NTNU
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Wind in the North Sea.

Effects of offshore grid design on power system operation.

Line Bergfjord

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Abstract

In this thesis a method was developed to evaluate and compare various offshore grid topology and capacity choices. A small power system was created for the purpose of the study, including prototypes of offshore grids. To perform the offshore grid study, preliminary steps had to be taken and four subtasks were thus defined:

1. Develop a scenario of wind park sizes and locations.
2. Obtain representative wind speed data for each of the locations defined.
3. Calculate resulting wind power production, given the scenario and the wind speed data.
4. Study wind power integration and effects of grid topologies.

The North Sea was chosen as a starting point and offshore wind power scenarios for the North Sea in 2025 and 2030 were first developed. Choices regarding which wind data to base the study on, i.e. re-analysis data, numerical weather prediction data or synthetic wind speed data, were evaluated. It was chosen for the final analysis to use a relatively high resolution wind speed data set, resulting from metrological data modelling. This wind speed data was then matched with the wind park locations and the wind power production for the North Sea scenario calculated. A multiturbine approach was applied for this conversion from wind speed to wind power. Finally, the resulting wind power could be included in an offshore grid structure and integrated into a power system.

A small power system was created including three main generation/ load areas based on the characteristics of the Norwegian, Dutch and the British generation portfolios. These areas where connected with link capacities according to the existing and planned HVDC links between the real countries. Three offshore wind areas where then added, interconnected and connected to their respective countries, creating an offshore grid structure. The benefits of different topologies were then investigated by varying the link capacities off the offshore grid structure. Simulations were performed using a unit commitment and economical dispatch simulation tool. The benefits were mainly evaluated in terms of wind integration, emission reductions and reductions in operational cost.

All cases are compared with a base case having only radial connection of the offshore wind clusters. The meshed grid structure results in increased wind integration reduced emission and reduced operational cost for all of the cases. The offshore grid was further found to facilitate both wind integration and trade. Though increasing the rating of the interconnections to shore above the capacity of the connected wind park cluster, as to accommodate for additional trade, was not found to give additional benefits. Regarding the capacities of the interconnections between the wind park clusters, the benefits were seen to saturate at a rating equal to the capacity of the smaller of the two connected wind park clusters. As investment cost was not considered in this thesis

further decisions regarding the optimal rating of the cables were based on the assumption that a high link utilisation is desirable. It is however recommended to apply a cost-benefit analysis for more accurate evaluations. As could be expected the effects on the onshore generation were unevenly distributed among the created areas depending on the generation mix. Finally, it should however be noted that since the case study only included three areas and an un-optimised hydro-scheduling method, results should be treated with caution.

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Abbreviations

CCGT	Combined Cycle Gas Turbine
CHP	Combined Heat and Power
ENTSO-E	The European Network of Transmission System Operators
EU	European Union
EWEA	European Wind Energy Association
EZ	Ministerie van Economische Zaken
GWh	Giga Watt Hour
HIRLAM	High Resolution Limited Area Model
HVDC	High Voltage Direct Current
IEE	Intelligent Energy Europe
MW	Mega Watt
NCAR	National Centre for Atmospheric Research (US)
NCEP	National Centre for Environmental Protection (US)
NSCOGI	North Sea Countries' Offshore Grid Initiative
NSTG	North Sea Transnational Grid
NVE	Norwegian Water Resources and Energy Directorate
NWP	Numerical Weather Prediction
PDTF	Power Transfer Distribution Factor
SAF	System Adequacy Forecast
SD	Standard Deviation
TSO	Transmission System Operator
TWh	Terra Watt Hour
VAR	Vector Autoregressive Model
WAsP	Wind Atlas Application and Analysis Program
WP	Work Package
WPP	Wind Power Plant
WWSIS	Western Wind and Solar Integration Study

1 Introduction

An energy transition is expected to take place in the near future, as the current energy system reaches its limitations. Towards this transition EUs Energy Policy is currently guided by its three core objectives– competitiveness, reliability and sustainability. These were agreed upon by the European council in 2007 and in the European Commissions' Green paper [6] the member states are asked to base their national energy policy on these values. The competition in the energy sector has been increasing with the liberalization of the electricity and gas markets and the unbundling of large national utilities, though a single European energy market is still far from reality.[7] Reliability and the security of supply are related to a steady growing energy demand, a constant need for a reliable supply and an expected decrease in availability of fossil fuels. This combined with increasing environmental concerns raises the need for sustainability. In this context renewable energies are receiving more attention and seen as a crucial part of the future energy system. In the transition towards a more sustainable future, the EU has become an important initiator and driving force. By issuing directives such as the EU Directives on Renewable Energy [8] including national renewable targets modified according to economic status, it aims towards the 20-20-20 goals presented in the EU Energy and Climate Package (2008). Among those goals is the 20% share of renewables in the European energy consumption within 2020. As we are approaching 2020, there is still a long way to go and action needs to be taken now by the individual EU countries in order for this goal to be reached. Large amounts of new technology and infrastructure is needed for the transition to 'green' energy to accelerate during the next decade. This will require large investments and is expected to create hundreds of thousands technology related jobs [9] . Though challenging as it is, the energy transition creates an '*ocean of opportunities'* [10].

1.1 Background

Wind power is considered one of the major ways to achieve a more sustainable electricity generation mix. As the wind blows stronger at sea the offshore wind resources are especially favourable. Estimations suggest that Europe's offshore wind potential could cover seven times its power demand [10]. A large share of the total amount of installed wind power is therefore to be installed offshore. The European Wind Energy Association (EWEA) targets 40 GW offshore wind power capacity for 2020 and 150 GW for 2030 and the share of wind power in the European electricity production is illustrated in Figure 1-1.

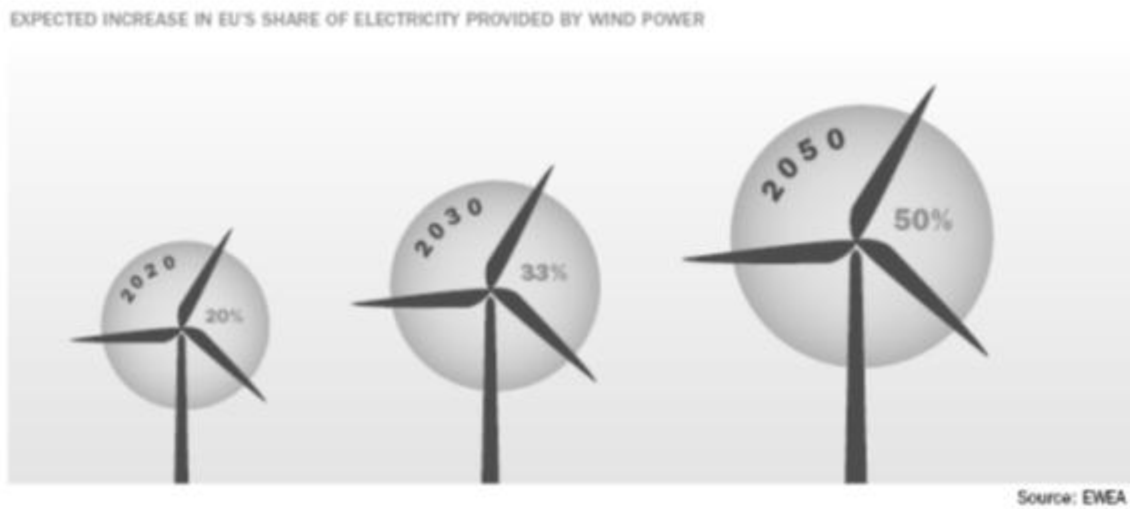


Figure 1-1: Expected increase in EU's share of electricity produced by wind power[11]

A few offshore wind parks are already operational, though in Europe this amounted to 3000 MW installed capacity in 2010 [12].This number is thus expected to grow significantly in the coming years. Future offshore wind power parks (WPP) will be larger in size and built further from shore and with this development comes challenges. The increase in distances complicate the grid connection and especially connection by ac: submarine cables produce reactive power, which limits the amount of active power that can be transported. This issue can however be solved by high voltage dc (HVDC) transmission, which is costly. To reduce the transmission costs, the utilisation factor, being the percentage of the total transmission capacity that is utilised at average, should consequently be increased. By interconnecting WPPs to each other or to more than one country to facilitate trade, this goal can be achieved, constituting (meshed) offshore transnational networks. Following this development, the North Sea Countries Offshore Grid Initiative (NSCOGI) signed their memorandum of understanding in December 2010. This collaboration between EU member states[1] and Norway share the common goal of reaching a low carbon future and the intentions to create a framework to deal with "*questions related to current and possible grid infrastructure developments in the North Sea*." [13]

1.2 Scope of the study

The amount of wind power foreseen to be installed requires rethinking on the way the future electricity grid is operated. The total generation mix will change from a largely fossil-fuel dominated mix towards a more sustainable, which fosters the gradual substitution of conventional generators by, most notably, offshore wind WPPs. Connection of these to the existing power system can be done in different ways, in terms of transmission technology and grid topology, depending on the wind power scenario. The effect on the operation of the existing power system depends on the

[1] EU member states involved in the NSCOGI: Germany United Kingdom, France, Denmark, Sweden, the

consequent interaction with land based generation. A range of plans for wind power development in the North Sea does already exist. To what extent these plans will be realised is however still uncertain. Scenarios for the future wind power development are thus to some respect guesstimates of location and sizes. Such scenarios for offshore power production are however crucial for investigations of a future North Sea offshore grid. By including this wind power with different grid topologies in a larger power system, impacts on the market dispatch results can be analysed. Considering the expected development, offshore wind must be included in power system expansion planning and studies on how these offshore wind parks will be connected are therefore needed.

1.2.1 Study framework: the NSTG research project

The North Sea Transnational Grid research project aims to investigate the economic and technical aspects of offshore grid developments in the North Sea. The project is coordinated by the Energy research Centre of the Netherlands and executed together with Delft University of Technology. It intends to determine a technical blueprint based on modular, flexible and cost efficient solutions and develop several scenarios which can be studied considering investment cost, operational cost, benefits and security of the power system [14]. The work includes a range of subtask and is thus divided into ten work packages (WP). The first two WPs investigate available technologies includes an initial technical-economic evaluation of different transnational grid configurations. These preliminary results will be used as input for the consecutive WPs.

This thesis is strongly related to the NSTG project as it partly will provide input data for some of its work packages. As consistency must be kept within the NSTG project, assumptions, findings and conclusions from WP2 will be discussed and considered in the related part of thesis.

1.3 Objective and approach

The aim of this M.Sc. project is to investigate future alternatives for connectivity of wind power production in the North Sea. As a main objective the impact of wind integration on power system dispatch and the benefits of building an offshore grid will be investigated. In order to achieve this objective a number of intermediate steps are required. Sub-objectives are therefore defined for four of these necessary steps:

1. Create a realistic wind park scenario for a certain time horizon, including locations and amounts of installed capacity.
2. Obtain adequate wind data for the defined area and period of time.
3. The total energy harvest must be estimated, based on the developed scenarios and the wind data.
4. Wind power integration in the power system and impacts of grid design can be studied, based on the calculated wind power output.

The studied geographical area is confined to the North Sea and includes areas belonging to Norway, Denmark, Germany, The Netherlands, Belgium and Great Britain. The studied time horizon is set to year 2025/2030. However, in the section covering the offshore grid analysis (chapter 5) the area studied is reduced and a simplified system is created based on the generation characteristics of Norway, The Netherlands and Great Britain.

When creating a future wind power production scenario it is important to be aware of the uncertainties regarding future wind park development, which are currently resulting in a diversity of existing scenarios and development plans. Though some areas are more certain than others there is no blueprint scenario to use for the whole North Sea area, which leaves each wind integration study to make its own assumptions and choices. These decisions should in any case be based on reliable sources and reasonably justified. In this thesis a bottom-up approach was first used, collecting information about all planned wind farms and developments areas in the North Sea. A top-down approach was then applied to modify the preliminary result according to national targets and development plans further adjusted by comparison with other wind integration studies.

Another very important part of wind integration studies is the wind speed data. Attention should be paid to this part as this data represent one of the main inputs in the study and may consequently influence the results. Such data can be obtained in different ways and the techniques are not always straight forward [15]. Real measurement data are limited and data sets are usually created by the use of weather simulation models, based on limited real measurements. The resulting data sets do however differ with a range of temporal and spatial resolutions available and limitations in the weather prediction models may further influence the quality of the data. Wind speed data can on the other hand be artificially created. By the use of statistical methods, characteristics of wind can be captured and reproduced. In this thesis one method for creating artificial wind speed time series is presented. Such multivariate regression models can be capable of producing arbitrary amounts of artificial wind speed data. For this thesis a model for only two locations is built and the results discussed. Expanding the model for more locations, such as for the whole North Sea will require some more computational power and make the verification of the model more complex. The method presented and the developed model will however merely serve as an example, especially since it was decided during the work on the model that the already available wind speed data would be sufficient for the further studies.

The next step is the relation between the wind speed and the power output from a wind turbine. This relation can be described by the turbine power curve, but studies do however show that simply up-scaling a single power curve is not sufficient for estimating power outputs from wind parks. A multi-turbine approach is therefore used for wind power calculations in this thesis, taking into account the regional wind speed climate.

Finally, a power system model is needed for the study of wind power integration and offshore grid topology. As this study assesses wind power in the North Sea, the power system is designed to resemble this area, though simplified compared to the real power network. Simplifications are done to highlight the main tendencies and mechanisms involved. Three areas with different generation characteristics representing Norway, Great Britain and the Netherlands are included together with three areas representing the offshore wind power associated with the Exclusive Economic Zone of each country. The remaining North Sea countries and other interconnected systems are not considered in this part. Interconnection capacities between the three areas considered are however modelled. A transportation model is used to calculate the power flows in the links between the generation areas. It is assumed that the latter assumption is appropriate as the transfer capacities represent HVDC links connecting large generation areas [16], and the power flow in these links are to a great extend controllable (unlike flows in an AC network). Different stages of offshore grid development are defined and cases created for each of these topologies including sensitivity on transmission capacities. Market simulations in terms of unit commitment and economic dispatch will then be performed using the software *PowrSym3*. The results will be evaluated in terms of production costs, CO2 reductions, change in generation mix and utilisation of transmission links. The objective is to identify the effects and possible benefits of creating a meshed offshore grid.

The wind park scenarios and the resulting wind power output developed in this thesis are to be used to back up the work in the NSTG[2] study.

1.4 Structure of the report

In chapter 2 wind park scenarios for the North Sea will be developed for the future years 2025 and 2030. These will be presented along with the results from a literature study covering research projects, visions and national plans concerning the future wind park development in the North Sea. Chapter 3 will then deal with wind speed data. Different data sets will be discussed and presented along with a method for developing artificial wind speed data. Description of the wind speed data which will be used for the consecutive parts of this thesis includes the explanation of the necessary corrections done to this data set. In chapter 4 the wind speed to power conversion is dealt with. A multiturbine approach is described and applied to calculate the resulting power output from the wind park scenario presented in chapter 2. Then in chapter 5, the offshore grid is introduced. The developed wind power is included in a power system with an offshore grid. Different cases of grid topology are created and the effects of offshore grid design on power system operation are studied. Finally, chapter 6 presents the final conclusions along with recommendations for future work.

[2] NSTG – North Sea Transnational Grid

2 Offshore Wind Scenario

This chapter describes the development of North Sea wind power scenarios for 2025 and 2030. The approach is first described before the resulting scenarios are presented, an overview of the literature study can be found in section 2.3 Background scenarios.

2.1 Approach

As a first step in the bottom-up approach, information about all existing and planned wind parks was collected. EWEA's wind map from 2009 [17] is frequently used as source for offshore wind scenarios, this is however not a regularly updated map and some of the projects included there are now cancelled or changed. An online database provided by the marine consultancy 4COffshore (see section 2.3.1) was therefore used as main source. This database contains information about all reported projects, ranging from operational wind parks to project with authorized consent to projects in a concept and early planning phase. Among these are also dormant and cancelled projects. From this data, projects with status 'cancelled' were consistently excluded.

In the top-down approach information from national wind development plans for the countries surrounding the North Sea and scenarios developed by larger, well known studies assessing wind in the North Sea was gathered. This information was used to modify the preliminary result from the bottom-up approach. The modifications are described the following section, before the resulting scenarios are presented and a comparison with scenarios from other wind integration studies is done. Finally the considered national reports and plans involving offshore wind integration is presented per country studies including North Sea wind integration and scenarios are described.

It must be noted that some of the North Sea countries have other sea areas in addition to the North Sea. Thus national numbers of estimated offshore capacity may include these areas too. This is the case for Great Britain (the North Sea, the English Channel and the Irish Sea), Germany (the North Sea and the Baltic Sea), Denmark (the North Sea, Kattegat, Skagerrak and the Baltic Sea) and Norway (the North Sea, the Norwegian Sea, and the Barents Sea). Whenever possible, the numbers for the North Sea only are specified.

2.2 Final North Sea Scenario

2.2.1 Modifications

Changes made to the total list of wind parks from the first collection include reductions in some of the UK development zones as to match the proposal in 'Round 3' and excluding of 'early plans' from the German and the Danish part as to be more in line with national plans and other comparable scenarios. The Dutch scenario is modified according to development plans presented by the Dutch transmission system operator (TSO) TenneT [18]. Regarding Norway, the development here is unsure considering the fact that no larger offshore wind park has been built there so far and most of the proposed projects are based on technology which is not yet proven, such as floating turbines as well as being installations situated considerably further from shore and on considerably deeper waters than existing wind parks. This is however also the case for some of the projects in the other countries and it is thus for Norway included already approved projects as well as projects were consent application has been sent. All proposed wind parks for Belgium are included. Wind parks smaller than 10 MW are not considered for any of the countries.

The resulting scenarios can be seen in Table 2-1 and Figure 2-1. For 2025 this includes a total of 136 wind parks and an installed capacity of 55.0 GW while the 2030 scenario includes 178 wind parks with a total installed capacity of 81.7 GW. A complete list of wind parks can be found in the appendix.

COUNTRY	SCENARIO (2025) [MW]	SCENARIO (2030) [MW]
The Netherlands	6214	10308
GB	23095	29965
Germany (NS)	18081	26146
Denmark (NS)	3169	4369
Belgium	1766	3766
Norway (NS)	2680	7180
TOTAL	55005	81734

Table 2-1: Created wind park scenario for the North Sea area in 2025 and 2030

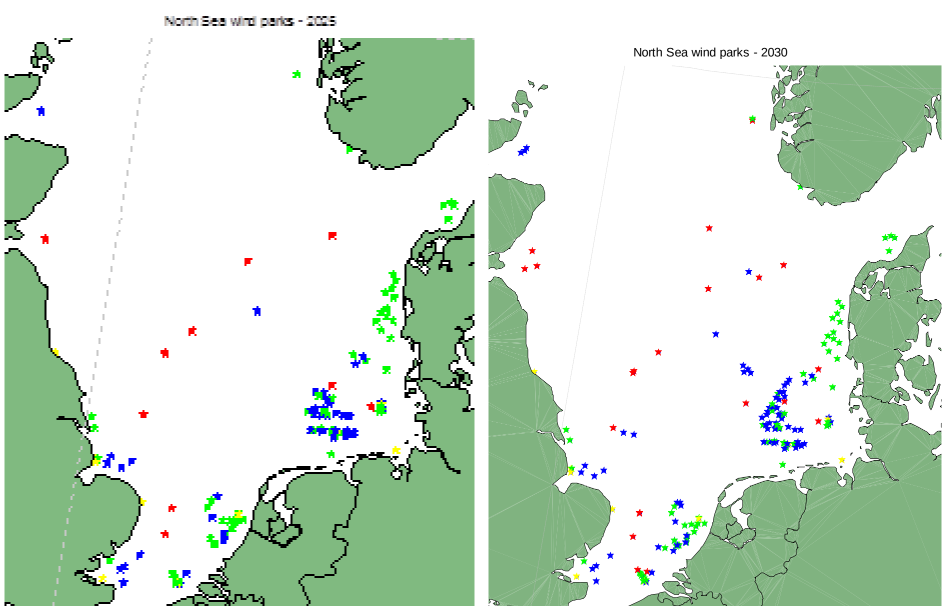


Figure 2-1: Wind parks in the North Sea 2025 and 2030 **(red>800MW, 800>blue>300,300>green>100,100>yellow)**

2.2.2 Comparison of scenarios

First of all it must be said that the development of wind power scenarios for the future to a large extent is based on 'guesstimates'. The different studies compared do as mentioned before, include somewhat different areas. This complicates the comparison. Table 2-2 shows that the currently installed capacities according to EWEA and the capacity of existing and approved projects according to 4COffshore are relatively low. It is thus expected that the development will speed up with time. Whether if and how fast such a development will happen is however difficult to predict. This results in a range of possible outcomes.

COUNTRY	INSTALLED CAPACITY 2008 (EWEA) [MW]	*INSTALLED CAPACITY 2010 (EWEA) [MW]*	EXISTING AND APPROVED (4C OFFSHORE) *[MW]*
The Netherlands	247	247	3199
UK	591*	1341*	3200
Germany	12*	92*	7570
Denmark	409*	854*	7570
Belgium	30	195	872
Norway	0	2*	0
TOTAL	1289	2731	22411

Table 2-2: Accumulative capacity for the North Sea countries' existing and approved wind parks.
*) cover more than the North Sea area. **) The 4COffshore numbers does not include wind parks smaller than 10 MW.

Firstly a comparison of the total number in the earlier studies (EWEA scenarios, ENSTSO-E scenarios, the TradeWind study, the Greenpeace [r]evolution report, the OffshoreGrid study and the Windspeed study) will be done. The numbers are given in Table 2-3. Secondly these will be compared with the new scenario made.

The 2020 scenarios are considerably lower than the 2030 scenarios, which suggest that the development is expected to accelerate in that time span. As EWEA only have 2020 scenarios, these are in the lower range though its 'high' scenario exceeds the other 2020 scenarios from ENTSO-E and OffshoreGrid. ENTSO-E's 2030 scenario is considerably higher and does also exceed Greenpeace's [r]evolution 2020/2030 scenario and the original TradeWind 2030 scenario. The Offshore TradeWind 2030 scenario is on the other hand higher, as is the OffshoreGrid 2030 scenario. It might however be expected that studies concerning offshore grids will have more optimistic wind power development scenarios as offshore grids are a consequences of larger offshore wind deployment. Having enough installed offshore wind capacity to make the building such a grid necessary and beneficial is thus a prerequisite. Above this the Windspeed study's 'Grand Design' is by far the most optimistic. This study is unlike the others focusing on available wind resources and though it considers constraints regarding the development it does not necessarily result in a likely outcome.

The new 2030-scenario developed in this thesis comes close to the ENTSO-E 2030 scenario and the medium TradeWind scenario and is somewhat lower than the OffshoreGrid scenario. These comparable scenarios do however include a larger geographical area than the North Sea. The new 2025-scenario is somewhere between the 2020 and the 2030 scenarios.

COUNTRY\ SCENARIO	ENTSO-E ** (2020) [MW]	ENTSO-E * * (2030) [MW]	EWEA SCENARIO LOW (2020) [MW]	EWEA SCENARIO HIGH (2020) [MW]	WINDSPEED* * BASECASE (2020-2025) [MW]	WINDSPEED** 'GRAND DESIGN' (2020-2025) [MW]
The Netherlands	2000	12000	4500	6000	6000	22454
UK (**GB)	11500	38500	13000*	20000*	23665	38752
Germany	10000	24000	8000*	10000*	18640	41435
Denmark	1000*	3400*	2300*	2500*	3169	26228
Belgium	2000	4000	1800	2000	3800	2242
Norway	0	1000	x	x	3000	16256
TOTAL	26500	82900	29600	40500	58274	147367

COUNTRY\ SCENARIO	OFFSHOREGRID (2020) [MW]	OFFSHOREGRID (2030) [MW]	GREENPEACE [R]EVOLUTION (2020/2030) [MW]	TRADEWIND - OFFSHORE GRID STUDY (L) (2030) [MW]	TRADEWIND - OFFSHORE GRID STUDY (M) (2030) [MW]	TRADEWIND - OFFSHORE GRID STUDY (H)(2030) [MW]
The Netherlands	4622	12122	12039	2200	12000	20000
UK (**GB)	15303*	38146*	22238	3500*	33000*	33000*
Germany	10249*	26553*	26418	20000*	25000*	30000*
Denmark	2329*	3799*	1577	2700*	3000*	3300*
Belgium	1994	3794	3846	700	3000	3800
Norway	957	7692	1290	0	2500*	7300*
TOTAL	35454	92106	67408	29100	78500	97400

Table 2-3: Offshore wind scenarios from relevant studies. *) incl. more offshore areas than the North Sea

2.3 Background scenarios

2.3.1 4Coffshore Online Wind Park Database

4Coffshore is a marine consultancy providing an online, public available wind farm database [19]. Their wind farm database includes specific information about the projects such as the size of the wind park and the location, as well as names of companies involved i.e. project developers, installation and manufacturing companies etc. According to the company the data is constantly updated when new information is confirmed and is thus more or less up to date. Routines cycles for checking the data in the database are regularly performed as well. Regarding the reliability of the data they are carful with who they accept information from, either they get information directly from the companies or they make sure to cross-check the information with other sources. All data are regularly checked for inconsistency. They cannot guarantee that all data are correct, but they do seem to have a good method for checking the data.

