber, the gas/air mixture is burned using 30 low-NO_x burners to form flue gases with a temperature of 1200°C. At this stage, the flue gases contain 30 mg NO_x per MJ of fired natural gas. The higher the temperature, the higher the efficiency of the gas turbine process will be. But there are also disadvantages, including high material temperatures and NO_x generation, which means that a compromise has to be made.
5. The flue gases expand in the turbine, in two air-cooled stages and one uncooled stage. This provides the driving force for the turbine shaft, which in turn drives the electrical generator (and the compressor). The rotor speed is 6,600 rpm. The flue gases exhausted from the turbine have a temperature of 538°C and contain around 15% oxygen by weight.
6. The flue gases are fed into the heat recovery steam generator (boiler), where they are heated to around 1,000°C by means of supplementary firing. As there is 15% oxygen left in the flue gases exhausted from the gas turbine, no further air needs to be added. Thanks to the relatively high level of supplementary firing, the Rya CHP Plant can produce more heat at low cost than other comparable plants.
7. The flue gases that are finally emitted into the environment via the stack have a temperature of around 70°C. After passing through the catalyser, the flue gases contain considerably less than 20 mg NOx/MJ of fired natural gas. One reason why it is possible to reduce the flue gas temperature to such a low level without unwanted side-effects, such as corrosion, is that the plant operates on a clean fuel. Another reason is that the district heating network can be utilised to remove the heat from the flue gases. It is therefore economically possible to reduce the temperature of the flue gases substantially and extract much of their energy content. This is the main reason why the plant can achieve an efficiency level as high as 92.5%.
8. The water in the steam process is pumped up to the right pressure, around 100 bar, by the feedwater pump.
9. In the heat recovery steam generator, the water is heated in several stages in two economisers (1 and 2). It is heated by means of the flue gases from the gas turbines, which flow in the opposite direction to the water.
10. Steam is separated from water in the steam dome. The water that has not yet become steam is fed down via faller pipes to the bottom of the steam generator to be re-circulated in the evaporation tubes via a self-circulation system.

11. The steam is superheated to 540°C in three superheaters.
12. The superheated steam from the three heat recovery steam generators is fed to the steam turbine.
13. In the steam turbine, the steam impacts the turbine's blades at a speed of around 700 km/h. The blades convert this speed into mechanical energy in over 20 stages and thus drive the turbine rotor. The steam turbine rotor in turn drives the electrical generator.
14. The steam that flows out of the steam turbine is condensed in the two heat condensers and the heat is fed to the district heating system. The advantage of having two condensers, rather than one, is that it is possible to let half the steam continue to expand in a further stage of the steam turbine. As the Rya CHP Plant is optimised for district heating, with a relatively large proportion of supplementary firing, there is a high level of heat production at low cost.
15. The steam has now passed into the water phase, i.e. it is condensate.
16. The condensate is cleaned and degassed and finally returns via the feedwater pump to start a new cycle via the heat recovery steam generator.
17. For increased flexibility, there is a dump condenser that is used for heat production in the event of operating problems preventing steam from being passed through the steam turbine. The dump condenser is also used when the plant is being started up.
18. Distribution pumps for the district heating network. The water enters at 40-60°C and leaves at 75-110°C.