2.3.2 National Reports and Plans

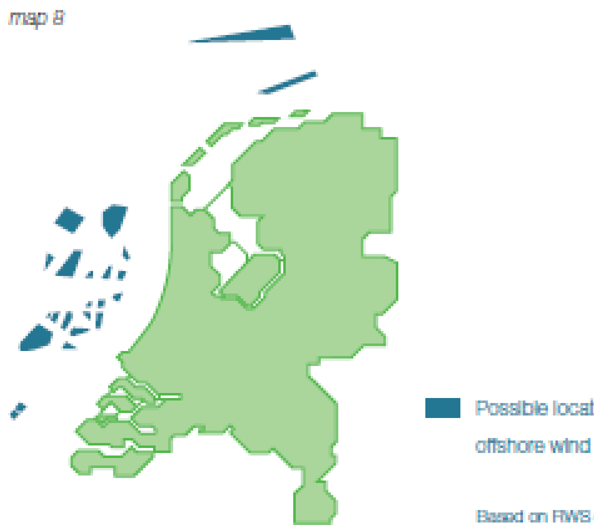
2.3.2.1 The Netherlands

2.3.2.1.1 TenneT - Vision 2030

The Vision 2030 report [18] was published in 2008 by TenneT, the Dutch transmission system operator (TSO). It provides analyses of the long term developments affecting the electricity supply including their expectations regarding offshore wind developments. Four scenarios are considered, depending on the development within the electricity consumption, location of the production, changes in the political environment and trends in the society. These four scenarios and the related wind power development is presented in Figure 2-2.The highest integration of offshore wind is assumed to be 6GW, which is in line with the national goal for 2020 set by the government. For this 'Green Revolution' scenario the connections points to the onshore grid is assumed to be according to Figure 2-3.

	Protectionism	Free market
Focus on renewables	Sustainable Transition 3.5 GW + 3.5 GW	Green Revolution 4 GW + 6 GW
Focus on fossil fuels	New Strongholds 2 GW + 1 GW	Money rules 3 GW + 2 GW

Figure 2-2: TenneT's Vision 2030 development scenarios with onshore and offshore wind capacities. [3]



	Conv.	Wind	Total
Borssele	5,7	1,0	6,7
Maasvlakte	2,5*)	2,5	5,0
IJmuiden	0,0	2,5	2,5
Eemshaven	0,0	0,0	0,0
Total	8,2	6,0	14,2

Figure 2-3: Green revolution scenario [18]

2.3.2.1.2 Net op Zee

The Net op zee report [5] was issued by the Dutch ministry of economic affairs (EZ) in 2009. It is based on the 'Kabel op zee' project done by Ecofys on request from the ministry, to investigate the connection of future offshore wind to the existing electricity network and defines the developments areas given in Figure 2-5 and the development scenario given in Figure 2-4. From the latter figure, it can be seen that a maximum capacity of 6 GW is assumed to be reach in 2020, according to the governmental goal.

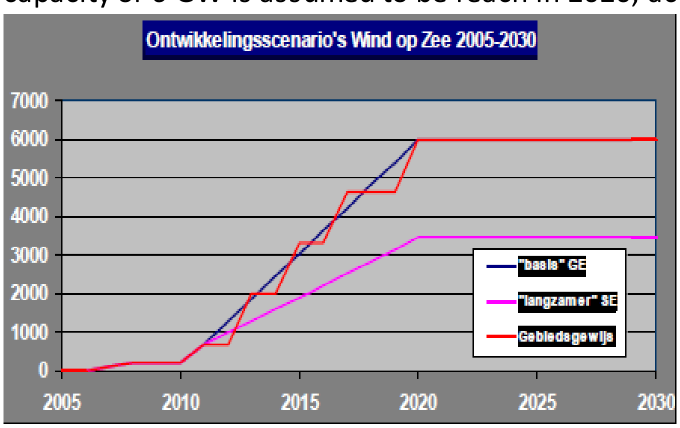


Figure 2-4 : Development scenario Wind op Zee 2005 -2030. (Blue: basis, pink: slow development, red: areal development) [5]

Figure 2-5: Developments areas. [5]

2.3.2.2 Great Britain

2.3.2.2.1 Round 3 - Offshore Wind Farm Connection Study

The Round 3 Offshore Wind Farm Connection Study [20] was carried out by Senergy Econnect and National Grid on behalf of the Crown Estate to aid the connection of the offshore wind farm areas indicated by the Round 3 development zones, involving a possible connection of 25GW within year 2020. An overview of the development zones and the expected capacities is given in Table 2-4. The areas situated in the North Sea are Moray Firth, Firth of Forth, Doggerbank, Hornsea and Norfolk /East Angelina, resulting in a total North Sea development of 18340 MW.

ZONE	OWF	Total Installed Capacity	Connection technologies	Connection Point (s)
Moray Firth	C	500MW	AC	New substation on coast
Firth of Forth	G	500MW	AC	Torness
Dogger Bank	H1	1237.5MW	DC	Creyke Beck
	H3	1237.5MW	DC	Creyke Beck
	J	1240MW	DC	Creyke Beck
	H2	1237.5MW	DC	Keadby
	H4	1237.5MW	DC	Keadby
	H5	1237.5MW	DC	Killingholme
	I1	1240MW	DC	Killingholme
	I2	1240MW	DC	Killingholme
Hornsea	M	1237.5MW	DC	New substation on Lincolnshire coast
	N	1240MW	DC	New substation on Lincolnshire coast
Norfolk (without Sizewell C)	T	1240MW	AC	Sizewell
	Z2	1240MW	DC	Sizewell
	U	1237.5MW	DC	Norwich
	Z1	1237.5MW	DC	Norwich
Hastings	AA	500MW	AC	Bolney
West Isle of Wight	DA	500MW	AC	Chickerell
Bristol Channel	EA	1500MW	AC	New substation on Torridge Estuary
Irish Sea	IA	1237.5MW	DC	Deeside
	LA	1240MW	DC	Deeside
	JA	1237.5MW	AC	Wylfa
	NA	1240MW	DC	Stanah
TOTALS		25,795MW		

Table 2-4 : Wind parks in UK's Round 3 [20]

Larger installed capacities are planned by the project developers for some of the considered areas, such as Moray Firth and Firth of Forth. These extensions might be planned for a longer time horizon than assumed in the Round 3 report.

2.3.2.3 Norway

2.3.2.3.1 Grid Development Plan for the Central Grid 2008-2025

The grid development plan [21] is issued by the Norwegian TSO *Statnett* and includes three different development scenarios. The 'windpower and consumption growth' scenario includes 6 TWh offshore wind production in 2025, corresponding 1500 MW [3].

2.3.2.3.2 Offshore Wind – Suggested developments areas

The Offshore wind report [22] issued in 2010 presents the result from a studied carried out for the Ministry of Oil and Energy. The study group was led by the *Norwegian Water Resources and Energy Directorate (NVE)* and aimed to define areas for offshore energy development, to be included in a strategic impact assessment. The suggested development areas for offshore wind are presented in Figure 2-6 and including known projects for the North Sea area in Figure 2-7

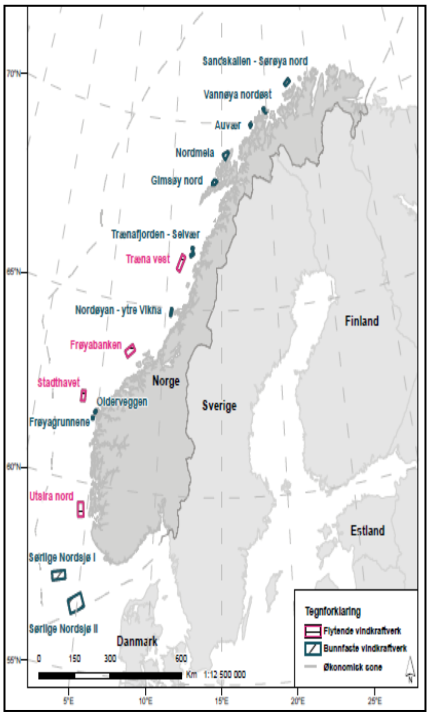


Figure 2-6: Development areas (pink: floating constructions) [2]

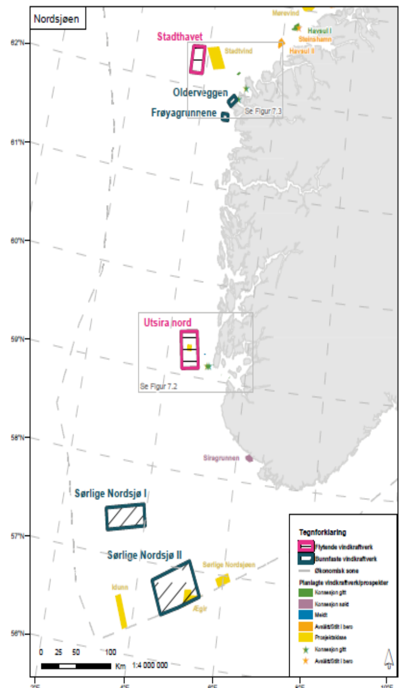


Figure 2-7: Developments area and known projects (yellow) [2]

2.3.2.4 Denmark

2.3.2.4.1 Future Offshore Wind

The Future Offshore Wind [23] report defines the expected future developments areas for offshore wind in Denmark and was issued by the Danish Energy Authority in 2007. The resulting areas and installed wind farm capacities expected for year 2025 are given in Table 2-5. The areas situated in the North Sea are: Horns Rev, Ringkøbing and Jammerbugten accumulating a total capacity of 2800 MW. This report was followed by an updated report in 2008 [24], though no changes to regarding the areas and installed capacities were done.

Oversigt over placeringsområderne, middeltal for områderne (5 MW mølle)												
	Kapaci-tet	NET udgift	Anlægs udgift	Samlet Investe-ring	Vind ressour-ce	Fuld-last-timer	Drifts-omkost-ninger	Nutids-værdi af drifts-omkost-ninger	Nutid-værdi af omkost-ninger	Produk-tion-somkost ninger	Afstand til ser-vice-havn	Hav dyb-der gen
	MW	Mio.k r/MW	Mio.kr/ MW	Mio.kr/ MW	m/s	timer	kr./ kWh	Mio. kr/MW	Mio/ MW	kr./kWh	Km	m
Djursland	2*200	3,3	13,9	17,1	9,65	4008	0,14	6,9	24,0	0,48	30	18
Horns Rev	5*200	4,4	14,5	18,9	10,22	4279	0,18	9,5	28.4	0,53	40	18
Læsø	3*200	5,0	13,5	18,5	9,7	4032	0,19	9,5	28.0	0,56	73	10
Jammerbugt	4*200	5,2	14,6	19,8	9,84	4097	0,18	9,3	29,1	0,57	44	20
Ringkøbing	5*200	4,2	16,4	20,6	10,26	4298	0,18	9,7	30,3	0,57	36	27
Kriegers Flak	4*200	5,6	16,6	22,2	9,73	4044	0,15	7,8	30,0	0,59	43	25
Rønne Banke	2*200	4,3	20,3	24,6	9,75	4056	0,14	7,1	31,7	0,63	30	35
S. Middelgrund	200	3,3	19,6	22,9	9,70	4032	0,18	9,3	32,2	0,64	63	30

Table 2-5: Offshore wind farms in Denmark 2025 [24]

2.3.2.5 Belgium

2.3.2.5.1 Maximum potential for renewable energies

[25] is a report from 2006 is a supporting document for the Commission on Energy 2030 final report. Results regarding offshore wind are presented in Table 2-6.

Limiting factor	capacity MWe	power TWhe/y	power PJe/y
Present grid connection :	600	2.0	7.3
150 kV grid connection :	900	3.0	11
Max. concessions :	3800	12.8	46
Max. suited sea areas :	13000	44	159

Table 1 : offshore wind limits

Table 2-6: Estimated offshore wind limits [26]

2.3.2.5.2 Prospects for offshore wind on the Belgian continental shelf

[26] is a report from a study financially supported by the federal government of Belgium. Investigating restrictions on offshore wind development the study concludes with an unrestricted offshore wind potential of 2-4 GW installed capacity.

2.3.2.6 Germany

2.3.2.6.1 Dena

'Planning of the Grid Integration of Wind Energy in Germany Onshore and Offshore up to the Year 2020' [27] was a study ordered by the German Energy Agency (dena) to investigate the coming changes in the electricity system with focus on the implementation strategy of wind energy and other renewable energies combined with the aging of the existing power plants and the agreed phase-out of nuclear energy. A prognosis of the wind development carried out by the German Wind Energy Agency (DEWI) estimates that 20.000 MW offshore wind power can be installed within 2020.

Another 16.500 MW, already planned is expected to be realised later. Their estimates for the years 2007, 2010, 2015 and 2020 are presented in Table 2-7

Year	Onshore	Repowering (growth)	Offshore	Sum
2007	21,620	768	476	22,864
2010	24,540	1,503	4,382	30,426
2015	26,544	3,601	9,793	39,938
2020	26,544	7,056	20,358	53,958

Table 2-7: Prognosis of wind development for the years 2007, 2010, 2015 and 2020, according to the DEWI scenario[27]

2.3.2.6.2 Energy Policy Road map 2020

The Energy Policy Road map 2020 [28] was issued by the German Environment Ministry in 2009 to demonstrate how such a policy can be design and what it will accomplish. Their integrated energy policy regards renewable energies and energy efficiency as key elements in a achieving a secure and sustainable energy supply in an environment highly affected by the climate changes and the financial crisis. They expect an installed offshore wind capacity of 10 000 MW within year 2020. According to the Lead 2008 study, also issued by the Environmental Ministry, the total wind production is expected to increase from around 40 TWh in 2007 to 90 TWh in 2020 and 140 TWh in 2030. Offshore wind production is expected to exceed land based production from year 2025 onwards.

2.3.2.6.3 Strategie der Bundesregierung zur Windenergienutzung auf See

This strategy paper issued from the German government in 2002 [29], presents scenarios for the expected offshore wind development. Table 2-8 gives the numbers for the total installed capacity in the North Sea and Table 2-9 presents the expected German share of this development. Thus within the year 2030, 25.000 MW are assumed possible for Germany.

Tabelle 1: : Anträge für Offshore-Windparks (AWZ, Stand Januar 2002)

Gebiet	Zahl der Windparkanträge	Leistung der ersten Baustufen (MW)	Beantragte Leistung nach Endausbau (MW)
Nordsee, AWZ	22	ca. 5.000	58.500
Ostsee AWZ	7	ca. 1.500	4.600

Table 2-8 : Total expected offshore wind capacities for the North Sea and East Sea [29]

Tabelle 2: Schrittweise Erschließung der Windenergienutzung auf See

Phasen	Zeitraum	Mögliche Kapazität	Möglicher Stromertrag
1. Vorbereitungsphase	2001 - 2003	-- MW	-- TWh p.a.
2. Startphase (Erste Baustufen)	2003/4-2006	mindestens 500 MW	ca. 1,5 TWh p.a.
3. Erste Ausbauphase	2007-2010	2.000 - 3.000 MW	ca. 7 - 10 TWh p.a.
4. Weitere Ausbauphasen	2011-2030	20.000 - 25.000 MW	ca. 70 - 85 TWh p.a.

Table 2-9: Estimated stepwise offshore wind development in Germany [29]

2.3.3 Related reports, studies and research projects

2.3.3.1 EWEA – "Pure Power"

The European Wind Energy Association (EWEA) is an organization promoting wind power in the interest of the wind industry. Among the members of this wind energy network are manufacturers, component suppliers, contractors, researchers, national wind and renewables associations, electricity suppliers etc. The organization publishes frequently reports covering wind power statistics, trends, scenarios etc. EWEA's 'Pure Power' report from 2009 [9] presents wind energy targets for the years 2020 and 2030. The numbers for EU-27 are given in Table 2-10. The location of the wind parks are not specified as the numbers are given per EU country. It can thus be assumed that the English Channel, the Irish Sea and the Baltic Sea are included. Numbers for Norway are not included as Norway is not a part of the EU.

	MW installed end 2008			MW installed 2020 low			MW installed 2020 high			Avg annual MW low (2008-2020)	Avg annual MW high (2008-2020)
Country	Onshore	Offshore	Total	Onshore	Offshore	Total	Onshore	Offshore	Total		
Austria	995	0	995	3,500	0	3,500	4,000	0	4,000	209	250
Belgium	354	30	384	2,100	1,800	3,900	2,500	2,000	4,500	293	343
Bulgaria	158	0	158	3,000	0	3,000	3,500	0	3,500	237	279
Cyprus	0	0	0	300	0	300	500	0	500	25	42
Czech Republic	150	0	150	1,600	0	1,600	1,800	0	1,800	121	138
Denmark	2,771	409	3,180	3,700	2,300	6,000	4,000	2,500	6,500	235	277
Estonia	78	0	78	500	0	500	500	100	600	35	44
Finland	119	24	143	1,500	400	1,900	2,000	1,000	3,000	146	238
France	3,404	0	3,404	19,000	4,000	23,000	20,000	6,000	26,000	1,633	1,883
Germany	23,891	12	23,903	41,000	8,000	49,000	42,000	10,000	52,000	2,091	2,341
Greece	985	0	985	6,500	0	6,500	8,300	200	8,500	460	626
Hungary	127	0	127	900	0	900	1,200	0	1,200	64	89
Ireland	977	25	1,002	5,000	1,000	6,000	6,000	1,000	7,000	417	500
Italy	3,736	0	3,736	15,000	500	15,500	17,000	1,000	18,000	980	1,189
Latvia	27	0	27	200	0	200	200	100	300	14	23
Lithuania	54	0	54	1,000	0	1,000	1,000	100	1,100	79	87
Luxembourg	35	0	35	300	0	300	700	0	700	22	55
Malta	0	0	0	100	0	100	200	0	200	8	17
Netherlands	1,978	247	2,225	5,000	4,500	9,500	5,400	6,000	11,400	606	765
Poland	472	0	472	10,000	500	10,500	12,000	500	12,500	836	1,002
Portugal	2,862	0	2,862	7,500	0	7,500	9,000	0	9,000	387	512
Romania	10	0	10	3,000	0	3,000	3,500	0	3,500	249	291
Slovakia	3	0	3	800	0	800	1,000	0	1,000	66	83
Slovenia	0	0	0	500	0	500	700	0	700	42	58
Spain	16,740	0	16,740	39,000	1,000	40,000	41,000	1,500	42,500	1,938	2,147
Sweden	888	133	1,021	4,000	3,000	7,000	8,000	3,000	11,000	665	832
UK	2,650	591	3,241	13,000	13,000	26,000	14,000	20,000	34,000	1,897	2,563
EU-27	63,464	1,471	64,935	190,000	40,000	230,000	210,000	55,000	265,000	13,755	16,672

Table 2-10: Wind power scenarios for EU-27. [9]

2.3.3.2 TradeWind

TradeWind [30] was a research project funded by the Intelligent Energy Europe (IEE) and co-ordinated by the EWEA. It assessed the challenges related to wind energy integration in the trans-European market. The research focus was on cross-border power flow and the influence on the power market, the work included 8 work packages. The project lasted from November 2006 until February 2009 and has after this been used as a reference for several projects. Scenarios (high, medium and low) were developed for the years 2010, 2015, 2020 and 2030 and the area studied includes in addition to the North Sea, Kattegat and Skagerrak, the English Channel, the Irish Sea, the Baltic Sea, the

Norwegian Sea. Specific scenarios where made to study the effects off an offshore grid [31], these are given in Table 2-11.

	2005	2008 L	2008 M	2008 H	2010 L	2010 M	2010 H	2015 L	2015 M	2015 H	2020 L	2020 M	2020 H	2030 L	2030 M	2030 H
BE	0.0	0.1	0.1	0.2	0.2	0.2	0.3	0.5	0.5	0.8	0.5	1.3	1.5	0.7	3.0	3.8
DE	0.0	0.0	0.1	0.2	0.1	0.9	1.7	3.8	9.8	12.5	9.8	20.4	24.6	20.0	25.0	30.0
DK	0.4	0.5	0.5	0.6	0.6	0.7	0.8	0.9	1.0	1.1	1.4	1.6	1.8	2.7	3.0	3.3
ES	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	2.0	4.0	2.5	5.0	7.0	4.5	9.0	10.0
FR	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.0	2.0	2.0	4.0	4.0	4.0	4.0	4.0	4.0
GB	0.2	0.6	1.6	2.1	2.0	3.3	3.8	2.5	4.8	5.8	3.0	6.3	7.8	3.5	33.0	33.0
GR	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.3	0.3	0.3	0.4	0.4
IE	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.4	0.7	0.3	0.4	0.8	0.3	0.5	1.0
NL	0.0	0.1	0.2	0.2	0.2	0.5	0.7	1.3	2.0	3.0	2.2	3.5	6.0	2.2	12.0	20.0
NO	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.7	0.0	0.5	1.9	0.0	2.5	7.3
SE	0.0	0.1	0.2	0.2	0.3	0.4	0.6	1.1	1.8	2.6	2.4	3.8	5.5	4.1	5.8	11.0
FI	0.0	0.0	0.0	0.1	0.1	0.1	0.2	0.2	0.6	1.1	0.7	1.2	2.1	1.2	1.8	3.9
Sum	**0.8**	**1.7**	**3.1**	**3.7**	**3.8**	**6.3**	**8.3**	**13.7**	**25.2**	**34.4**	**27.0**	**48.1**	**63.2**	**43.5**	**99.9**	**127.7**

Table 2-11: Updated offshore wind power capacity scenarios (GW) [31]

2.3.3.3 Greenpeace – "A North Sea Electricity Grid [r]evolution"

The [r]evolution report [32] was published in 2008 by Greenpeace, as a contribution to the energy debate. With this report they wanted to show how "*a massive expansion of offshore wind power by 2020-2030 would work in practice*."[32] The wind power scenario in this report is developed in close relation to the TradeWind study. The area studied includes the North Sea only and the time horizon for the scenario is 2020-2030.

COUNTRY	INSTALLED CAPACITY [MW]	ELECTRICITY / YEAR [TWH]	AVERAGE CAPACITY FACTOR [%]	TOTAL ELECTRICITY CONSUMPTION 2006 [TWH]
Belgium	3,846	13.1	38.9	89.9
Denmark	1,577	5.6	40.5	36.4
France	1,000	3.4	38.8	478.4
Germany	26,418	97.5	42.1	559.0
Great Britain	22,238	80.8	41.5	405.8
Netherlands	12,039	41.7	39.6	116.2
Norway	1,290	4.9	43.7	122.6
Total	**68,408**	**247.0**	**41.2**	**1,808.3**

Table 2-12: Offshore wind power scenario for the North Sea [32]

2.3.3.4 OffshoreGrid

The OffshoreGrid project is a techno-economical study within and funded by the IEE program. It aims to develop a scientific view on a transnational offshore grid in North Europe along with a suited regulatory framework, targeted for policy makers, industry, transmission system operators and regulators [33].Project start-up was in May 2009 and it is expected to finish in 2011. The studied time horizon for the scenarios was 2008, 2010, 2015, 2020, 2015 and 2030. Their wind scenarios are mainly based on TradeWind and EWEA scenarios, though new records have also been added. Regarding the area studied, this also includes the Baltic Sea, the English Channel and the Irish Sea in addition to the North Sea.

2.3.3.5 ENTSO-E – "Offshore Grid Development in the North Sea"

The European Network of Transmission System Operators for Electricity (ENTSO-E) represents all European TSOs as well as TSO in connecting areas. This body covers Europe wide planning and operation roles. It was founded by the TSO with the intention of playing an important role in the rule (and regulation) making process like the EU's 3rd Energy Package as well as pushing network codes and Europe wide network planning. A recent report, "Offshore Grid Development in the North Sea" [34], was published in February 2011. This report presents the views and recommendations of the ENTSO-e together with expected volumes of offshore wind. A specific assumed volume for 2020 is taken as a starting point for the 2030 scenario. The area studied includes Skagerrak and Kattegat in the North Sea and excludes the English Channel and the Irish Sea.

Country	Starting position (2020) in GW	Potential volumes that could be expected by 2030 in GW
Belgium	2	4
Denmark	1	3,4
Germany	10	24
The Netherlands	2	12
Norway	0	1
Great Britain	11,5	38,5
Total	**25,5**	**82,9**

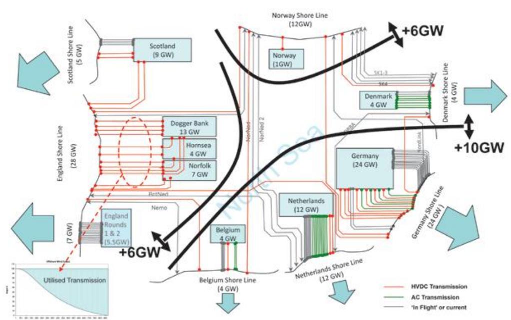


Table 2-13: Expected offshore wind in the North Sea (incl. Skagerak, Kattegat, Irish Sea and English Channel) [34]

2.3.3.6 WINDSPEED

The Windspeed project [3] is supported by IEE and involves from partners from large research institutes in Norway, The Netherlands, UK and Germany. Its final deliverable was recently published, presenting a roadmap defining realistic targets and developments up to 2030 for offshore wind energy in the central and northern North Sea. In this study four different scenarios are made depending on different aspects influencing the offshore wind development. The scenarios and resulting total numbers can be seen in the figures below.

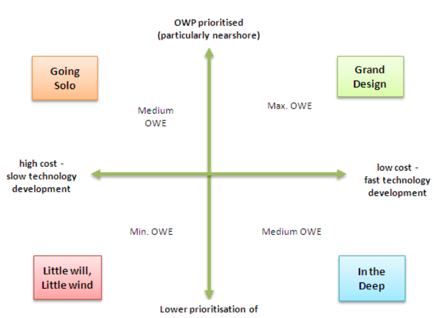


Figure 2-9: Windspeed scenarios [3]

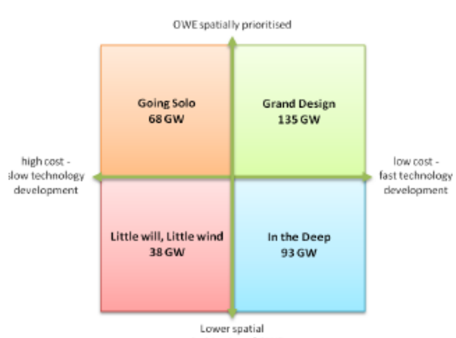


Figure 2-8: Overview of resulting capacities for the 2030 scenarios [3]

3 Wind Speed Data

This chapter will discuss wind data for wind integration studies. Being a complex and extensive field of study, this can only serve as an introduction. For further reading please consult the references. As available real wind data measurement are limited, large scale studies cannot solely be built on those and wind data must be obtained elsewhere. An introduction to some of the existing wind data sources will here be given, followed by an overview of the wind speed data used in some of the larger wind integration studies. The data used in this thesis will then be presented and finally, as an alternative to the previously discussed sources of data, a method for developing artificial wind speed series is described.

3.1 Obtaining Wind Data

Different sources of wind data with varying levels of detail and accuracy are available. Among these, two main sources of data can be defined – real measurements or computer model output.

Real measurements are first of all limited. Though weather data is collected from a range of sources these measurement stations are sparsely spread out, especially offshore and supply data of variable accuracy. On-site measurements offshore are commonly carried out using cup-anemometer or non-tower based remote sensing devices such as SODAR (Sound Detection and Ranging) or LIDAR (Light Detection and Ranging). Other sources collecting offshore weather data in the observational network are meteorological buoys, light vessels and observation platforms.

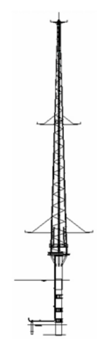


Figure 3-1: Meteomast

One useful and widely used global source of wind data is the Re-analysis project [35]. This project aimed to produce a homogenous data set of wind data, covering at least a decade and processed with the same assimilation methods. Data was collected from numerous measurement stations and used as input for a numerical weather prediction model. The project resulted in a consistent global long term Re-analysis dataset, though with a relatively coarse resolutions. Examples of such data sets are Re-analysis data from the National Centre for Atmospheric Research (NCAR, USA) , the National Centre for Environmental Prediction (NCEP, USA)[36], and the Re-analysis data set (ERA40) from the European Centre for Medium-Range Weather Forecasting (ECMWF)[37].

For more detailed studies of wind at specific locations, the relatively high spatial and temporal resolution of long term data sets such as the Re-analysis data, might not be sufficient. As an alternative to direct observations, localised wind speed data can be derived from long term wind speed data sets. Statistical data mining is one way of achieving such downscaling, where the measure, correlate predict (MCP) method can be used for spatial downscaling. Though a good alternative to data mining are the numerical weather simulations (NWS) [15]. These models aim to simulate the physics of the atmosphere, given a set of initial conditions and within certain boundary conditions solving equations describing the relations between the atmospheric variables. These models require large amount of computational power and might be restricted by this. The synoptic scale models operated for larger areas do result in a coarse resolution and cannot model all physics in detail. A higher detail level can be obtained for so called mesoscale models, being NWS models operated on smaller temporal and spatial scales.

When no measurement data available the 'wind atlas method' is commonly used. A wind atlas can be defined as a: '*…collection of regional wind climates (RWC) derived by the wind atlas methodology*' [1] represented by a volume of tables, chart or plates. Such a representation can be seen in Figure 3-3. This methodology makes it possible to give information about one site (prediction site) based on information from another site (predictor site). It can further be divided into observational wind atlas methodology, where the predictor site is a real measurement site and numerical wind atlas methodology, where the predictor site is a virtual measurement site. The wind atlas methodology is currently available in the form of the WA^{S}P program which has been applied in national, regional or local studies of the areas seen in Figure 3-2.

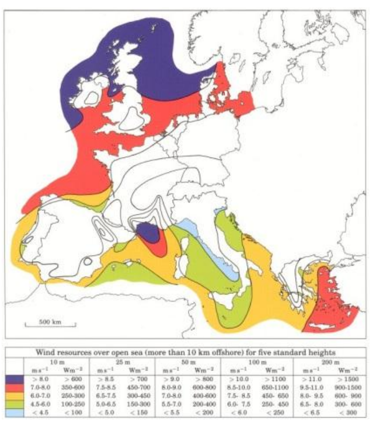


Figure 3-3: A Wind Atlas picture of offshore wind speeds [1]

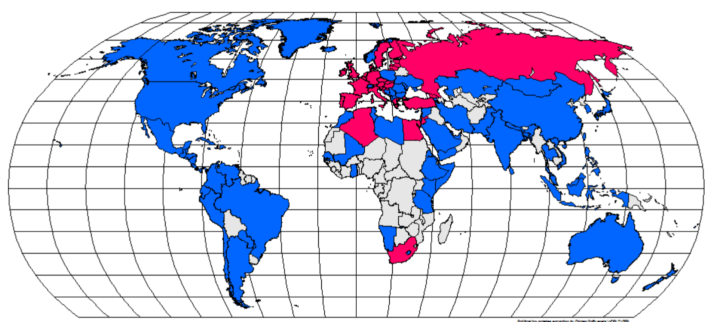


Figure 3-2: Areas with existing wind atlas [1]

The above discussion is mainly related to achieving long term data. Short term modelling (forecast) is a somewhat different topic, usually performed through NWP. The High Resolution Limited Area Model (HIRLAM) of the Danish meteorological institute is one of those. It is run on-line twice a day and had in 1997 a maximum prediction horizon of 48 hours [38]. Such short time scheduling is important in the operation of the power system as the conventional power generation is scheduled based on expected wind power production. With increasing amounts of wind power this forecasting is becoming more crucial. This thesis will further focus on long term wind speed data.

3.2 Wind Speed Data in Wind Integration Studies

In order investigate common practice for wind data use in wind integration studies, an overview of the type of data used in a few of these larger studies is presented briefly.

The **TradeWind** project used the Reanalysis data from the national Centre for Environmental Prediction (NCEP). With 6 hourly data for a grid of 2.5 degrees spacing, this is data with relatively high temporal and spatial resolution as can be seen in Figure 3-4. For the purpose of the study hourly data was needed and the original reanalysis data was linearly interpolated and downscaled to hourly data.

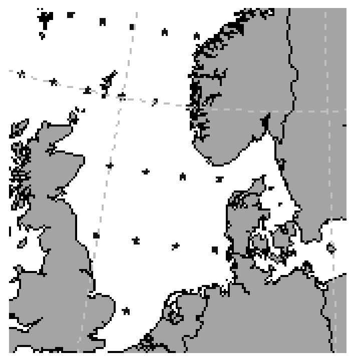


Figure 3-4: Re-analysis data grid used in the TradeWind study

The **Western wind and Solar Integration Study** a mesoscale numerical weather prediction model was used to create a fine gridded data set with 2 km spatial resolution and 10 min temporal resolution.

The **OffshoreGrid study** used the Weather Research and Forecasting model (WRF), a mesoscale numerical weather prediction model, having global analysis data (Final analysis, FNL) from the United States' National Centre for Environmental Prediction as input data. The resulting 6 hourly, 1 degree spaced data was downscaled to hourly values on a 9km by 9km grid.

The **Greenpeace study** used similar data as the OffshoreGrid study.

The **WINDSPEED study** investigated wind resource potentials based on a combination of three independent sources: offshore mast measurements, earth observation data and mesoscale modelling.

3.3 Wind Speed Data in This Study

In this study two sets of data from different sources are used. The first data set is the hourly Re-analysis data used in the TradeWind study. It will be used in the development of the wind speed model presented later in this chapter and for comparison purposes with the other data set. The second source is a more extensive data set with higher temporal and spatial resolution. This is the main data set and the results from the power calculations with this data will be given to the NSTG project and in thesis serve as input for the power system model in chapter 5. The provider[3] of the second data set gives the following description: 'Modelled meteorological data with 10 minute and 9x9 km resolution including virtual potential temperatures and gradients, wind speed and direction, pressures at multiple heights, Monin-Obuhkov length, friction velocity and boundary layer height, derived based on a mesoscale regional re-analysis.'[39] The background data for this modelling is the NCAR/NCEP reanalysis data. These data sets will further be referred to as the TradeWind data and the Sander data.

3.3.1 Data corrections

As the real system is highly complex and a detailed modelling and simulations require extensive computational power, weather simulation models are not yet capable of perfectly modelling all the mechanisms involved. This may result in the output being somewhat inconsistent, having certain unphysical features and differ from real measurement data depending on the input data, the model used, the computational power etc.

In [15] strength and weaknesses of excising techniques for developing wind data for wind integration studies are discussed. Some comment are there given on the corrections applied to the wind data used in the Western Wind and Solar Integration Study (WWSIS). Due to the magnitude of the area needed to be modelled at high resolution and the limitations in processor memory they were forced to divide the area into smaller domains. This resulted in the edges of the domain not becoming perfectly aligned and as a correction method the data were 'blended' at the overlapping boundaries, resulting in a single large dataset. It is also stated that numerical weather prediction models have a tendency of producing smoothed wind speed series not accurately capturing the natural short time variations.

Regarding the Sander data available for this study, some corrections had to be done to the data in addition to adjustment techniques applied by the provider. Among the latter adjustments was 'nudging' of the simulation output data to closer approach the background data. From the data received from the provider, 3 years of wind speed data could be extracted. These were however not all complete years and included some unphysical jumps in the values around midnight. The latter caused by frequently restarting of the model as it only runs for one day at the time. Corrections were needed to smooth theses jumps and it was decided to apply a ramp correction. This correction can be seen in Figure 3-5.

[3] Sander + Partner, Switzerland

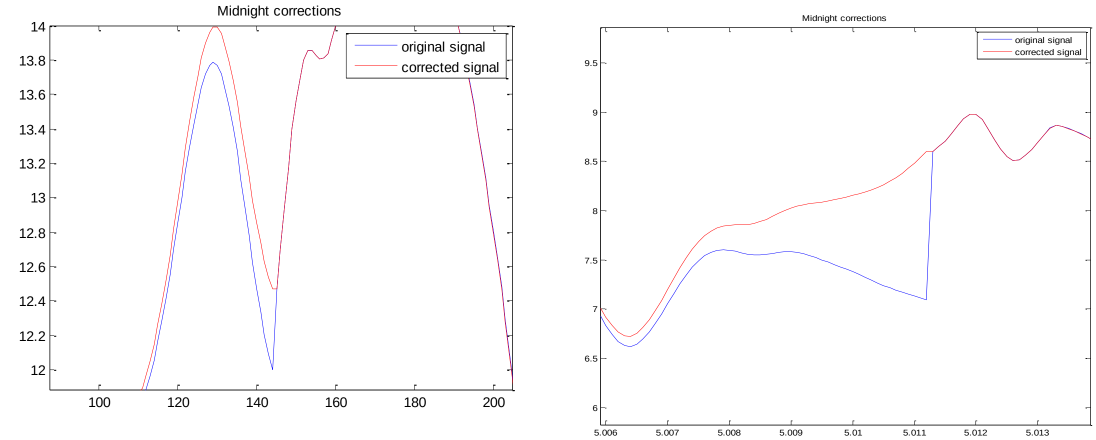


Figure 3-5: Examples of midnight corrections performed on the Sander data

3.4 Stochastic wind data modelling

An alternative source of wind speed data is artificial wind data simulated from time series models. A statistical model is extracted from an available data source (e.g. measurement data) and by capturing certain characteristics of the source data arbitrary amounts of wind speed data can be created. Such methods can be used to create stochastic generation scenarios [40] and in this case create arbitrary amounts of wind data. Among the methods available are Markov Chains [41], ARMA[4] [42] [43], ARMA-GARCH[5] [44] etc. In this case a simple multivariate vector auto-regression (VAR) model is chosen. To build this model a multivariate time series from the TradeWind reanalysis data is used, consisting of three years (2000-2002) of 6 hourly measurements of wind speeds for two locations (35N, -10E and 35N, -7.5E), in a distance of approximately 280 km.

3.4.1 Characteristics of wind speed time series

A model creating artificial wind time series should be capable of reproducing the characteristics of such time series. In order to know which properties to pay attention to in the process of building the model and in the validation of the results, these characteristics must be identified. Thus the identified main characteristics are: distribution, temporal dependence (autocorrelation) and periodic behaviour (daily and seasonal trends) and spatial dependence (cross correlation). These will first be discussed in more detail before the VAR-method is introduced.

[4] Autoregressive Moving Average

[5] Autoregressive Moving Average - Generalised Autoregressive Conditional Heteroskedasticity

3.4.1.1 Distribution

As can be seen from the empirical distribution plot (histogram) in Figure 3-6, the wind speed data does not have a normal distribution.

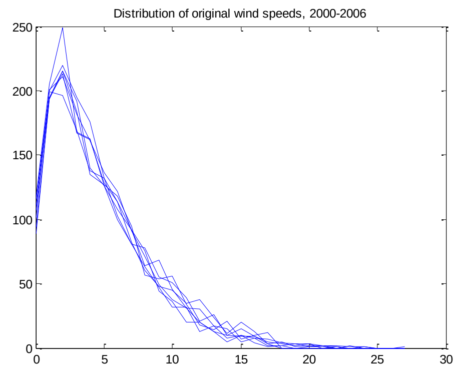


Figure 3-6: Empirical distribution plot of the original wind speed data

The shape of the distribution function is not symmetric but skewed with a tail toward the higher quantiles and only positive values occurs as wind speed cannot be negative. The wind speed is often assumed to be Weibull distributed as it has been found to describe the distribution of the wind speed data well [45] [46] [47] The probability density function for a Weibull random variable x is given in eq. 3-1.
Where k > 0 is the shape parameter and λ > 0 is the scale parameter.

$$F(x;\lambda,k) = \begin{cases} \frac{k}{\lambda}(\frac{x}{\lambda})^{k-1} e^{-(x/\lambda)^k} & x \geq 0, \\ 0, & x < 0, \end{cases} \qquad \text{3-1}$$

3.4.1.1.1 Daily and seasonal trend

On a daily base the wind speed series may have a daily pattern known as a diurnal pattern. This is caused by temperature differences between sea and land, which increases as the sun heats the land areas, causing the wind speed to increase accordingly. Due to this temperature relation it can further be expected that the wind speeds differs somewhat between the seasons. The strength and visibility of such daily and seasonal trends are largely dependent on the location. Offshore locations have stronger winds than onshore locations, because of less roughness of the surface and a daily pattern is often not present. Regarding the effect of the seasons it can be expected that the wind on average will be lower in the summer months. Whether a seasonal trend is present or not can be detected by plotting monthly averages or seasonal averages of the wind speed series. Daily trends can be detected by plotting the hourly wind speeds or by an autocorrelation plot.

3.4.1.1.2 Checking for seasonal trends in the original wind speed time series

The first step to identify a seasonal trend in the wind series is a purely visual evaluation of a plotted time series of one (or more years). Two such plots of a one year long time series are given in Figure 3-7. In both of the time series the presence of a ‘u’ shaped trend, with higher wind speeds in the start and the end of the year, is visible. This pattern is clearer in Figure 3-8 showing monthly averages for 7 years of the original data.

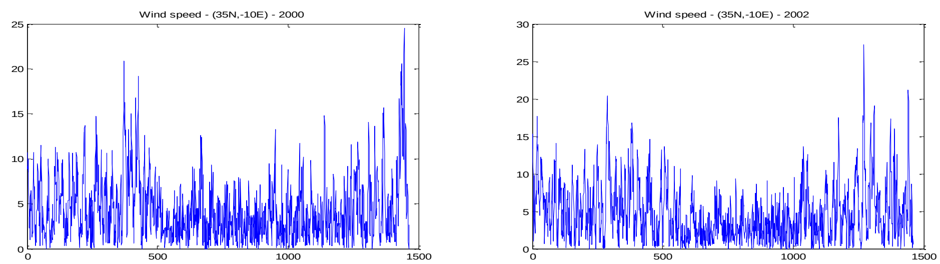


Figure 3-7: Original wind speed time series

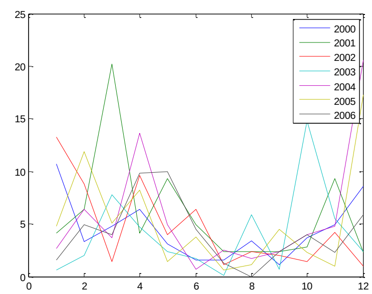


Figure 3-8: Monthly averages for 7 years of original wind speed data

To investigate this further a box-plot of the wind speed per month is plotted for three years of data (2000- 2002). The box-plot shows the median value as a red line, the edges of the box is the 75^{th} and 25^{th} percentiles and the whiskers include the rest of the data not considered as being outliers, the latter is plotted as red crosses.

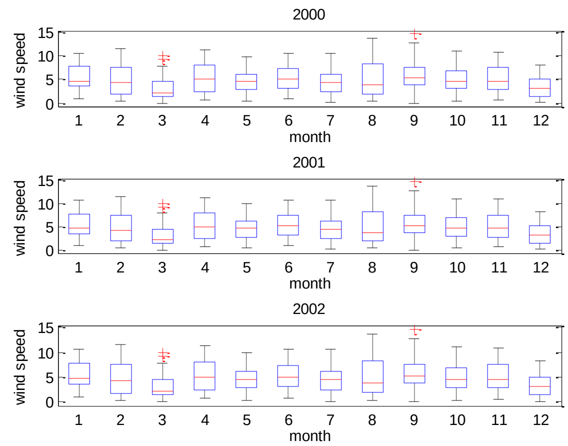


Figure 3-9: Box-plots of monthly wind speed ranges for the original wind speed data

In the box-plots some variations in wind speed can be seen, though the trend is not very clear. By dividing the year into 'seasons[6]' and plotting only the average wind speed per season, the possible seasonal variations should be more visible. Thus for one location, five averages per year is computed and plotted for 7 different years. The result is given in Figure 3-10.

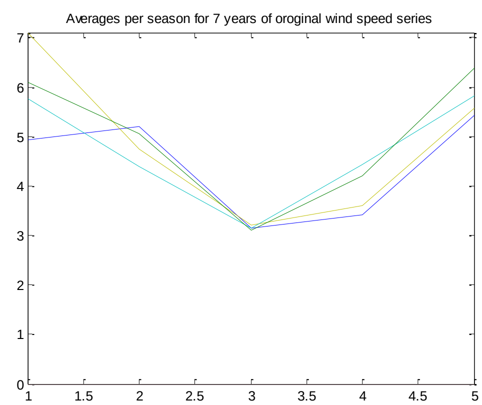


Figure 3-10: Average wind speed per 'season' for 7 years of the original wind speed data

As was expected, the plotted values show a clear tendency of higher wind speeds in the start and in the end of the year, corresponding to the winter months. In the summer months the average wind speed is the lowest, creating an u-shaped graph. The wind speeds do also seem to be more stable in this period while the winter months have a larger variation.

It can thus be concluded that significant seasonal trend is present in these wind speed series. Consequently, the data must be treated for this before it can be used to fit the VAR-model.

---

[6] The year is here divided into five periods/seasons

3.4.1.1.3 Checking for daily trends in the original wind speed series

A daily trend, also known as a diurnal trend, is another important feature of wind speed series. Because of temperature differences between sea and land, the wind often blows stronger in the middle of the day. This is however dependent on the season and the location. When a daily pattern is present it can be expected to be stronger in the summer than in the winter but for location at sea there is often no daily pattern. In order to check for daily trends in the wind speed data, plotted average values per hour of the day for each of the seasons are plotted in Figure 3-11.

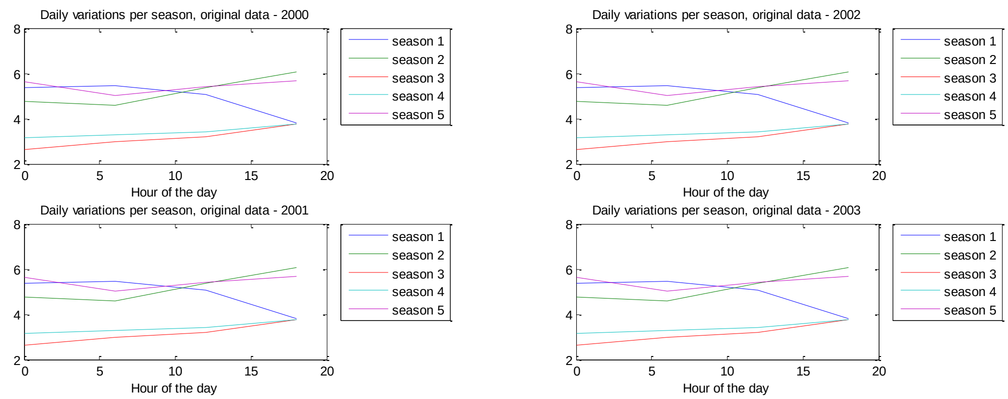


Figure 3-11: Average value per hour of the day for each of the five 'seasons'. For 4 years of original wind speed data

From these plots it can be seen that the seasonal variations are important also in relation to the daily variation. Different daily patterns can be seen depending on the season. For most of the seasons the wind speeds seems to have the lowest value in the early morning (around 06.00) and then increase during the day before decreasing again in the evening (after 18.00). In the start of the year the trend is quite different, with the highest wind speed in the morning followed by a decrease during the day. A daily trend cannot clearly be seen and no conclusion regarding the daily trend can be drawn.

3.4.2 Correlation

As the wind at one point of time is related to the wind at the next time step and the wind at one location is related to wind at another location, wind speed time series are temporal and spatial correlated. A scatterplot is one way to show correlation, where a higher correlation corresponds to the points being centred along the x=y line, as can be seen in Figure 3-12. This correlation is an important property that needs to be captured in the simulated stochastic process.

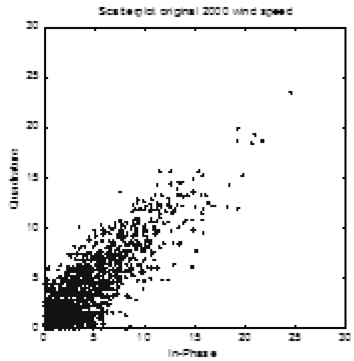


Figure 3-12: Scatter plots of an original wind speed time series (year 2000)

3.5 Method

3.5.1 VAR-model

The VAR-model is a model used to capture the evolution and the interdependencies between multiple time series .It is described by a linear function of the variables past evolution as described in eq. 3-2.

$$Y_{(t)} = A_1 Y_{(t-1)} + A_2 Y_{(t-2)} + \ldots + A_p Y_{(t-p)} + \varepsilon_t \qquad 3\text{-}2$$

- $Y_{(t)}$ = A N x 1 vector containing the wind speeds at time t for N locations.
- A_1, A_2 … A_p = N x N coefficient matrices in the model equation
- p = number of time lags
- ε_t = error term, ~ N (0,σ) , where σ is a N x N matrix

With N =2, the equations are as follows:

$$\begin{bmatrix} y_{1(t)} \\ y_{2(t)} \end{bmatrix} = \begin{bmatrix} a^1{}_{11} a^1{}_{12} \\ a^1{}_{21} a^1{}_{22} \end{bmatrix} \begin{bmatrix} y_{1(t-1)} \\ y_{2(t-2)} \end{bmatrix} + \ldots + \begin{bmatrix} a^p{}_{11} a^p{}_{12} \\ a^p{}_{21} a^p{}_{22} \end{bmatrix} \begin{bmatrix} y_{1(t-p)} \\ y_{2(t-p)} \end{bmatrix} + \begin{bmatrix} \varepsilon_{t1} \\ \varepsilon_{t2} \end{bmatrix} \qquad 3\text{-}3$$

3.5.2 Requirements regarding normality and stationary behaviour

It is important to consider the distribution of the wind data. Looking at the distribution of the raw wind speed data Figure 3-13, it is clear that it is not a normal distribution. Since the VAR-model can only be applied to normally distributed data, the raw data must first be pre-processed and transformed to normality.

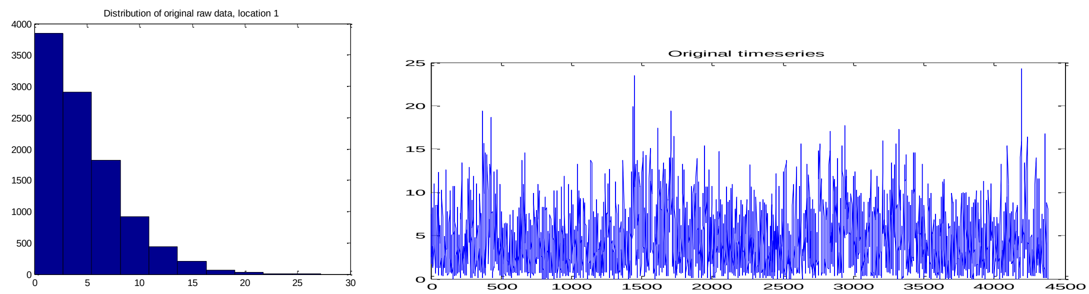


Figure 3-13: An original wind speed time series and its distribution

Another requirement for using the VAR-model is a stationary time series. According to [48] t*ime 'series { X_t , t=0, ± 1, … } is said to be stationary if it has the statistical properties similar to those of the "time-shifted" series { X_{t+h} , t=0, ± 1, … } for each integer h.'* Wind speed series with their periodic variations are according to this examples of non-stationary time series. As both daily and seasonal trends are present in the wind speed data, those trends must be removed from the time series before used to create the VAR-model.

3.5.2.1 The algorithm

The algorithm used for creating synthesized multivariate time series can be described briefly as follows, based on [49] [44] [40]:

1. Transform into normality domain
   a. sort the data according to the season and the hour of the day
   b. transform each hour (diurnal trends) per season (seasonal trends) separately to uniformity
   c. transform the uniformly distributed time series to normality
2. Identify the VAR model
   a. Estimation of parameters
3. Simulate synthetic time series based on the identified model
4. Back-transform the simulated multivariate time series to wind speed domain
   a. Reversed procedure of the transformation process
5. Validation
   a. Check if the simulated data has the same characteristics as the original data

3.5.3 Pre-processing of data (Transformation)

The features of the wind speed series not compatible with the requirements of VAR-modelling are: the distribution (non-normality) and the seasonal and diurnal trends (periodicity).

There are several ways in which trends can be removed, trend components can be estimated and subtracted from the data or the data can simply be differentiated [48]. None of those methods were found to give a satisfactory result in this case. In this case the trends are taken care of in the transformation process to normality. The procedure is illustrated in Figure 3-14. By rearranging the data and sorting it by season and hour of the day, data from different time periods can be transformed separately. In this way, only data with the assumed same characteristics are transformed together and the different characteristics are captured in the transformation process. This is important since the information from this transformation will be used again to back-transform the simulated artificial data, in order to give it the same characteristics as the original data. Thus, for each season the wind speed at a certain hour is transformed separately, taking into the account the differences in the trend component and the transformation to normality is in this way taking care of the trends.

	Hour	Data for one year
Season 1	**1**	
	6	
	…	
	24	
…	**1**	
	6	
	…	
	24	
Season 5	**1**	
	6	
	…	
	24	

Figure 3-14: Data rearranging before transformation

The resulting outcome from the transformation is then checked if it is ready for VAR application, e.g. being stationary and normally distributed. A time series from the new domain is plotted in Figure 3-16 and its distribution in Figure 3-15.

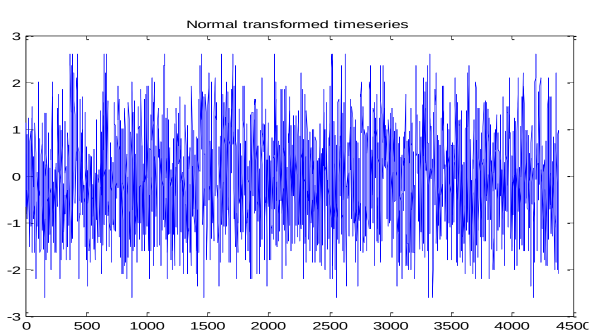


Figure 3-16: Transformed time series

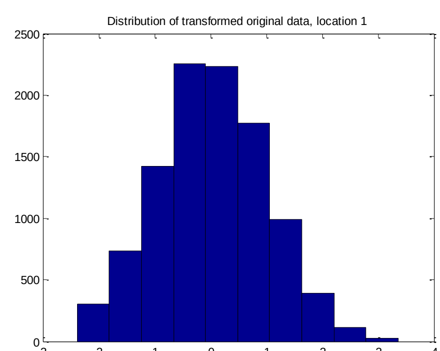


Figure 3-15: Distribution of transformed time series

3.5.4 VAR-model specification and estimation

Before the model parameters can be estimated the model is specified by choosing the number of time lags (p) included in the model. An optimal number can be found though an information criteria (AIC[7] [50] or BIC[8] [51]), based on a goodness of fit measurement and a so-called penalty function. As these criteria are included in the Matlab *arfit* – package, the selection of lags (p) is automatically included in the method. The remaining parameters describing the VAR-model, as given in eq. 3-2, are further estimated using the maximum likelihood estimator implemented in the Matlab package. The resulting values are given in Table 3-1 together with the estimated error and the calculated t-statistics. The t-statistics indicates if the parameters are statistically significant and is calculated according to eq. 3-4 e.g. by taking the parameter itself and divided it by its error. If this value is greater than 2 the corresponding parameter can be regarded as being statistically significantly different from zero.

$$Tstat_i = \frac{a_i}{a_{i,err}} \qquad \text{3-4}$$

- Coefficient matrix: $A = [A_1, A_2, (\ldots), A_p]$ where A_1 - A_p are k x k matrices.
- Number of time series : $k = 2$
- Number of chosen lags: $p = 5$.

	P=1		**P=2**		**P=3**		**P=4**		**P=5**	
A-matrix	**a11**	**a12**	**a13**	**a14**	**a15**	**a16**	**a17**	**a18**	**a19**	**a110**
	0,4750	-0,0212	0,1705	-0,0680	0,0229	-0,0361	0,1725	0,0409	-0,1067	-0,0312
	a21	**a22**	**a23**	**a24**	**a25**	**a26**	**a27**	**a28**	**a29**	**a210**
	0,2370	0,2536	0,0511	0,0667	-0,0122	-0,0289	0,1494	0,1349	-0,1350	-0,0436
Aerr	**da11**	**da12**	**da13**	**da14**	**da15**	**da16**	**da17**	**da18**	**da19**	**da110**
	0,0375	0,0366	0,0400	0,0375	0,0403	0,0378	0,0400	0,0375	0,0386	0,0361
	da21	**da22**	**da23**	**da24**	**da25**	**da26**	**da27**	**da28**	**da29**	**da210**
	0,0382	0,0373	0,0407	0,0382	0,0411	0,0385	0,0408	0,0383	0,0393	0,0368
T-stat	**t11**	**t12**	**t13**	**t14**	**t15**	**t16**	**t17**	**t18**	**t19**	**t110**
	12,6642	-0,5788	4,2681	-1,8128	0,5673	-0,9552	4,3087	1,0906	-2,7684	-0,8655
	t21	**t22**	**t23**	**t24**	**t25**	**t26**	**t27**	**t28**	**t29**	**t210**
	6,1974	6,7947	1,2538	1,7445	-0,2966	-0,7504	3,6610	3,5236	-3,4344	-1,1842

Table 3-1: Model parameters

[7] Akaike Information Criterion.
[8] Bayesian Information Criterion.

A few comments can be made regarding the a-values for the first lag (p=1). At location one the parameter related to the previous wind speed at the same location (a_{11}) is definitely significant while the parameter related to the previous wind speed at the other location (a_{12}) is not. Thus regarding the previous time step, location one is mostly dependent on how the wind blew at the same location. For location two, a different result can be seen. Regarding the previous time step, this location seems to be just as dependent on location one as location two. The t-statistics should be simultaneously looked at to have an idea about the significance of the parameter.

3.5.5 Post processing of the data (Back-transformation)

The simulated time series are back transformed to obtain the same characteristics that were removed from the original time series. Information from the transformation of the original time series to normality is stored and used for the back transformation. In this way the characteristics of the original distribution as well as the daily and the seasonal variations are reproduced in the artificial time series. Whether the model succeeds in doing so will be checked in the following section.

3.5.6 Validation of model

In this part the original time series are compared with the artificial time, in order to validate the model results.

3.5.6.1 Visual comparison

A simulated time series is in Figure 3-17 plotted against the one of the original time series used to build the model. They should obviously not be equal, though not possess any major significant differences.

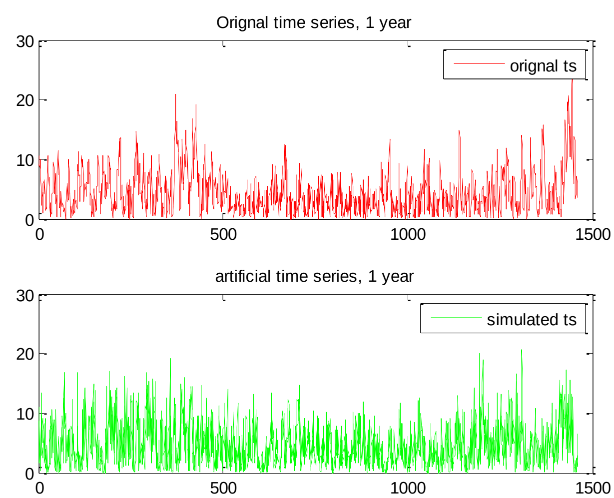


Figure 3-17: Original time series versus simulated time series

The plotted time series are in the same range of magnitude, both have some kind of seasonal variation and a mean reverting behaviour. By visual comparison, there seems to be no significant difference and the next step is thus statistical validation.

3.5.6.2 Distributions

When comparing distributions of single time series which are not equal and of limited length some deviation in the results can be expected. However, by simulating multiple time series a confidence bound can be formed. If the original time series can be found in this confidence bound the model can be considered accurate with respect to distributions. In the figures below, 100 simulated time series are plotted together with the original time series. This is done for the same data in both the normality and the wind speed domain. In the wind speed domain, the simulated time series are plotted against both an original time series used to build the model (2000) as well as another time series (2006). This is done to expand the validation by showing that the simulated time series are indeed representative of the wind speed at this location and not only the wind speed series used to build the model. As can be seen in the figures the plotted original time series are all within the range of the simulated ones.

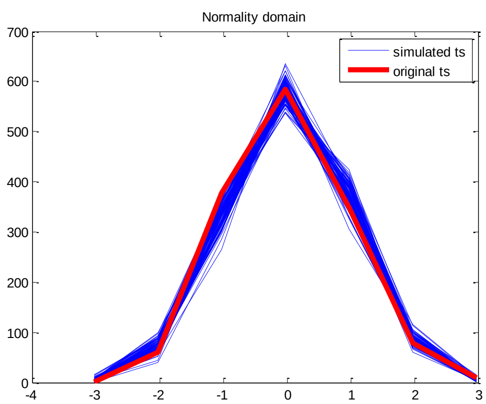


Figure 3-18: Distribution of simulated and original time series in normality domain

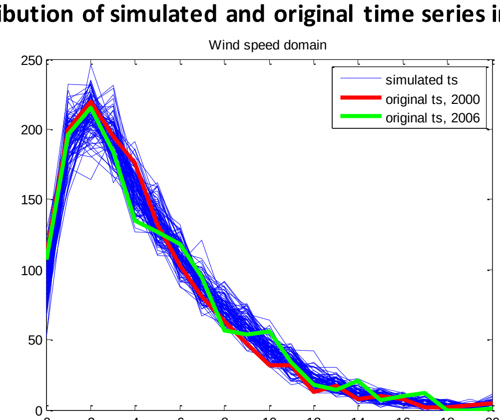


Figure 3-19: Distribution of simulated and original time series in wind speed domain

3.5.6.3 Correlation

3.5.6.3.1 Auto-correlation

Autocorrelation represent the correlation in time within one time series. Peaks in the plotted autocorrelation represent increased correlation at a certain lag frequency and suggest reoccurring patterns (trends) in the time series. In Figure 3-20 a simulated time series is plotted against two original time series, out of which one has been used to build the model (2000) and the other not (2006).

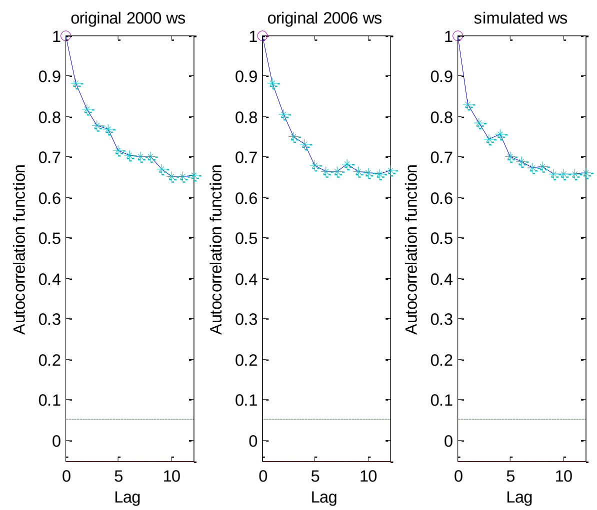


Figure 3-20: Autocorrelation plot of original versus simulated time series

The autocorrelation plots for the original and the simulated series does by visual inspection seem to be very similar. They both have a slow decay, the magnitudes are within the same range and all having small peaks at the 4th and 8th lag. With each lag being 6 hour, the 4th lag represents a 24 hour frequency and the 8th lag a 48 hour frequency. This can be translated into a diurnal pattern.

3.5.6.3.2 Cross-correlation

Cross-correlation represents the spatial correlation between simultaneous occurring wind speeds at different locations. The cross-correlation between the two locations is thus plotted for all the time lags. In Figure 3-21 100 simulated time series are plotted together with two of the original time series. It can here be seen that the correlation of the original time series are in the bound created by of the simulated.

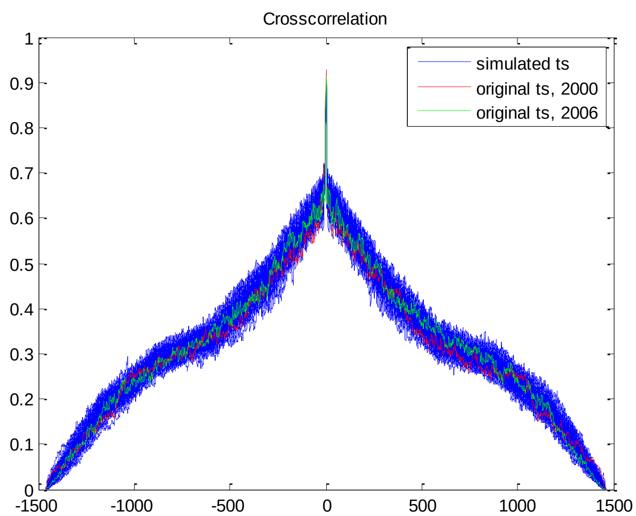


Figure 3-21: Cross-correlation of simulated time series vs. original time series for all time lags

3.5.6.4 Trends

Finally it will be checked it the model succeeded in capturing the characteristic of the original time series and reproducing the same trends as seen in the original time series plotted in 3.5.2. The autocorrelation check suggests that at least a diurnal trend should be present in the simulated data, though this trend was not very present in the preliminary plots of the data. Whether the more characteristic seasonal variations are captured should be more easily recognized.

3.5.6.4.1 Checking for daily trends in the simulated wind speed series

Daily variations in two simulated wind speed series are computed and plotted in the same way as for the original time series. The resulting graphs can be seen below.

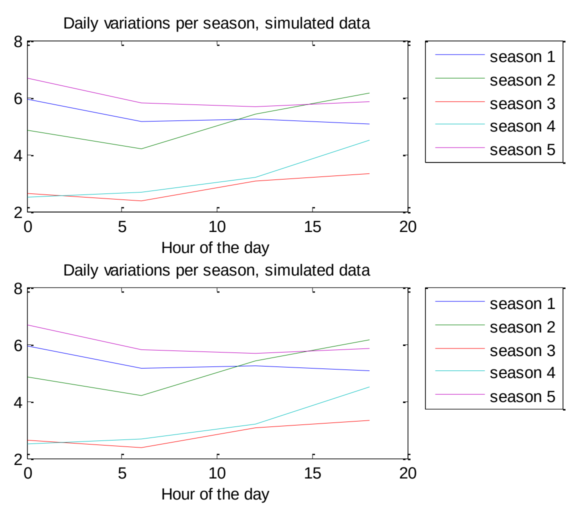


Figure 3-22: Averages per hour of the day per season for two simulated time series

The simulated wind speed series seems to follow the same pattern as the original series. It can consequently be assumed that the model is capable of capturing the different daily trends as well.

3.5.6.4.2 Checking for seasonal trends in the simulated time series

As was done for the original time series, the year is divided into five seasons and averages computed and plotted. This is done for 10 simulated/artificial time series and the result is given below.

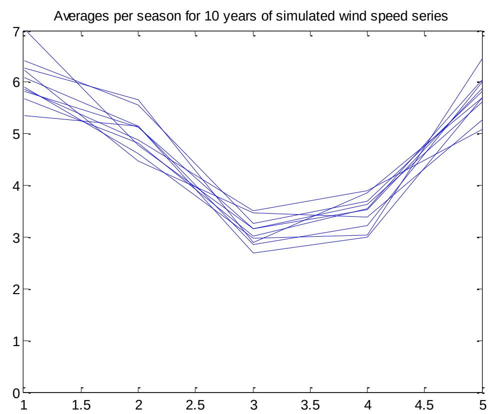


Figure 3-23: Average wind speeds per season for 10 simulated time series

Both in terms of the shape of the graph as well as the range of values, these simulated time series shows the same trend as the original wind speed series. Hence, confirming that the model is capable of capturing the seasonal trend feature of real wind speed series.

3.5.7 Model conclusions

A method for creating artificial stochastic multivariate time series, here representing wind speed time series, has here been presented. A brief validation has been done to show the strengths and possibilities of such a method. Though for further studies it is recommended to consider and check for conditional heteroscedasticity[9] [52], add a diagnostic checking of the residuals (Ljung-Box test) and possibly extend the validation section with. As it for this research (in relation to the NSTG project) was decided that the available amount of Sanders data would be sufficient for the further studies, the developed model with its capability of creating large amounts of wind speed time series, was not needed to be developed further.

[9] Heteroscedasticity – a sequence of random variables with different variance

4 Power Production

4.1 Wind to power

The power (P_w) in the wind that flows through the area A with ρ density and speed V is calculated according to eq.4-1.

$$P_w = \frac{1}{2}\rho A V^3$$ 4-1The

density of the air is dependent on air pressure and temperature, i.e. cold air contains more molecules per volume unit. Considering wind turbines, the area A is the area swept by the blades of wind turbine rotor.

$$P_w = \frac{1}{2}\rho A V^3$$ 4-1

The power (P_{wt}) extracted by the wind turbine is further dependent on the power coefficient Cp of the wind turbine as shown in 4-2. This power coefficient changes as the pitch angle θ and the tip speed ratio λ changes (i.e. the ratio between the blade tip speed and the wind speed).

$$P_{wt} = C_p(\lambda, \theta) P_w$$ 4-2

In the power calculations done for this thesis, a power curve is used to convert the wind speed to power.

4.2 Power Curve

The power curve describes the relationship between the wind speed and the power output for a specific turbine for wind speeds between the cut-in speed and the cut-out speed. It describes the performance of the turbine, though it should be noted that this performance is specified for a certain design and measured under certain conditions.

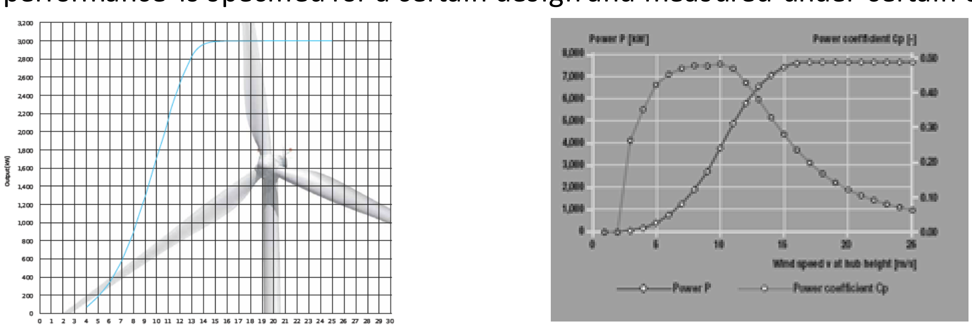


Figure 4-1 : Power Curves for a Vestas V90-3.0MW turbine [53] and an Enercon E-126 7.5 MW turbine [4]

In this case, one turbine was chosen to represent the whole wind turbine portfolio and two different currently available turbines were considered and compared. A Vestas V90 3 MW turbine, with a cut-in speed of 4 m/s and a cut-out speed of 25 m/s and a Enercon E-126 7.5 MW turbine, with a cut-in speed of 2m/s and a cut-out wind speed of 25 m/s. Different turbine concepts can be expected to have different power curves and these are plotted on a per unit base in Figure 4-1 : Power Curves for a Vestas V90-3.0MW turbine [53] and an Enercon E-126 7.5 MW turbine .

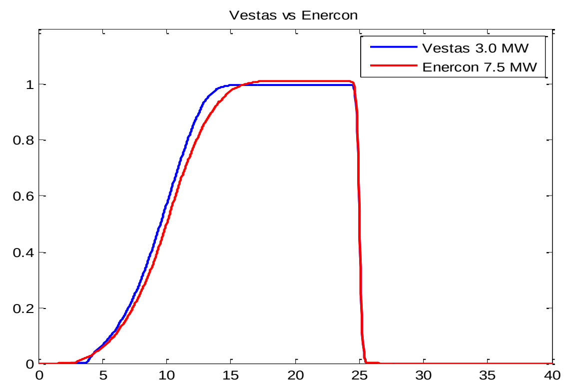


Figure 4-2: Comparison of the Vestas turbine and the Enercon turbine on a per unit base

When considering the trends in the offshore industry the first half of 2011 resulted in average installed capacity of 3.4 MW compared to 2.9 MW for the same period in 2010 [54]. The trend is clearly towards larger turbines as has been anticipated and can be seen in the proposed plans for future wind parks, e.g. The Round 3 Offshore Wind Park Study uses 5 MW and 7.5 MW as indicative wind turbines capacities. Based on the trends towards larger turbines, it was decided to use the 7.5 MW Enercon turbine, with a rotor diameter of 127 m and a hub height of 135 m.

4.2.1 Hysteresis and cut-out effect

To decrease the hysteresis and cut-out effect occurring at high wind speeds, storm control is available for some turbine types.

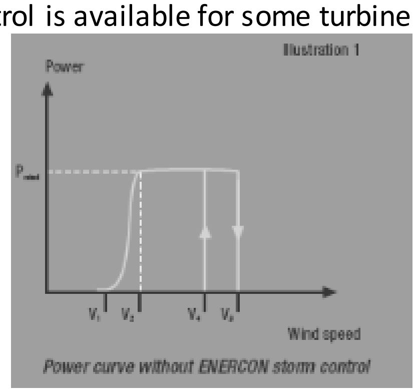


Figure 4-3 : Enercon power curve without storm control [4]

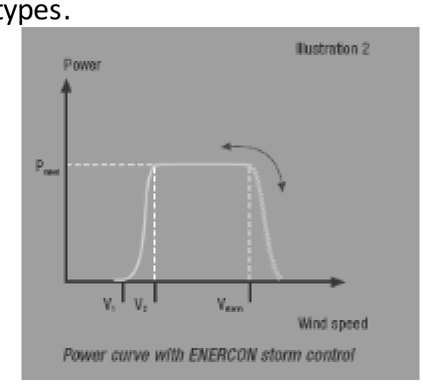


Figure 4-4 : Enercon power curve with storm control [4]

As pictured in Figure 4-3, in cases of wind speeds above the turbine cut-out speed (V_3) a regular turbine will immediately shut down and no power will be produced. When the speed drops the start-up process may have a substantial delay leading to a lower start up speed (V_4) and a prolonged time without power production. This restart is also referred to as the hysteresis loop.

To mitigate this effect and increase the power output, storm control can be implemented and the effects seen in Figure 4-4. With storm control, the wind turbine will when exceeding cut-out speed (V_{storm}) have reduced operation instead of complete shut-down. This will result in increased energy yield as the turbine is still operating and will increase the rotational speed and resume to full power as soon as the wind speed is below this limit again. The storm control is not implemented for the Enercon turbine used in this thesis. Though, as the turbine in this case is simply modelled by a power curve the hysteresis effect is not included.

4.2.2 Park effects

The wake effect or shadow effect occurs when the turbine slows down the wind speed as energy is absorbed by the rotor. In the shade of the turbine a high turbulent, slower wind is created. This turbulence will increase the loading of the turbines, while the reduced wind speed will lead to reduced power output for turbines behind the first row. Because of this, large distance between the turbines in the prevailing wind direction is preferable.

This will however increase the wind farm area and the cost of connecting the turbines to the electricity grid. Thus a compromise must be made. The UK Round 3 Wind Farm Connection Study [20] refers to a standard spacing principle of seven diameters spacing in the prevailing wind direction and 4 diameters spacing in the perpendicular direction. According to [55], spacing between the wind turbines of 6 times the rotor diameter is in accordance with experience from existing offshore wind parks. Though comparing with existing wind farms, the *Thanet* wind farm situated off the coast of Kent, England applied a spacing of 5.6 times the rotor diameter along the rows and 8 times the rotor diameter along the columns [56] while the Danish wind farm *Horns Rev 1* has a spacing of 7 times the rotor diameter [57]. For this study the spacing is chosen to be 7 times the rotor diameter.

4.2.3 Power curves for wind integration studies

Larger wind integrations studies, such as TradeWind, Greenpeace [r]evolution and OffshoreGrid all modified their power curve due to park and aggregation effects. The OffshoreGrid study modified their multi megawatt turbine curve only according to the wake effect. They did however use regional wind speed series, created by averaging data from all grid points within each of the defined regions and calibrated to satisfy certain capacity factors. The TradeWind study created a regional power curve, taking into account array efficiency (85%) due to wake losses, higher cut-out speed (30 m/s), spatial averaging/smoothing, availability (92%) and electrical efficiency (97%).The Greenpeace [r]evolution study also used an aggregated power curve being the equivalent power curve developed for the TradeWind study.

4.3 Aggregated wind power production

Power output will differ for simultaneously operating turbines, even for adjacent turbines in a park [15]. Wind variability and the influence of this on large scale wind power production has been the subject of several studies [58] [59, 60] [61]. Those studies all show that geographical spreading of wind power production will reduce the variability. Figure 4-5 illustrates this effect which is, depending on the scale of the study, affected by the number of turbines within a park, the number of parks and geographical spreading of the wind parks. Aggregated wind power production is thus seen as beneficial in power system operation, as variations are smoothed out. The quantification of this smoothing is however a point of discussion.

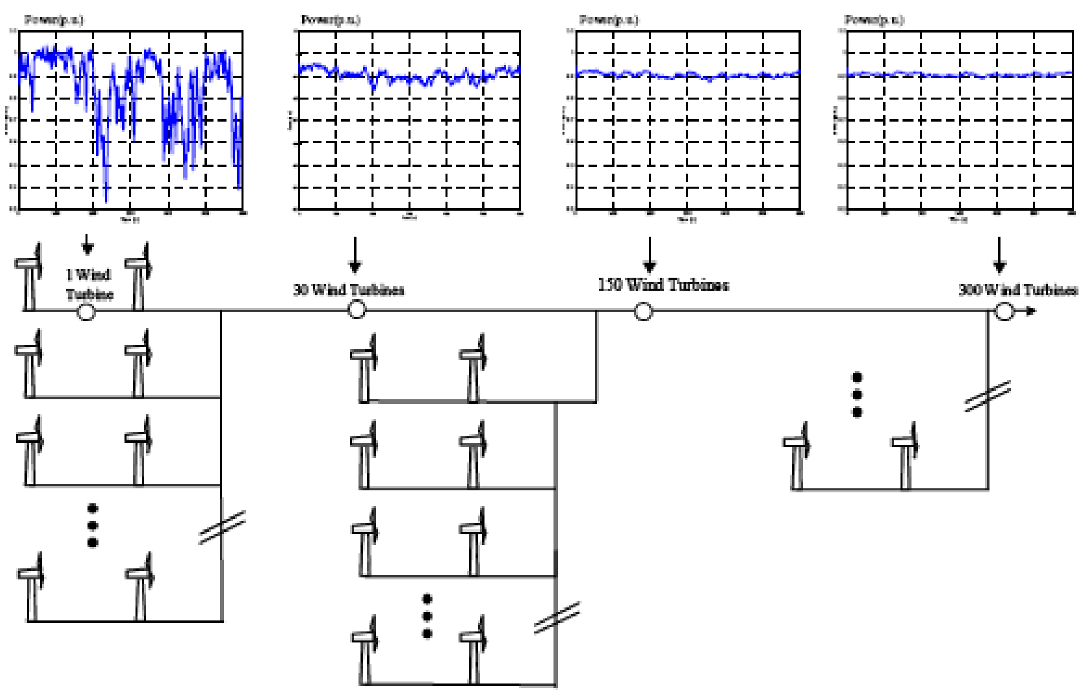


Figure 4-5: Aggregated wind power [58]

Correlation describes the dependency between the winds at different points and as the wind at one point is not independent of wind at surrounding points, the wind is correlated. Though the question is how correlated and within which geographical range it is significant. One factor influencing the variability and persistency of the wind power production is the size of the weather fronts. Low pressure weather fronts, associated with stronger wind are typically in the order of 1000 km [62]. It can further be expected that this number will influence the correlation of the wind, resulting in higher correlation within the area of the weather front. By plotting the correlation of wind speed versus distance, an estimate of the variation and dependency between the sites within the region can be made. This can further indicate the effects on the regional wind power production. Concerning the smoothing effect a small value for the correlation coefficient will lead to a smoother aggregated power curve [63]. As the wind within a larger area is less correlated than within a smaller area, the smoothing becomes larger. This is known as geographical smoothing.

The extent of the smoothening effect is dependent on the size of the area and the characteristics of the wind. Based on these parameters, several methods for quantifying the smoothing have been proposed and further applied to wind integration studies.
Holttinen had single-point measurements represent wind farm production by converting the speed to power through sliding average smoothening before applying an aggregated, multiturbine power curve on the smoothed wind speed. The approach is described in [60] and the aggregated area may range from a few km to several hundreds of km, representing a wind farm or a region. In [55] a similar approach was taken. The study assessed wind power production in The Netherlands and applied a multiturbine method proposed by [61]. This latter multiturbine method will be used in this thesis and will be explained in section 4.4.

4.4 Multiturbine Approach

A multiturbine approach will be used to convert wind speed to wind power. The approach is based on a method developed in [61] and applied in [55]. The method describes the creation of smoothed, park aggregated power curves, though it does not take park effects, such as the wake effect, into account.

Due to the previously discussed smoothing effects, short term fluctuations in power output from the individual turbines will be somewhat smoothed out depending on the size of the area and the number of turbines. Within a wind park, differences in wind speed cause corresponding differences in power output from the individual turbines. If close to the cut-in and cut-out wind speed parts of the wind park might not even be producing at all. As only one measurement point is used per wind park the single power curve is smoothed into a aggregated multi-turbine power curve. The influence of this smoothening is most visible around cut out wind speed, between full power and no power, as can be seen in Figure 4-6.

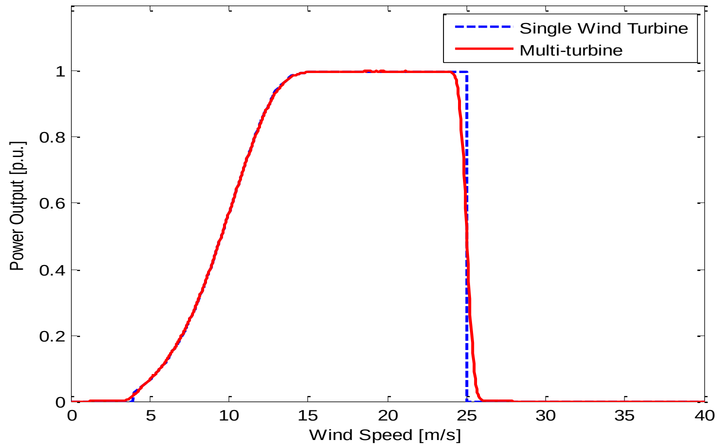


Figure 4-6: Multiturbine versus single turbine

4.4.1 Method

For each park the total installed capacity and a single wind speed series is given as input. Other parameters needed are the size of the individual turbines and the associated power curve as well as the decay of the wind speed correlation in the area. By applying a Gaussian filter to a single turbine power curve the multi turbine power curve is created. The width σ_F of this filter describes the regional variation of the wind speeds. It is based on the local standard deviation (SD) of the wind speed, estimated from the given wind speed series, and further approximated by taking the decay (D_{decay}) of the wind speed covariance and the distance (d_{ave}) between the wind turbines into account. The idea is to describe the local wind climate by modifying the SD (σ) of the wind speed at the single data point. The filter width (σ_F) is calculated according to equation 4-3.

$$\sigma_F = \sigma\sqrt{\frac{1}{2}(1-e^{-d_{ave}/D_{decay}})} \qquad 4\text{-}3$$

The distance between the wind turbines is approximated since the exact location of each wind turbine is unknown. This is done based on the number of wind turbines (N) and the area of the wind park (A) and calculated according to eq. 4-4.

$$d_{ave} = \frac{2}{3}\sqrt{\frac{A}{\pi}}(1+\frac{2}{\sqrt{N}}) \qquad 4\text{-}4$$

To find the decay parameter describing the decay of the correlation of the log wind speed for 70 locations in the North Sea is plotted against the distance between the locations [55]. The correlation is described by the covariance, as given in eq. 4-5, where x_1 and x_2 are random variables (wind speed), with finite mean $E(x_1) = \mu_1$ and $E(x_1) = \mu_1$.

$$C(x_1, x_2) = E((\underline{x}_1 - \mu_1)(\underline{x}_2 - \mu_2)) \qquad 4\text{-}5$$

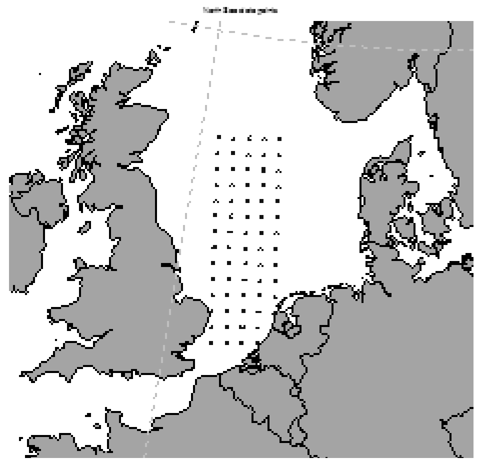


Figure 4-7: Data points used for plotting the covariance

By applying exponential curve fitting according to eq. 4-6 the decay parameter, also known as the characteristic distance is estimated. The location of the chosen data points in the North Sea are pictured in Figure 4-7 and the correlation versus distance (x) is plotted in Figure 4-8.

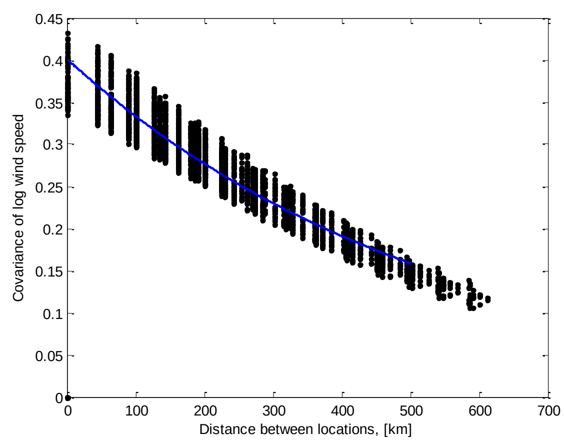


Figure 4-8: Covariance versus distance for 70 locations in the North Sea

$$y = a \cdot e^{(-\frac{1}{D_{decay}}x)} = 0.4 \cdot e^{(-\frac{1}{540}x)} \qquad 4\text{-}6$$

This fit results in a characteristic distance (D_{decay}) of 540 km, which is comparable to the 500 km reported by[60], based on data for the Nordic countries and by Landberg [64], based on Danish locations, the 610 km found by [55] based on 18 Dutch locations onshore and offshore and the 723 km reported by [63], based on wind farm data for Europe.

Assuming a square area per wind turbine, this area (A_t) is calculated according to eq. 4-7, where D_{rot} is the diameter of the rotor and s is the spacing parameter. The choice of turbine will mostly be significant for this parameter.

$$A_t = (s \cdot D_{rot})(s \cdot D_{rot}) = (7 \cdot 127m)(7 \cdot 127m) \quad 4\text{-}7$$

Finally, when calculating the power output from a wind park the availability of the wind turbines must be estimated. As mentioned before the TradeWind study assumed an availability of 92 % while [55] used a relatively high availability of 95%. A concept study within the DOWEC project assessing achievable availabilities found availabilities at its design locations 35 km off the Dutch coast ranging from 85 % to 94 % [65]. For this study an availability of 95 % was chosen. This is a relatively high value, which consequently results in a higher wind power production and can from an operational point of view be seen as a conservative choice [55], as the power system is required to handle a larger amount of wind.

4.5 North Sea Power Production

For each wind park in the developed scenarios, one coordinate point was specified. Those locations were matched with the grid points of the chosen wind speed data set (see section 3.3) and wind speed series extracted for each wind park location. The wind speeds were then transferred into power series through the multiturbine approach described in the previous section. As the wind power data will be used as input data for the market simulations, hourly data points were needed. The data sets available for wind power calculations were:

- TradeWind Reanalysis based data with hourly temporal resolution over a grid of 2.5 degrees by 2.5 degrees
- Sanders WPM data with ten minutes temporal resolution over a grid of 9 km by 9 km

Calculation of the North Sea wind power production was done for both the Sanders data and the TradeWind data. With the Sanders data, each wind park location was matched with the closes available grid data point and wind speed at 120 m height was extracted. As a higher temporal resolution than needed was available, ten minutes power series were produced and then averaged to hourly values. This was considered more accurate than averaging at an earlier point, as larger variations of the wind will affect the power output. Regarding the TradeWind data, some adjustments of the original reanalysis data were needed, as described in [66] and [67]. The data was first downscaled from a 6-hourly to an hourly temporal resolution using linear interpolation, this data hourly data was available for this study. In the TradeWind study the wind speed data was further adjusted for terrain type and hub height. A hub height of 70 m was assumed for the offshore turbines though it was further stated that because of the low power shear exponent for these locations, modifications to account for higher hub heights in the future was not seen as necessary. The assumptions and correction factors used in the TradeWind study are given in Table 4-1.

	OFFSHORE
Terrain wind speed adjustment factor (T_F)	1.30
Hub height [m]	70
Power law shear exponent, α	0.1
Hub height wind speed adjustment factor (H_F)	1.00

Table 4-1: TradeWind correction factors for offshore wind sites [66]

It was however for this study chosen to modify the hub height adjustment factor. The power law shear exponent assumed for the TradeWind study was used to account for the increase in hub height from 70 m to 120 m hub height. This was done according to the wind profile power law relationship given in eq 4-8, where u is the wind speed at height z (120 m), and u_r is the reference wind speed at height z_r (70 m).

$$\frac{u(z)}{u_r(z_r)} = \left(\frac{z}{z_r}\right)^{\alpha} \qquad 4\text{-}8$$

The terrain wind speed adjustment factor was kept and the applied correction factors are given in Table 4-2. As the reanalysis data set is relatively sparse, the wind speed at each wind park location was found by bilinear interpolation of the four closest grid points.

	OFFSHORE
Terrain wind speed adjustment factor (T_F)	1.30
Hub height [m]	120
Power law shear exponent, α	0.1
Hub height wind speed adjustment factor (H_F)	1.06

Table 4-2: Correction factors for offshore wind sites applied in this study

4.5.1 Results

The resulting total offshore wind power production for the North Sea is presented in Table 4-3 Calculations are done for three different years of the Sanders data and one year of the TradeWind data. Comparing the different years the yearly variations in available wind can be seen, with 1994 being a 'high' wind year , 2003 a 'low' wind year and 2007 is somewhere in between. When comparing the different data sets, the resulting numbers are quite different. This might have to do with the different methods applied, though it does suggest that the choice of the wind data makes a difference for the study.

DATA	TOTAL NORTH SEA POWER 2025 [TWH]	TOTAL NORTH SEA POWER 2030 [TWH]
Sander - 1994	187.93	280.77
Sander - 2003	151.71	227.67
Sander - 2007	180.34	269.27
TradeWind - 2003	182.90	270.56

Table 4-3: Resulting offshore wind power production in the North Sea

5 Offshore Grid

As the offshore wind power deployment in the North Sea is increasing, the connection of these power sources to the existing grid and the integration of wind power in the power system are becoming important transnational issues. European electricity markets are becoming more and more integrated and a transnational offshore grid is seen as an efficient way of integrating large amount of wind power as well as facilitating increased power exchange and trade [reference]. As can be expected for such great infrastructural vision a range of challenges and barriers do exist. Uncertainties regarding the rate of wind power expansion, technological challenges, high investments cost and the obvious need for transnational cooperation, planning and regulation are some of the issues concerning the future of an offshore grid. If such a grid vision is to be realised it is crucial that policy and decision makers are aware of and understand the benefits of putting effort and money into such a project. Such benefits have already been assessed by studies like the Greenpeace [r]evolution report, the OffshoreGrid study and the TradeWind study. These were also aimed to provide recommendations and guidelines to policymakers.

In this chapter, different offshore grid topologies, drivers and benefits will first be discussed based on results from the previous studies mentioned. Market simulation will then be used to assess power system wind integration with different park connections. The objective of the latter part is to investigate the benefits of developing a (international) meshed grid compared to a radial connection structure and the effects of capacity choices.

5.1 A North Sea Transnational Grid

As the number of wind parks increase new transmission solutions are needed. Up until now the offshore wind parks have been relatively small and near shore. Future wind parks are expected to increase in size and move to areas further from shore. New solutions are required as current solutions reach its limitations and become less efficient and beneficial. E.g. due to the increase in distance HVDC connections will replace AC connections. When it comes to grid structure radial point-to-point connections are currently employed, connecting each wind park directly to shore, as the number of parks is still low. These connections are design to handle 100% power output from the wind parks so that no wind is wasted, which leaves the connections underutilized as the typical load factor of a wind park is 30%-40% [34].With increasing numbers of wind parks, clustering and interconnections between clusters should be considered and connections further dimensioned to achieve higher utilisation. The TradeWind and other offshore grid studies predict a meshed grid structure to develop, though whether this is based on national solutions or international solutions is dependent on the level of international cooperation.

An internationally meshed grid is considered to provide benefits regarding wind integration as well as trade. Some acknowledged benefits of having an internationally meshed grid are:

- o Wind power is better integrated on a European scale, due to the variability and unpredictability of the wind
- o Increasing the connections between the regional power markets will result in a more efficient market, higher liquidity and lower prices
- o As reinforcement of the on-land grid is constrained, due to infrastructural limitations and public opinion, offshore reinforcement may be a solution
- o Increased security of supply as connections to other generation areas are increased

The development of the grid structure and the design is at this stage difficult to predict and different topologies are proposed. In order to predict this development the OffshoreGrid study identifies, in line with several energy developers, NGOs, industry and policy makers, security of supply, trade and efficient wind integration as main drivers for the grid development [68]. The first stage of offshore electricity structure is further assumed to be driven by connectivity between power markets. Then later, when the development of offshore wind parks results in more and larger wind parks further from shore, economically efficient integration of this wind power is likely to become the main driver and multi terminal converter stations may at this point contribute to the creation of offshore transmission hubs. One of the main objectives in the OffshoreGrid study was to assess these assumptions through technical and economic analyses. Thus depending on the relative influence of the defined drivers characteristic prototype grids were made. Figure 5-1 shows one topology following the assumed development described above compared to two extreme cases with either wind or trade as main driver. These topologies were are all compared with a reference case representing business as usual by including only existing and planned interconnectors (2010)

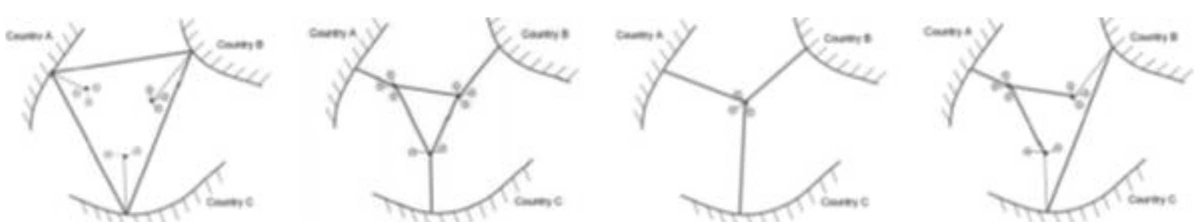


Figure 5-1: Different topologies considered in the OffshoreGrid study. From the left: wind parks connected to shore and direct interconnectors (Trade driven), meshed interconnectors (Wind driven), meshed interconnectors - special cluster (Wind driven) and finally the mixed approach. [68]

Another approach to identify grid topologies was presented in [16]. A transportation model of the power system is there used to identify optimal grid expansions. Other topologies have been presented by TradeWind, Entso-e, Statnett (Norwegian TSO), Greenpeace etc., some of which can be seen in the figures below.

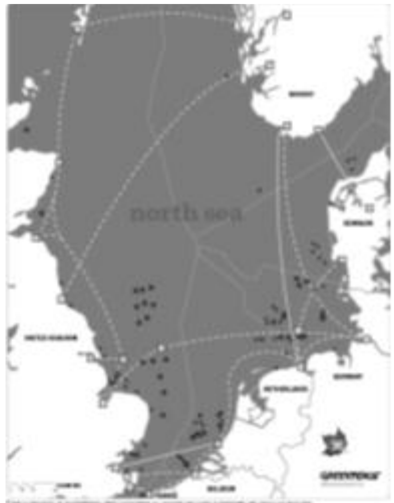


Figure 5-2: A North Sea offshore grid [32]

Figure 5-3: Radial and meshed connections of wind parks connections [31]

For each of these grid designs the capacity if the interconnections represent another degree of freedom. Should the connections have a rated capacity smaller, equal or larger than the amount of installed wind power connected? Smaller capacity will give a higher utilisation of the cables, but more wind is likely to be wasted. Equal capacity may result in underutilisation or if facilitating trade this might even be insufficient. Larger capacity means on the other hand higher investment cost. Thus when assessing offshore grid design, the sensitivity and relative benefit of capacity choices should be considered, and preferably in combination with a cost benefit analysis.

5.2 Market simulations

The following simulations will assess the effects on the market outcome in terms of generation dispatch and power exchange between the generation areas. In this work, a high level representation of offshore and onshore grid is adopted, where only limitations in the interconnection capacity between areas in a transportation model are considered. The only cost considered is the operational cost of the power system.

5.2.1 Unit Commitment and Economical Dispatch

With the overall goal of matching generation with demand, generation units are committed to operation and production is allocated to those available units while satisfying the objective of minimum costs. Finding the optimal generation schedule is done by unit commitment and economical dispatch (UC-ED) [69]. For a certain subset of generation units the allocation of production can be done by considering production cost and using the marginal cost principle. The decision of which units shall be in operation and the scheduling of production over several time steps does however require that the additional start-up and stopping cost are considered and the economical optimum for the whole time horizon is found. Thus, in principle all combinations of units within each time interval and each combination of those time intervals for the whole time horizon should be considered to find the optimal combination resulting in minimum costs.

At a given time there will be a certain amount of generation units available, which will be less than the complete generation portfolio due to forced or planned outages. Or with the increasing amount of variable energy sources (renewable energy sources) in the power system, due to the lack of primary energy such as wind, solar etc. For a given load there will then be a number of combinations that can cover the load and for each of these subsets an economical dispatch can be found. The economical dispatch problem is a part of the unit commitment problem, assuming N units connected to the system and finding the optimal allocation of load to these units. This is found by minimising total cost subjected to certain constraints (such as covering the load and stay within the power limits of each unit).

The unit commitment problem consists of deciding which units to bring on line or shut off, to find the optimal combination of these units and to find an optimal sequence of combinations. This is as well subjected to constraints being spinning reserve requirements, minimum up and down time, ramping time, fuel limitations etc.
Due to certain technical or administrative issues units can be given a special commitment status such as 'must-run' or 'full-load-must-run'. Otherwise they will be dispatched according to the economical optimisation.

5.2.2 Generation Units

In the economic dispatch the marginal cost of each generation unit is used to find the optimal schedule. For thermal units this cost is relatively straight forward, being mostly dependent on the fuel costs and the emission costs. The scheduling of wind and hydro plants is however more complex. They have low marginal cost which gives them priority in the dispatch but are both dependent on prediction of resource availability.

5.2.2.1 Hydro

Hydro production is opposed to thermal generation not directly dependent on fuel prices but on the value of the water. As the water is (usually) a limited resource, its value is estimated based on the choice of using the water now or later. This water value is the value of an additional kWh in the reservoir and thus indirectly dependent on expectations regarding future demand, inflow and cost of other generation/market price. The problem of scheduling hydro can be divided into different time horizons. According to [70] long term scheduling has a planning horizon of 3-5 years, a medium term scheduling has a planning horizon of 1-2 years, while the short time scheduling is covering one week. The general operational principle for hydro as described in [69] can be described according to eq. 5-1, where P_L is the power demand, P_H is the hydro power, P_T the power from the thermal plants and E being the energy difference between the available hydro energy and the total energy demand. This difference (E) is to be covered by thermal energy. The idea is to use all the available hydro energy as to reduce the cost of the thermal production.

$$\sum_{j=1}^{j_{\max}} P_{Lj} n_j - \sum_{j=1}^{j_{\max}} P_{Hj} n_j = E$$ n_j = number of hours in period j 5-1

This leaves the thermal energy production to cover the remaining load (E) according to:

$$\sum_{j=1}^{N_t} P_{Tj} n_j = E$$ N_t = number of periods the thermal plant is run 5-2

Resulting in the remaining scheduling problem having the objective of minimising thermal operational cost according to eq.5-3, where F is the cost associated with the thermal power production P_T.

$$MinF = \sum_{j=1}^{N_s} F(P_{Tj}) n_j$$ 5-3

It should be however be notes that the energy E is an outcome of a long term hydro optimisation problem which is considered outside the scope of this thesis.

5.2.2.2 Thermal units

The operational flexibility of a thermal unit is represented by its unit commitment constraints. Minimum uptime and downtime is restricting the unit from being turned off or on immediately after start up or shut down, the ramping rate is describing the maximum rate of change of the power output and spinning reserve requirements usually require every thermal unit to have a certain percentage of the maximum power reserved for emergencies, which constraints them from running fully loaded. When it comes to commitment status, flexible gas units usually have an economical operation only, while less flexible coal units and nuclear units can have a must-run status which combined heat and power (CHP) units also might have due to the heat demand. Considering the diversity of thermal units the variation in fuel price, fuel use and emissions will further influence the different scheduling of these units.

5.2.2.3 Wind

Due to the variability of wind and its low marginal cost in the electricity market, wind can be expected to have a large influence on the dispatch schedule. The variability and unpredictability of the wind creates challenges regarding predictions needed for power scheduling. According to [71] forecast errors may however be considerably reduced depending on the forecast time, as seen in Figure 5-4.

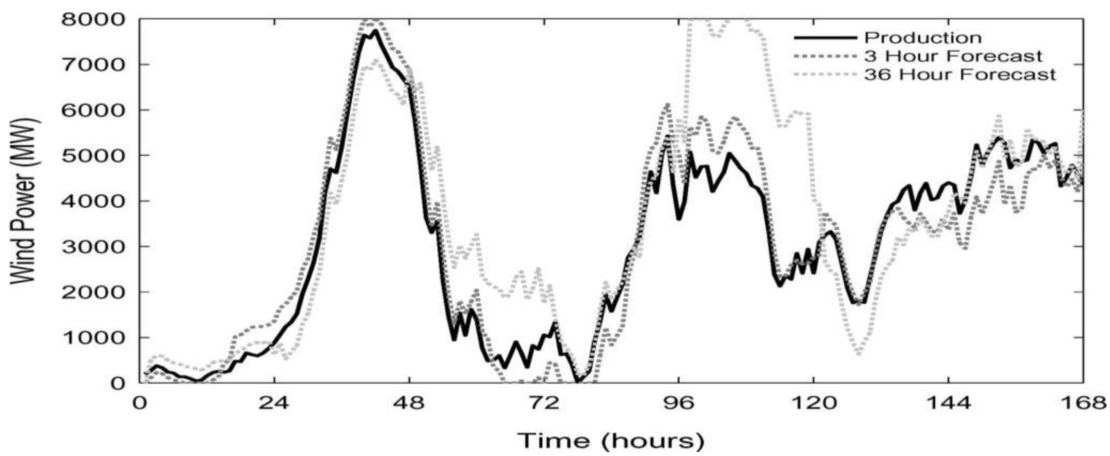


Figure 5-4: Wind power forecast, 3h and 36h ahead, compared with realized wind power production [71]

Though representing an ideal situation which could almost be reached with a market closure time of 1 hour ahead, perfect wind forecast is assumed for the following simulations. In order to dispatch as much wind as possible the marginal cost of wind power is set to zero.

5.2.3 UC-ED tool

PowrSym3™ will be used as UC-ED tool for the market simulations. The program was developed in corporation between Operation Simulation Associates, Inc. and the former Dutch Utility, SEP with support from Tennessee Valley Authority (TVA), USA. It is a multi-area, multi-fuel, chronological production cost simulation model for electrical power systems including combined heat and power [72].It was used for central UC-ED planning in the Netherlands until the start of the unbundling in 1998. As a power system database has been maintained since then by the current Dutch TSO TenneT, the program is still used for system studies.

Power flows between areas are economically determined and computed using a transportation algorithm (not load flow [10]).The transportation method is a very simplified way of modelling the power system network but is considered appropriate for systems with large aggregated generation areas and controllable high voltage direct current (HVDC) links [16]. As the system considered in the following simulations is a rather simplified system and indeed consisting of HVDC connected large, aggregated systems - the transportation model should be sufficient.

The needed **input data** for the system is:

- Generator capacities, fuel consumption, fuel cost, ramp rates, min up and down time, heat values, hydro reservoir sizes, spinning reserve …
- link capacities and link losses
- loads per area
- wind power time series

In addition to simulate production cost, the program schedules unit maintenance and calculates reliability statistics. A yearly simulation is in this case performed and output data can be selected for the resulting reports.

Among the available **output data** from the simulations are:

- Power generation on a unit, area and system base
- Start up and fuel costs on a unit, area and system base
- Emission costs on a unit, area and system base
- Power exchange between areas and link utilisation

The optimisation structure is based on three execution time horizons – annual, monthly and weekly. The annual horizon is used for reliability calculations and maintenance scheduling. The weekly time horizon is used for economic optimisation of generation.

[10] By including power transfer distribution factors (PTDF) in the model, power flows are more accurately estimated taking into account the impedances in the network and the parallel load flows are thus also considered.

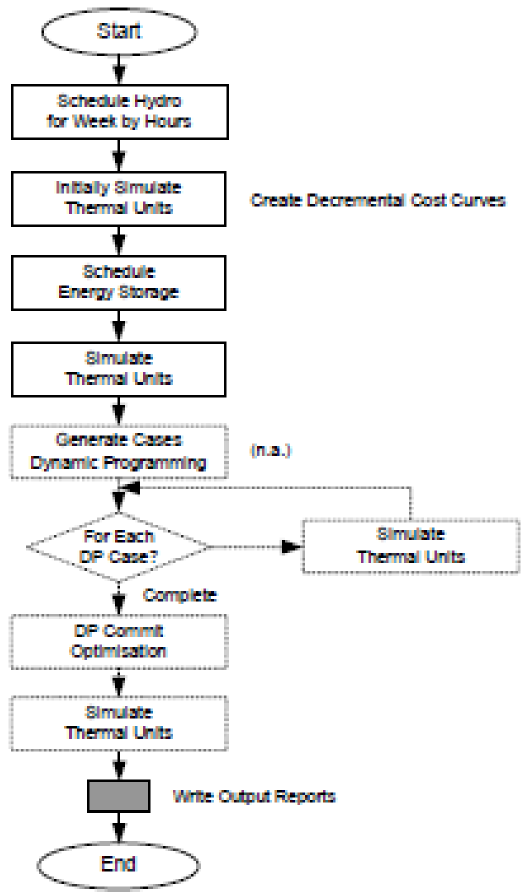


Figure 5-5: Flow chart of weekly simulation, PowrSym3 [73]

As can be seen in the flow chart of the weekly simulations (Figure 5-5) the hydro units are the first to be scheduled before wind, thermal units and energy storage. There is no longer term (medium or long term) scheduling incorporated and as a consequence of this a certain amount of hydro energy is set to be available every week. This amount (labelled as *HYDRO ENERGY*) represents the reservoir inflow and is a user defined variable. The same amount of energy is available for every week, though hourly dispatch is optimised based on the systems marginal cost, reservoir limits, load prediction and wind power forecast. Thermal units are then scheduled using the Equal Incremental Cost Method (see sequential dispatch figure) while considering system load, heat requirements, wind power and technical constraints.

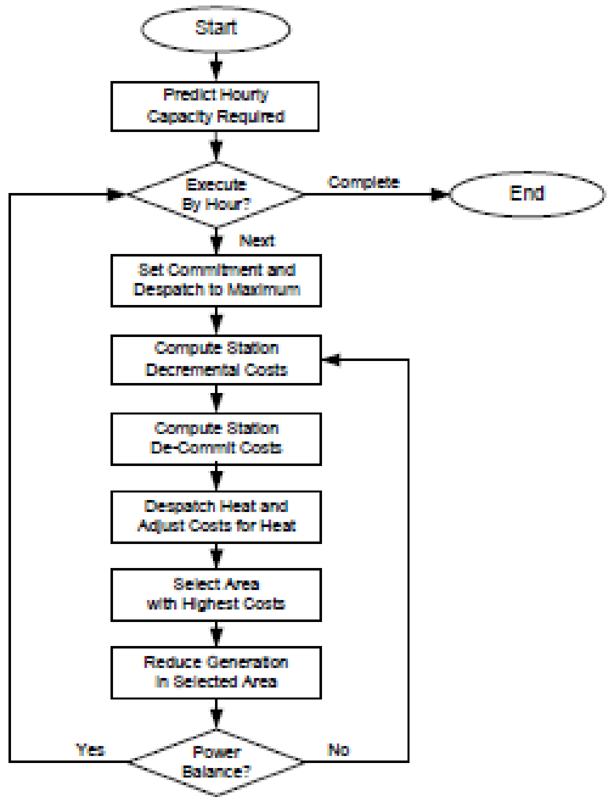


Figure 5-6: Sequential dispatch method, PowrSym3 [73]

Due to the higher complexity of hydro scheduling and the subsequently simplifications in the software, some additional comments on the hydro scheduling is necessary. The main issues are related to the lack of long term scheduling and the decision regarding the weekly available hydro energy. Short time scheduling have been considered sufficient in other power system studies [55],though when considering systems with large amount of hydro and little diversity in generation units (such as Norway) such simplifications might have a larger impact on the simulation results [74]. The systems sensitivity to hydro will therefore be assessed in the simulation results.

5.3 Model

5.3.1 Design of the system

The test system is constructed to have a resemblance with the North Sea area. It consists of six production areas, where the three largest have the characteristic generation mix of Norway, The Netherlands and Great Britain and the three smaller areas represent their respective offshore wind production.

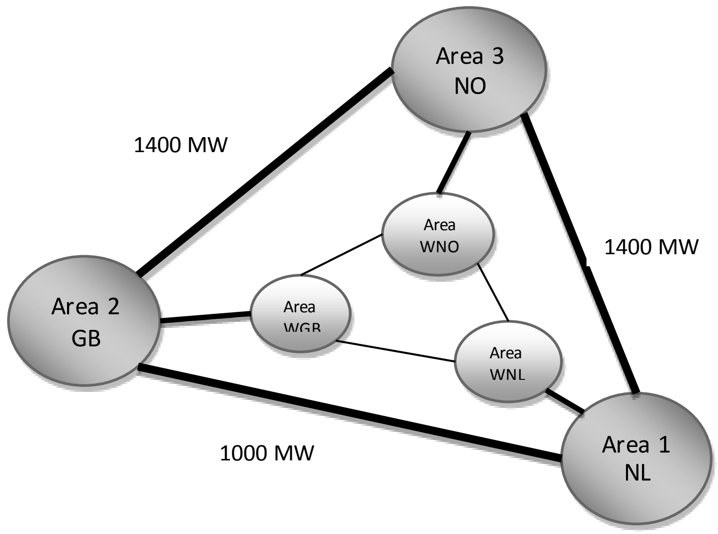


Figure 5-7: System topology

Regarding the design of the offshore grid, the chosen topology is based on the same assumptions as the OffshoreGrid mixed approach pictured in Figure 5-8.

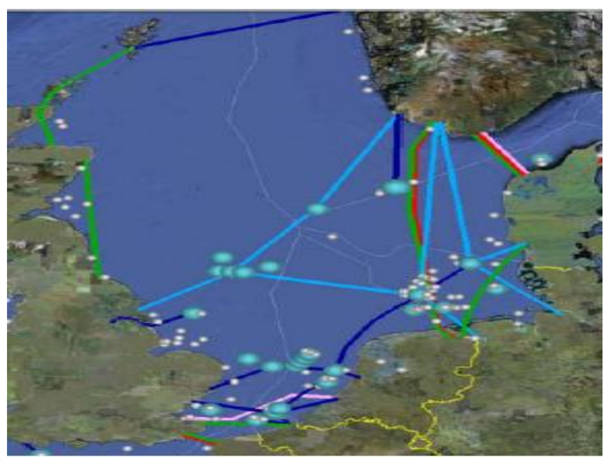


Figure 5-8: Mixed approach [68]

Based on the work presented earlier in this thesis and the objective of studying the effects of different North Sea Grid design, year 2025 is chosen as time horizon for this study and the simulations are carried out for this year. To create a relatively realistic test system PowrSym3™, a range of sources were used. Scenario B from Enso-e's System Adequacy Forecast (SAF) 2010-2025 report [75] was used as a reference for sizing the generation parks as well as for scaling historical load data. The created generation portfolio is given in Table 5-1. A complete table including numbers from SAF can be found in the appendix. Generation-demand ratios are there compared to ensure a realistic balance between generation and demand.

AREA	TECHNOLOGY	GENERATION SCENARIO [MW]
NL	Nuclear power	500
	Coal	7350
	Gas	12800
	Ccgt* & Ccgt-heat	20740
	Offshore Wind	6000
	Onshore Wind	5400
	System Capacity NL	**39870**
GB	Nuclear power	11870
	Coal	19800
	Ccgt*	32778
	Offshore Wind	23000
	Onshore Wind	8000
	System Capacity GB	**89848**
NO	Ccgt*	986
	Hydro	28800
	Offshore Wind	2500
	Onshore Wind	6000
	System Capacity NO	**34030**

*Ccgt =combined cycle gas turbine

Table 5-1 : Generation capacities per area

Wind capacities are however modified compared to the SAF scenario. Onshore wind capacities are based on EWEA's Scenario for EU 2020 [9], except for the Norwegian wind which is based on a possibility study of land based wind in Norway done by the Norwegian Water Resources and Energy Directorate [22]. Offshore wind capacities are based on the offshore wind scenario presented in chapter 2 of this thesis. Onshore wind time series are obtained from the TradeWind study [30] time series and offshore wind time series are obtained from wind speed data with higher resolution (Sander), both wind series are transformed to power series with a regionally smoothed power curve (chapter 4). The offshore power production per area is plotted in Figure 5-9.

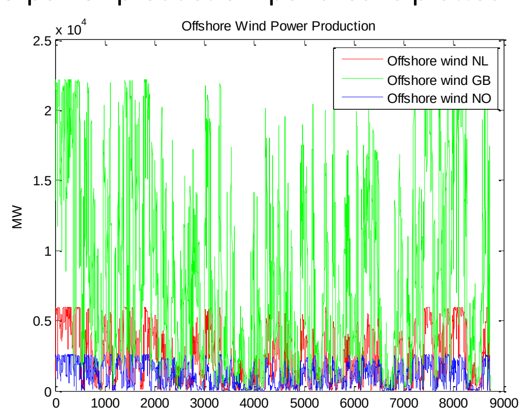


Figure 5-9: Offshore wind production 2025.
Installed offshore wind capacity: NL: 6 GW, NO: 2.5 GW, GB: 23 GW

Other data assumptions regarding the power plants are based on [55] Fuel prices were updated based on the World energy outlook [76] published by the International Energy Agency. Interconnections between the load areas are dimensioned according to existing and planned HVDC connections between The Netherlands, Great Britain and Norway. These are based on [77] and given in Table 5-2.

PROJECT	COUNTRY	CAPACITY	YEAR	COMMENT
BritNed	GB-NL	1000 MW	2011	Operational
BritNor	GB-NO	1400 MW	2017/2020?	Planned
NorNed	GB-NL	700 MW		Operational
NorNed 2	GB-NL	700 MW	?	Consideration

Table 5-2: Existing and planned direct HVDC links between Norway, Great Britain and The Netherland

5.4 Method

Possible grid development steps are defined based on the OffshoreGrid study and NSTG WP2[14]. As the currently proposed wind power parks are mainly situated in the south of the North Sea (see chapter 2) NSTG WP2 suggests that the development will start here. It is thus likely that a southern development of the grid will precede a northern expansion. The NSTG report defines a ten-step development (see Figure 5-10) where a connection to Norway is realised early due to the assumed beneficial hydro-wind combination.

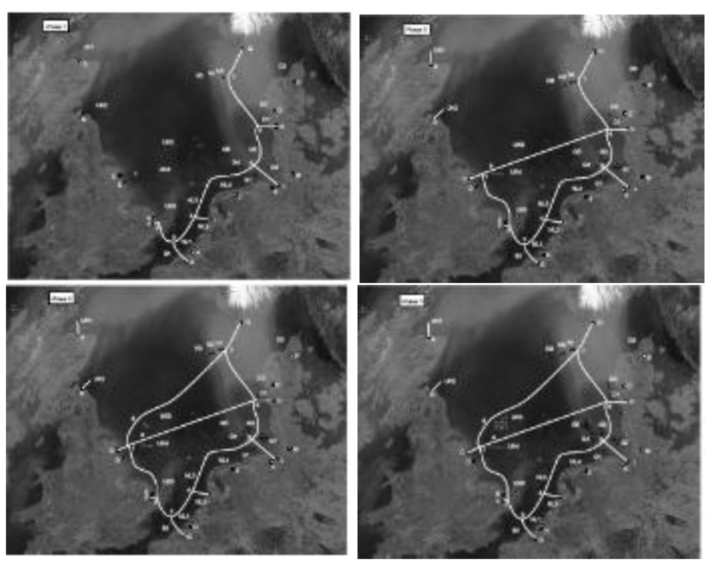


Figure 5-10: Expected grid development phases according to NSTG WP2 [14].
Top left: phase 1; top right: phase 5; bottom left: phase 6; bottom right: phase 10.

Based on these assumptions three main cases are created, representing different stages of grid development. These are pictured in Figure 5-11

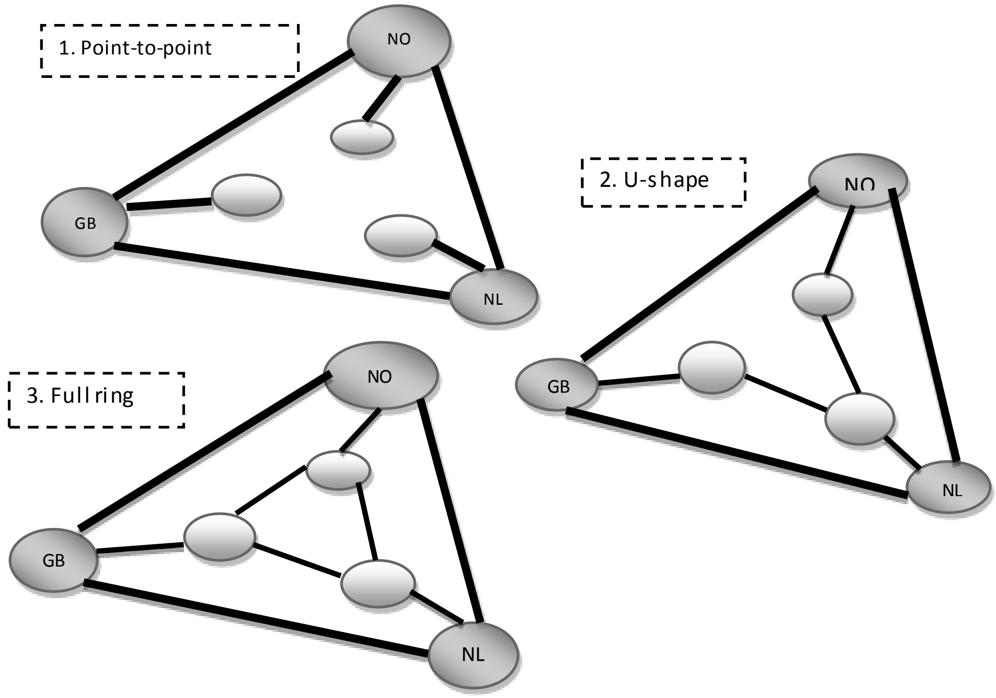


Figure 5-11: The three simulation cases representing different stages of grid development

5.4.1 Objective

The objective of these simulations is to study the benefits of developing a (international) meshed grid compared to a radial connection structure. Results will be dependent on capacity choices and this sensitivity is considered.

Three main cases constructed to study the effects of offshore grid design:

- *Radial Point-to-point (base case)*
- *U-shape*
- *Full ring*

Sensitivity of interconnection capacities in the offshore grid will be considered for:

- *Between the wind farm areas (inter-cluster connections)*
- *Between land area and wind farm area (connections to shore)*

The simulation results will be evaluated in terms of:

- *Operational costs*
- *Emission reduction*
- *Wind curtailment*
- *Link utilisation*

5.4.2 Approach

First the radial configuration will be simulated with a 100% wind farm cluster capacity per link and the results will be used as a base case. For the other two configurations, a stepwise increase in the capacities of the point-to-point connections is considered, with ratings at 80 %, 100%, 120% and 200 % of the connected wind capacity. For each of these capacities to shore, the 'u-shape' configuration and the 'full ring' configuration will be simulated with varying connection capacities between the wind farm clusters. These capacities will first be rated to 50 % of the smallest connected wind park cluster, secondly increased to 100 %, and then further increased to 100% of the largest connected wind farm cluster capacity. Finally they will be increased enough to represent no capacity constraint. This latter case can be seen as a copperplate representation of the interconnected offshore hubs. The described approach is visualized with a flow chart in Figure 5-12. A total of 41 simulations has here been performed, including two additional capacity optimisation cases and three cases for the sensitivity analysis.

Regarding the objective of the study, the base case represents a minimum grid design consisting of only radial to-shore-connections of the wind park hubs. The other cases represent the development of an offshore grid and by comparing those topologies with the base case the possible benefits of interconnecting the wind parks and creating an offshore grid can be assessed. Effects of grid topology and capacity choices will be included in this evaluation. Results and benefits are mainly compared on a system level and not for each 'country' separately.

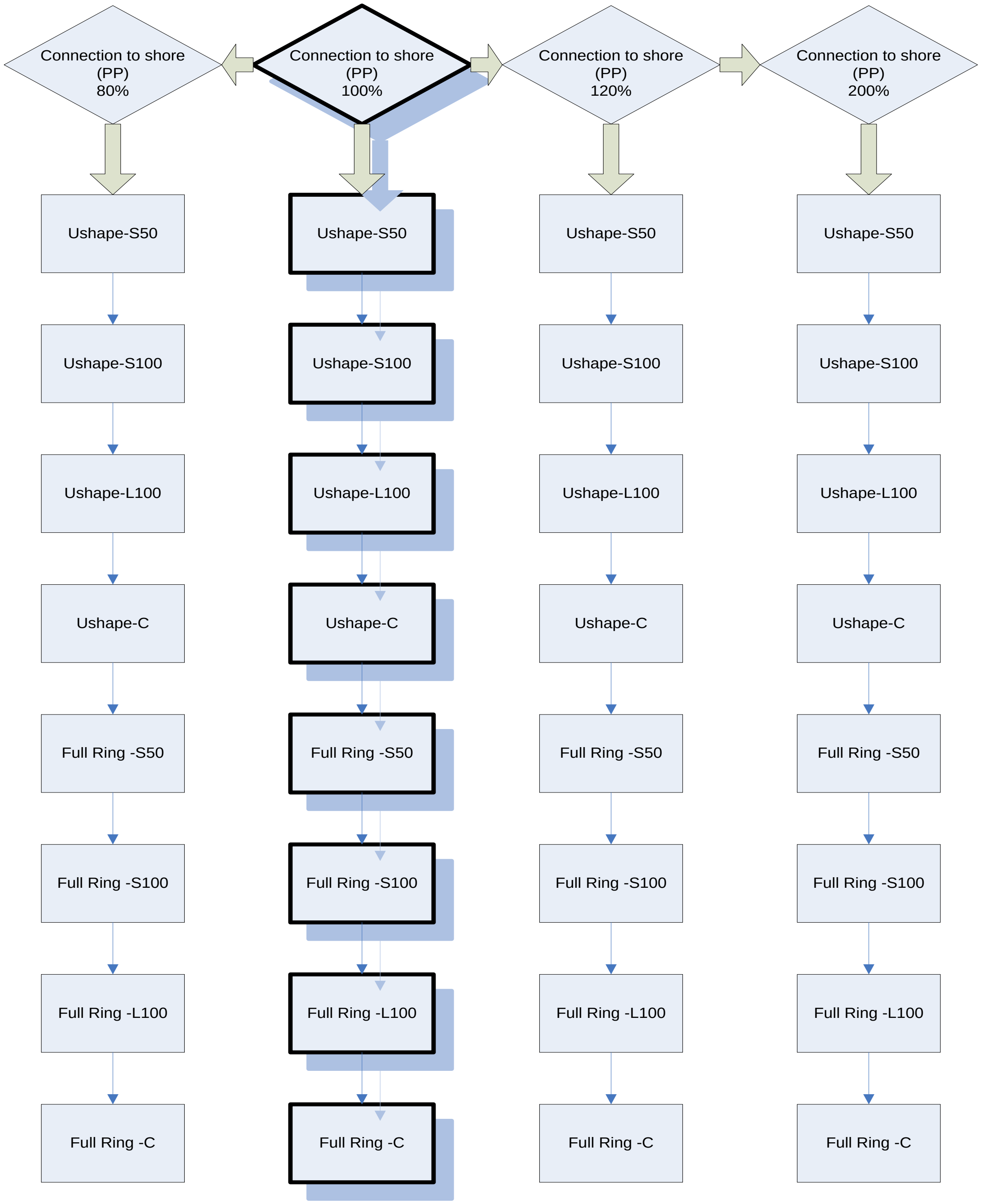


Figure 5-12: Simulation step flow chart

(S=smallest connected wind farm, L=largest connected wind farm, C=copperplate, 25=25%, 100=100% ...)

5.4.3 Model assumptions and limitations

An international power system is highly complex and modelling of such a system involves assumptions and simplifications, depending on the objective of the study. This study aims to investigate systemwide impacts related to wind integration and offshore grid design. The level of detail is thus linked to this. In this presented project some of the simplifications can however also be attributed to the software used. Although a simplified system may allow for easier interpretation of the results and better understanding of the mechanisms involved, they do introduce limitations regarding the conclusions that can be drawn.

The main simplifications and limitations regarding this work are:

- Assuming a well-functioning market
- No requirements for reactive power and other balancing and control tasks
- Each country/land area is represented as one generation area, thus grid structure, power flows and possible congestions within the land areas are not considered
- Wind parks are clustered per country and considered as national wind park hubs
- Power flows between areas are computed according to a transportation model subjected to the defined link capacities (PTDF[11]s are not considered)
- Only operational cost computed, investment costs are not explicitly considered
- Uncertainties regarding load and generation scenarios
- Hydro modelling: lack of longterm hydro scheduling and limitations due to software tool used. Hydro being dispatched before any other resource, incl. wind.
- Connections to other generation areas are not considered

Some of the assumptions results in the system becoming less representative as a North Sea system, the results become less accurate and the conclusions more general. As a first approach to assess the effects of offshore grid design on power system operation and taking into account the uncertainties of generation scenarios, general results may be sufficient and can provide recommendations and a starting point for further more detailed studies.

5.5 Results

In this subchapter the results will be presented and evaluated. General results are first presented for all the simulation cases and a few results are then chosen for further evaluation. The main parameters used for comparison are amount of wind integration, wind curtailment, generation mix, link utilisation, total operational cost and emission cost. All cases are compared to the base case values given Table 5-3 and calculated according to eq.5-4.

[11] PTDF=Power Transfer Distribution Factor

SYSTEM VALUES	BASE CASE
Wind production [GWh]	158547
Wind curtailment [GWh]	26317
Average link utilisation [%]	50%
Production Cost [M€]	14404,5
Emission Cost [M€]	2286,3

Table 5-3: System values for the base case scenario

$$DeltaValues = BaseCaseValues - CaseValues \quad (5\text{-}4)$$

In order to assess the effects of the grid topology, differences between the configurations *'u-shape'* versus *'full ring'* and high capacity versus low capacity are highlighted.

Interconnecting the offshore wind parks shows in all cases a reduction in overall system production cost. As the capacity of the interconnections are increased the cost are reduced because of better allocation of resources. This reduction do however saturate when the interconnection capacity reaches the capacity of the larger of the two connected wind park hubs. For these high interconnection capacities the u-shape topology and the full ring show now significant difference. Regarding the influence of the capacity of the 'to-shore' connections, seen in Figure 5-13, increasing these above 100% does not have any significant influence on the operational cost. As larger capacities do not seem to add any value, further evaluation of results will focus on the cases with the 'to-shore' connections rated to 100% of the connected wind park capacity.

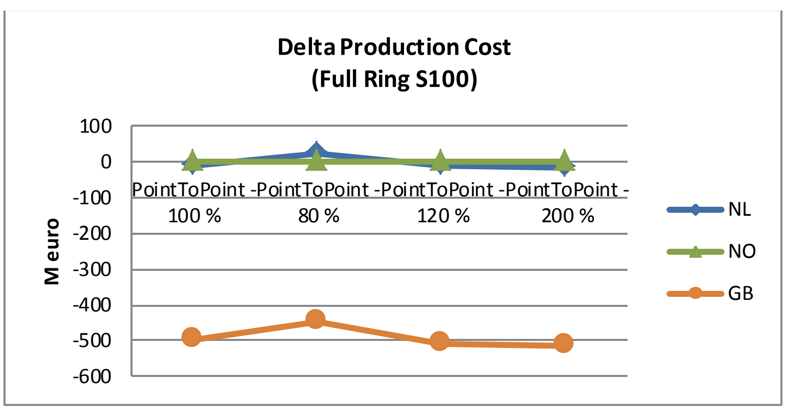


Figure 5-13 : Delta production cost, different capacities to shore

Among other general results are the relative sensitivity and effects on the different areas due to the different generation portfolios. The GB area consists of large amount of coal which makes it sensitive for cheaper green production. Thus the largest reduction in operational cost can be observed for the GB area, mainly attributed the reduced coal production. In addition to decrease total operational cost, increased interconnections does as well reduce emissions and emission cost in a similar manner. Another important observation is that the system is already in the base case able to accommodate a large amount of wind power (81% utilisation of the available wind). As wind is well integrated in the base case, the potential increases in wind related benefits are limited and increased interconnection has consequently little effects on the wind integration. One exception is the wind in the hydro dominated area, which is caused by a hydro-wind competition. Due to the way hydro is committed in the software, the event of having more energy than needed will lead to other resources, including wind, being curtailed before hydro. The effect of this assumption on the system will be further assessed in a sensitivity analysis.

Although this grid design evaluation is done from an operational point of view and does not explicitly consider investment cost, it is important to bear in mind that the investment cost is a crucial factor in the grid design decision. More interconnectors and larger capacities are on one hand expected to result in larger benefits in terms of reduced operational cost, reduced emissions and increased wind integration. On the other hand, installing larger cable capacities implies higher cost. One way to assess this balance without directly considering investment costs is to ensure a high utilization of the built interconnectors. As it could be expected the utilisation of the links decreases as the capacity is increased. The smallest capacity of the intra wind park connections does however only result in 30 – 55 % utilisation. The interconnection capacity was therefore reduced further to increase the utilisation. The link utilization for all interconnectors can be seen in Figure 5-14. With intra wind park connections dimensioned to 25% of the installed capacity of the smallest connected wind park hub (S25), utilisations of these links are increased to 40-65%.

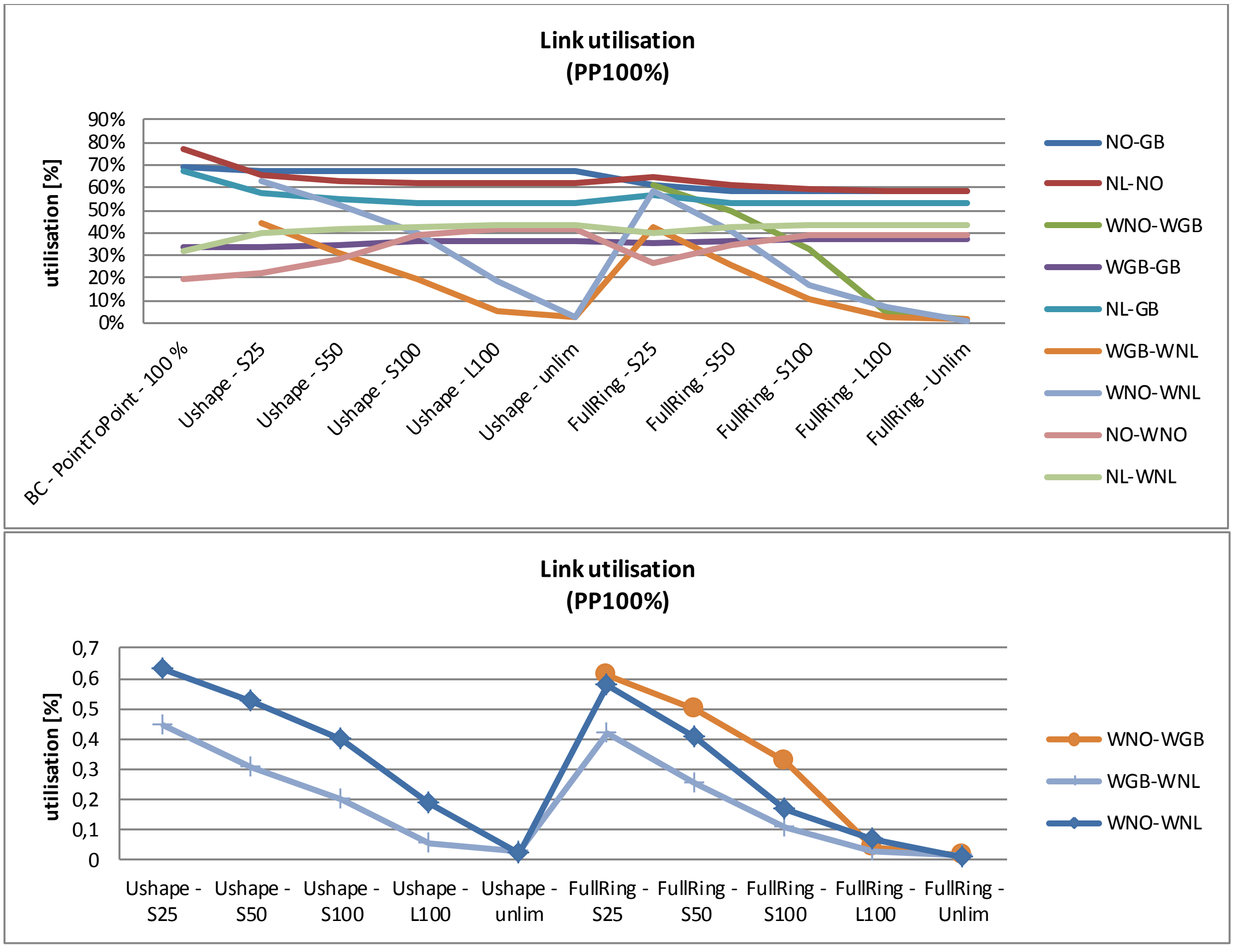


Figure 5-14 Link utilisations

Having the 'to-shore' capacity fixed, the effects of the different capacities of the hub-to-hub connections can be studied. As a first conclusion it can be seen that changing the grid structure (u-shape vs. full ring) only influence the results for the lower capacities. In terms of wind integration (Figure 5-15) the grid changes mainly affect the wind production in them the hydro dominated area, which is due to the previously mentioned hydro-wind competition.

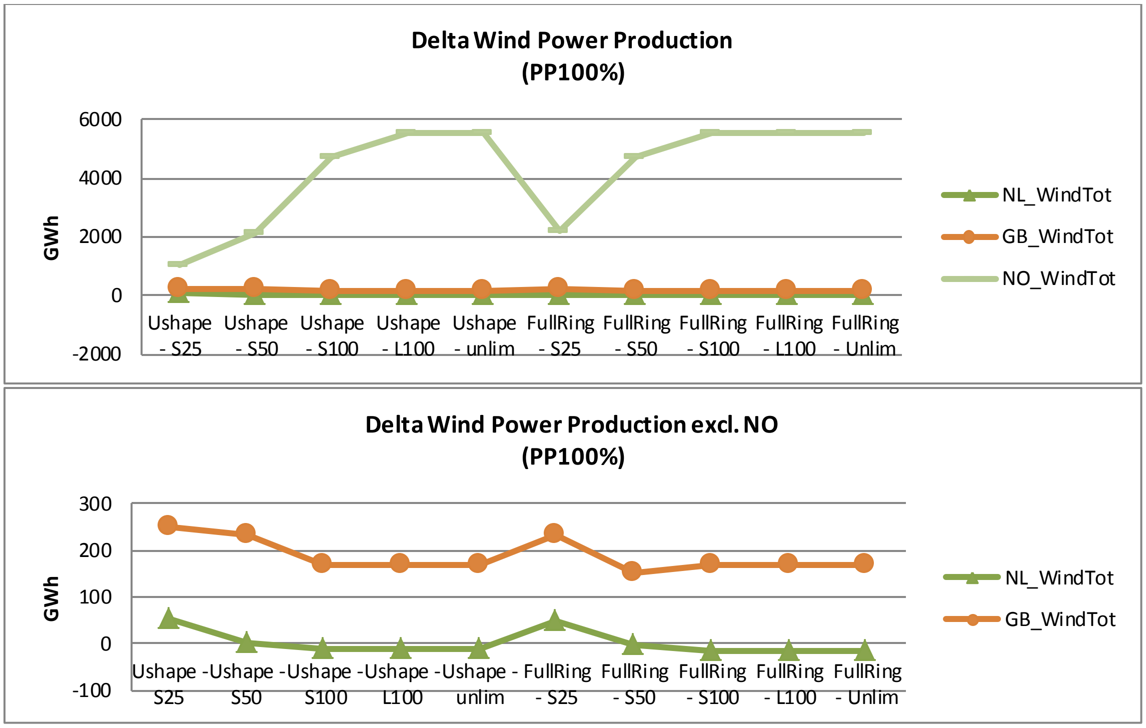


Figure 5-15: Delta wind power production and wind curtailment

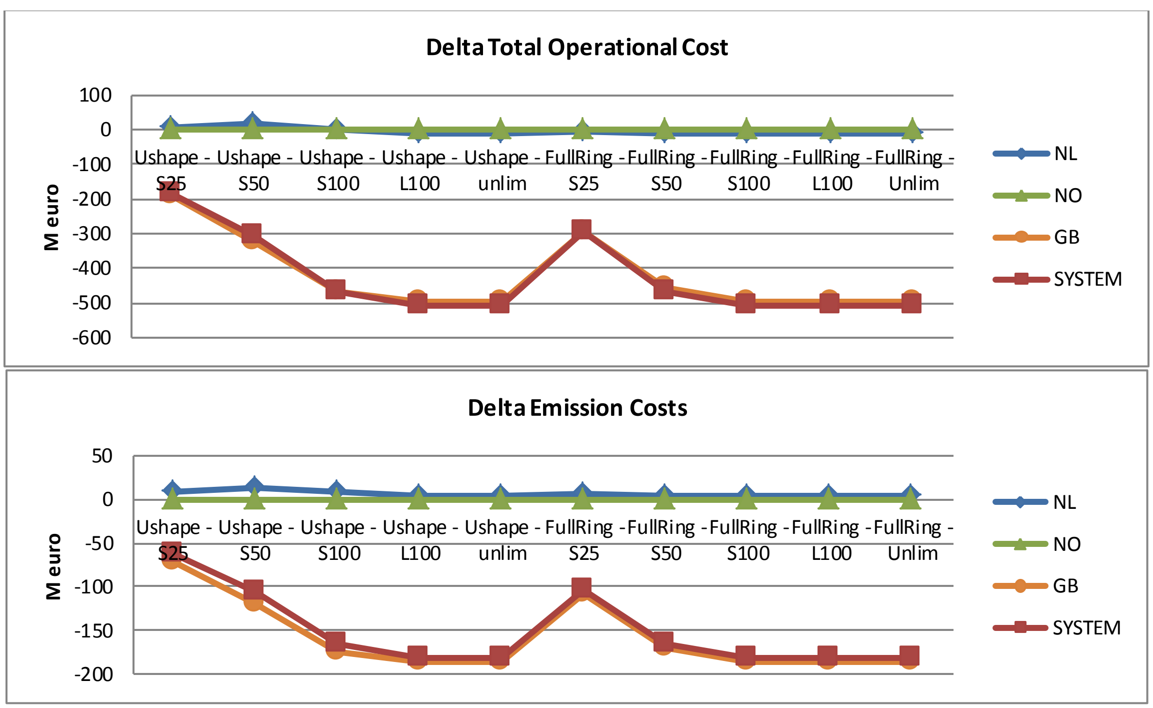


Figure 5-16: Delta total cost and emission cost

All the cases do however result in reduced total operating costs, though lower capacities (S25, S50) results in somewhat lower reduction than the higher capacities (S100, L100, C). To evaluate if these additional reductions in cost for higher capacities justify the increase in capacity, the reduced operational cost should further be compared with the additional investment cost.

As a rough estimation to give an idea about the size of infrastructure investments needed, a calculation of cable investment cost is done. According to [32] the investment cost can be calculated according to eq. 5-5 cable cost estimated according to Table 5-4 and installation cost to be 200.000 €/km for each cable pair. Only cable costs are considered, as converter and transformer stations are already built for the hub connections to shore. Data and results are given in Table 5-5.

$$CablePairCost = CableLength \times (InstallationCost + CableCost) \tag{5-5}$$

CABLE RATED POWER [MW]	220	350	500
COST PER CABLE PAIR [M€/KM]	0.30377	0.4453	0.6086

Table 5-4: Cable cost [32]

HUB-TO-HUB CONNECTION	TRANSFER CAPACITY [MW]	APPROX. CABLE CAPACITY [MW]	APPROX. DIST. [KM]	APPROX. COST [M€]
GB-NO S100	2680	(500x4+350x2)=2700	300	1357.5
GB-NO S25	670	(350x2)=700	300	387.2
NL-NO S100	2680	(500x4+350x2)=2700	350	1583.8
NL-NO S25	670	(350x2)=700	350	451.7
GB-NL S100	6214	(12x500+220)=6220	250	2551.7
GB-NL S25	1554	(2x500+350+220)=1570	250	691.6

Table 5-5: Investment Cost

Based on the large difference in cost the higher link utilisation, the S25 topology is chosen for further evaluation. Results for the S25 case is given in Table 5-6.

SYSTEM VALUES	FULL RING – S25
Delta Wind production [GWh]	2515
Delta Wind curtailment [GWh]	-2515
Average link utilisation [%]	49%
Delta Production Cost [M€]	-296,7
Delta Prod. Cost [%]	-2%
Delta Emission Cost [M€]	-103,1

Table 5-6: System results, case 'full ring - S25'

For more accurate cost-benefit evaluations the operational cost savings should be considered over the lifetime of the asset and the net present value calculated for comparison. Such a cost-benefit analysis is however considered outside the scope of this thesis.

5.5.1 Sensitivity analysis

A few sensitivity cases will further be applied for this case, as shown in the flow chart in Figure 5-17.

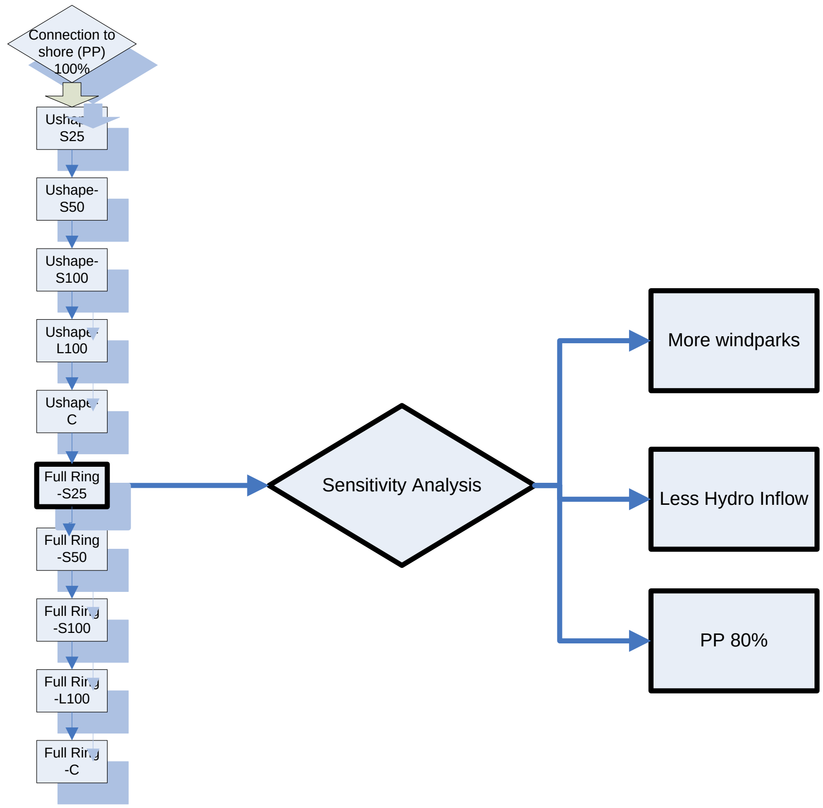


Figure 5-17: Simulation flow chart incl. sensitivity analyses

Firstly the system is tested for its sensitivity towards the amount of available hydro energy, which will vary between years depending on the inflow to the reservoirs. It is thus useful to define different inflow scenarios for a wet and a dry year. The Norwegian hydro system has a potential of 205 TWh, this is however not a representative number for the available energy which in the period from 1970-1999 had a medium production of 123.4 TWh and the production during the last ten years ranged from 106 TWh (2003) to 142 TWh (2000) [78]. Comparing with the weekly dispatched hydro already used in the simulated cases, the amount used corresponds to a wet year and a dry year will thus be simulated for sensitivity purposes. The inflow scenarios are given In Table 5-7.

SENSITIVITY	REAL CASE (NORWAY)	SIMULATED CASE (NO)	WEEKLY DISPATCHED HYDRO ENERGY
Wet year	142 TWh	145 TWh	2800 GWh
Dry year	106 TWh	104 TWh	2000 GWh

Table 5-7: Hydro inflow scenario

Secondly, the sensitivity towards a wind park scenarios with a higher amount of installed capacity. As the construction of an offshore grid is a relatively long process with limited design flexibility in the final stages. The design should account for possible changes in initial wind park scenario as well as future developments (increased amounts of wind parks). The 2025 offshore wind park scenario is thus replaced with the 2030 scenario presented in chapter 2 while the rest of the system is kept as it is. The offshore wind scenarios are given in Table 5-8.

	INST. CAP. 2025 [MW]	INST. CAP. 2030 [MW]	INCREASE [MW]	INCREASE [%]
WNL	6214	10308	4094	66%
WGB	23095	29965	6870	30%
WNO	2680	7180	4500	168%
TOTAL	31989	47453	15464	48%

Table 5-8: Offshore wind scenarios, 2025 and 2030

As a third case, the connections to shore is again changed to 80% of the connected wind park capacity. This is done to assess the question whether coordinated offshore development can save money. The resulting influence of these three sensitivity cases on wind integration, link utilisation and operational cost can be seen in the figures below.

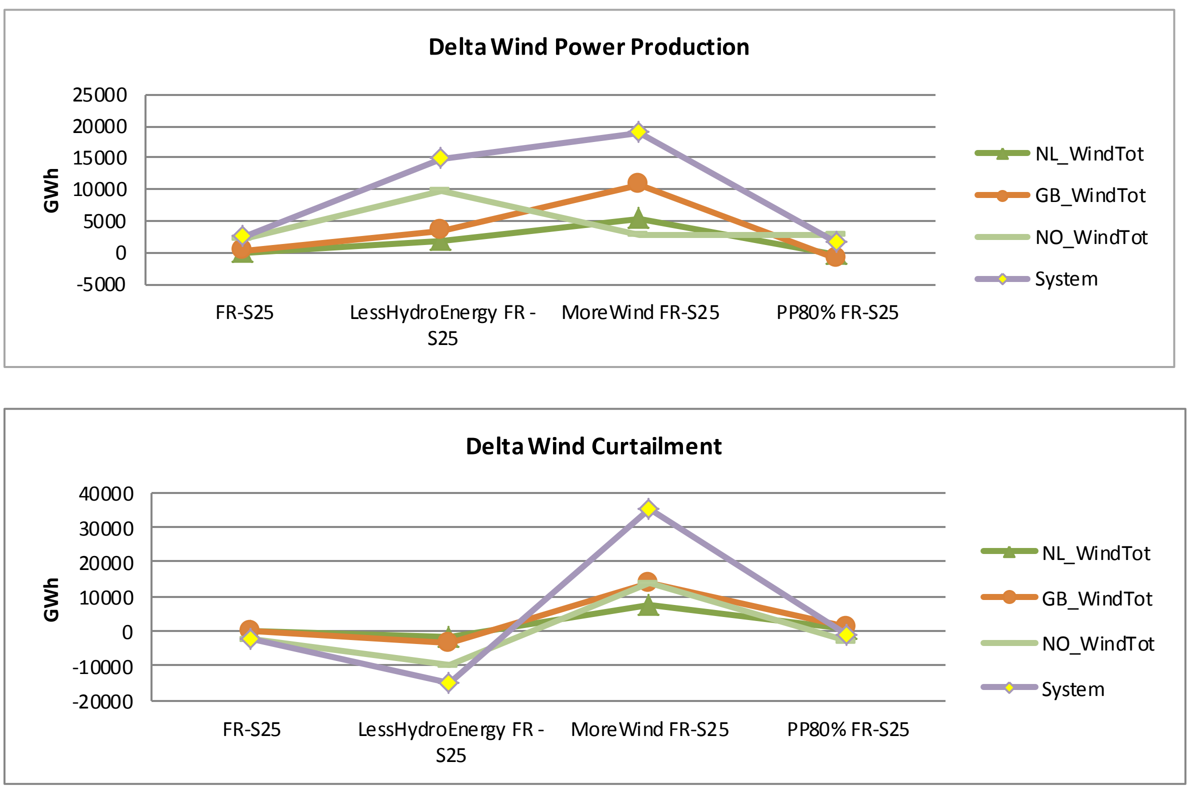


Figure 5-18 : Delta wind production and wind curtailment (case: full ring S25)

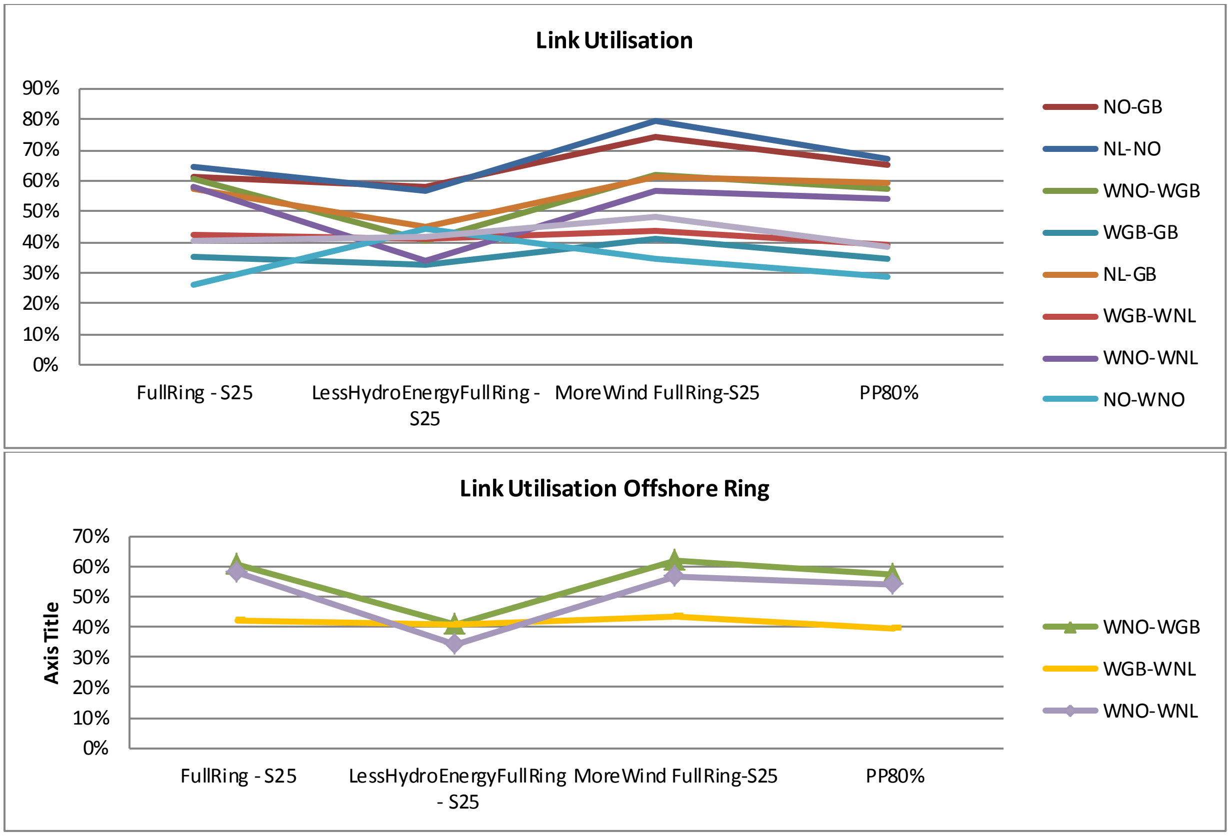


Figure 5-19: Link utilisation (case: full ring S25)

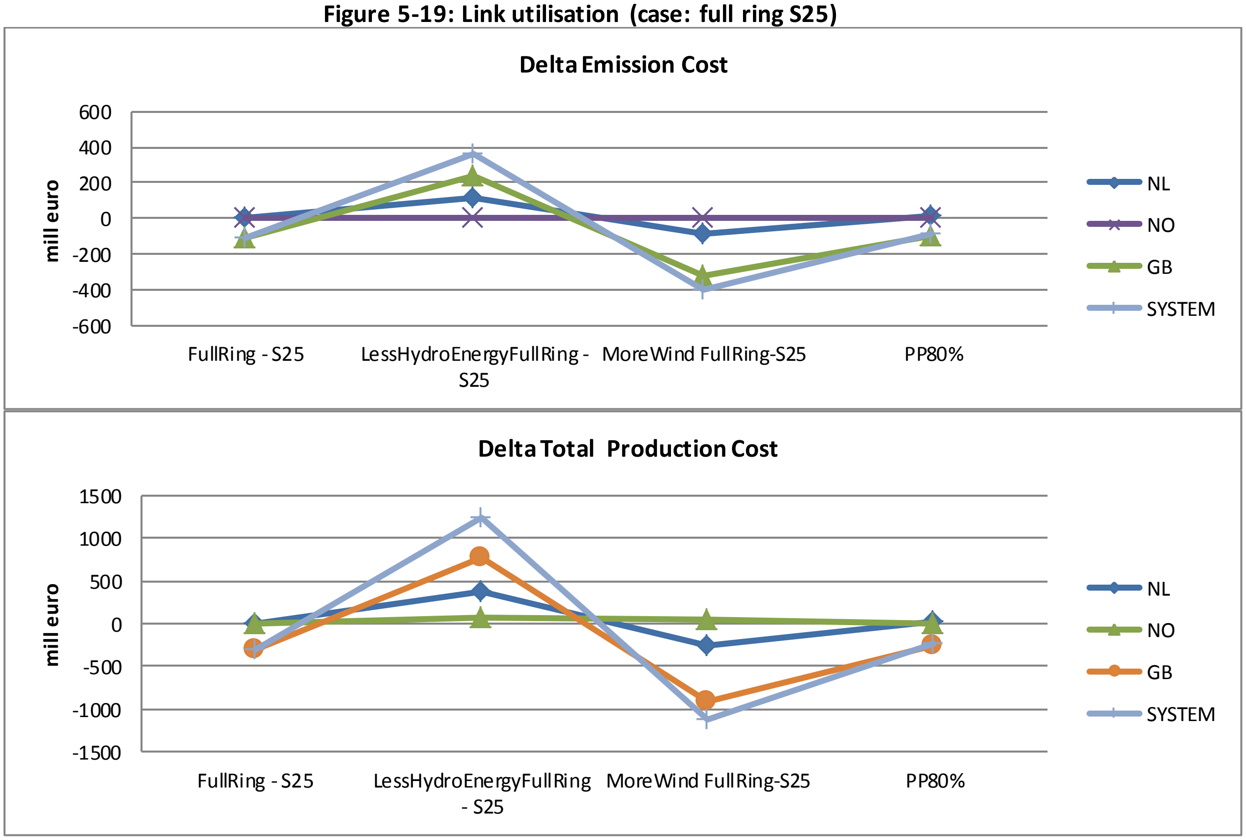
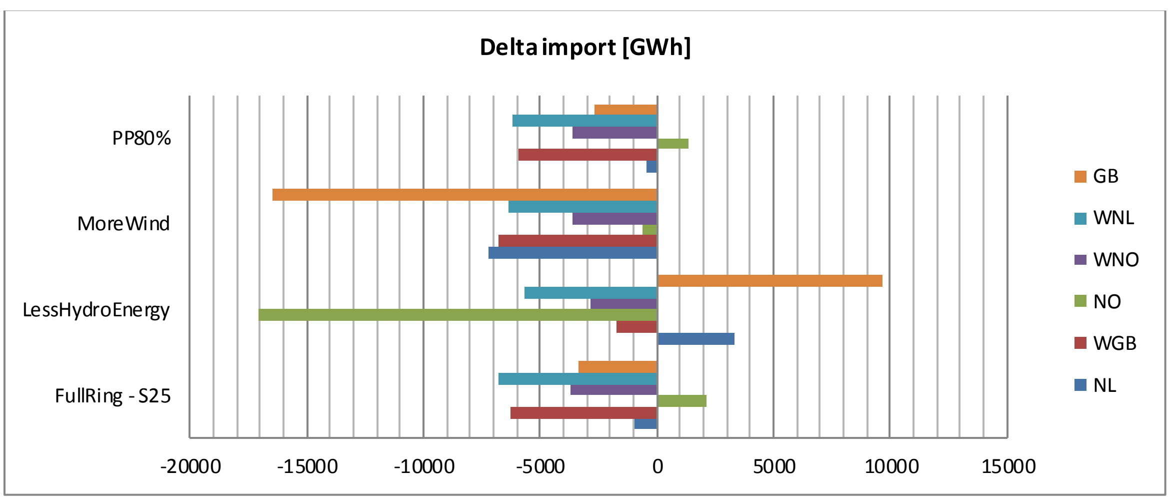


Figure 5-20: Delta production cost and emission cost (case: full ring S25)

SYSTEM VALUES	FR – S25	LESS HYDRO	MORE WIND	PP80%
Delta Wind production [GWh]	2515	14867	19068	1377
Delta Wind curtailment [GWh]	-2515	-14867	35200	-1377
Over-all link utilisation [%]	49%	44%	56%	49%
Delta Production Cost [M€]	-296,7	1238,8	-1134,6	-243,2
Delta Production Cost [%]	-2%	9%	-8%	-2%
Delta Emission Cost [M€]	-103,1	367,5	-404,1	-85,1

Table 5-9 : Sensitivity results

The amount of hydro energy in the system can be seen to highly influence all of the measured parameters. As the hydro in this system will be dispatched before any other resource, the integration of wind, which is usually dispatched first due to zero/low marginal cost, can be expected to be sensitive to large amounts of hydro. Due to this hydro-wind competition the reduction in available hydro energy leads to increased production in all wind areas and accordingly reduced wind curtailment. The increase is largest for the NO-wind. With higher wind production a higher utilization of the links could be expected, this is however not the case. As can be seen in Figure 5-19 the utilisation of all links, except NO-WNO are reduced, which suggest that the offshore grid to a large extent is utilized for hydro based trade (not only hydro export from NO, but trade facilitated by the flexible and cheap hydro production).



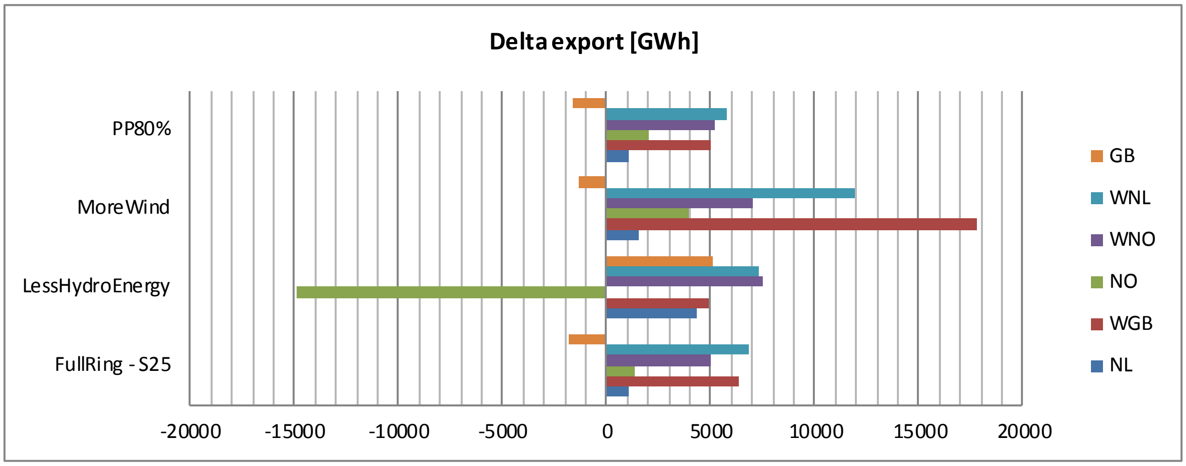


Figure 5-21: Delta import and export (case: full ring S25)

In the cost figures a large increase in the cost of the total system can be seen, showing that even if the wind production is increased the wind is not capable of replacing the hydro and the production cost increase as conventional generation with higher marginal cost is dispatched. This is confirmed when looking at the change in production mix in Figure 5-22, where coal based power production is seen to be a large contributor. Though it should be noted that the inflow values used for comparison represent quite large variations, it can thus be concluded that the hydro plays a very important role in this system and the amount of available hydro will have a relatively large influence on other generation areas with different generation portfolios.

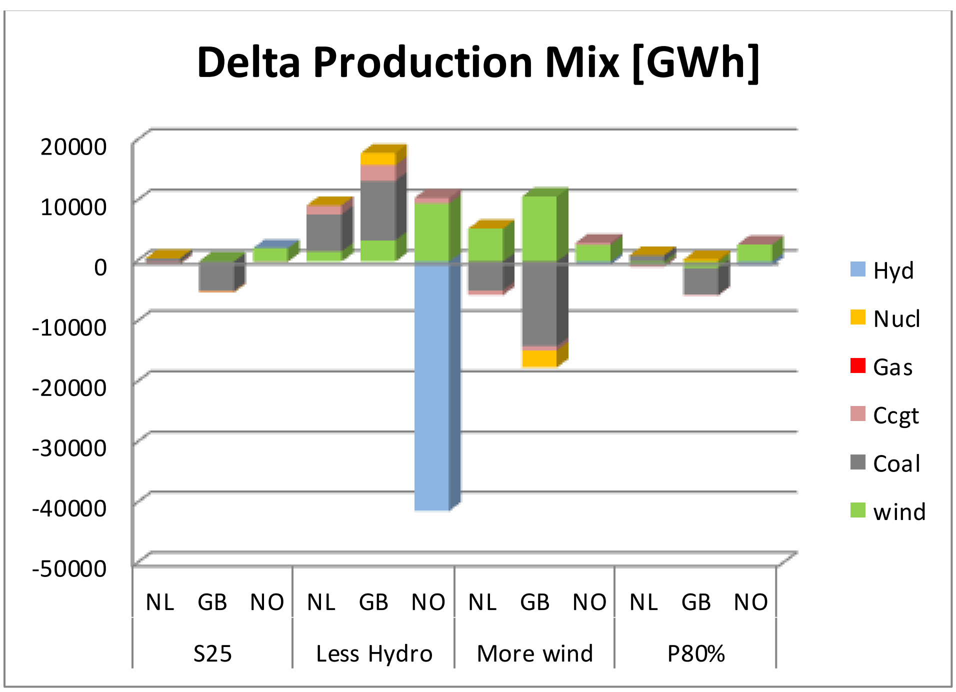


Figure 5-22: Delta production mix (case: full ring S25)

In the case of a larger wind capacity installed, the wind production related to GB and NL is considerably increased because of the large increase in capacity; as is the amount of curtailed wind. The increase in curtailment is in fact even larger than the increase in production. The link utilisation is further increased for the direct links NO-NL and NO-GB, due to increased export of hydro. This suggests that hydro is an important contributor to the integration of wind in the whole system. As a consequence of high hydro and wind production, conventional generation (mainly coal, but also nuclear and gas) is reduced and production cost reduced accordingly. This change in production mix also reduce system emissions and system emission cost. Though the chosen system configuration is not fully capable of absorbing large increase in wind power it can be seen that increasing wind power will lead to increased benefits in terms of large reduction of production cost and emissions.

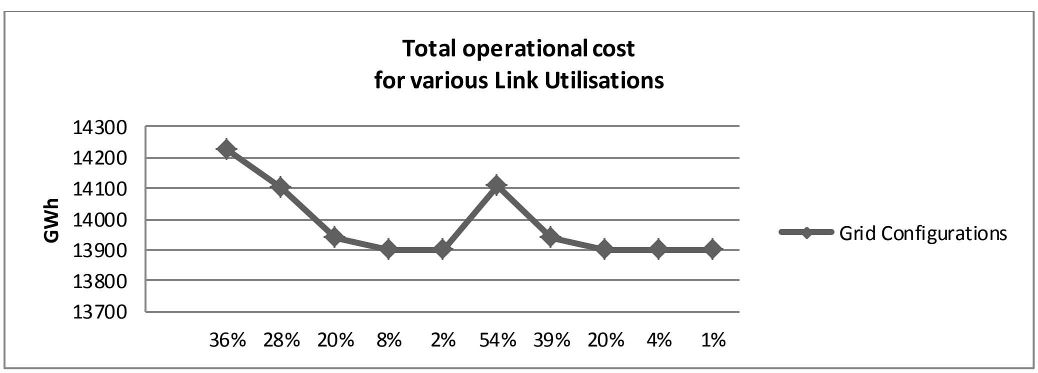
In the final case where the connections to shore are reduced to 80%, does as could be expected lead to lower wind power production and higher curtailment than for the 100% case. Link utilisation is more or less equal to the 100% case for all links, with an average link utilisation of 49% in both cases. Reduction of the capacity to shore does not seem to constrain the power flows in the offshore grid though the total production cost is slightly higher than the 100% case, due to the lower wind power production. In this case it is not clear whether a coordinated development of offshore grid is beneficial as interconnections between hubs can facilitate reductions in capacity of the connection to shore.

6 Conclusions & recommendations

In this thesis, a method was developed that can enable decision makers to evaluate and compare benefits of various offshore grid topology and capacity choices. Due to limitations in size and detail level of the modelled power system, including an un-optimised hydro-scheduling method, the results should be treated with caution.

6.1 Simulation results

Regarding the topology of the offshore system, a meshed grid with interconnections between the wind park clusters does in all cases lead to increased wind integration, increased trade, decreased operational cost and decreased emissions. Considering the radial connections to shore there is little value added by increasing these above 100% of the wind park cluster capacity. Regarding the interconnections between the clusters no additional benefits arise when increasing the cable rating beyond the 100% capacity of the smallest connected hub. The added value of having a full offshore grid ring instead of a u-shaped configuration is dependent on capacity choices for the individual segments and in this system only seen for lower link capacities. Further benefits of the full ring may become obvious when reliability criteria are taken into account. It is however assumed that a high link utilisation is desirable since though additional benefits may arise from larger link capacities the investment cost will increase accordingly. The capacity of the offshore ring was therefore reduced compared to the initial cases, and the lower capacity option (see Figure 5-17) was chosen for further studies. As can be seen in Figure 6-1, where this lower capacity option is seen as a local max/min, this do lead to less wind being integrated and a consequently smaller decrease in operational cost than for the higher capacities. Thus Figure 6-1 visualises the trade-off made between benefits and link utilisation.



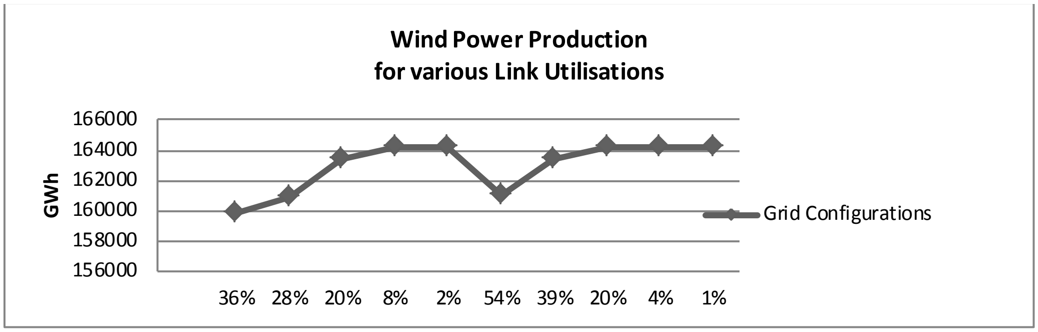


Figure 6-1: Total operational cost and wind power production for various link utilisations. The grid configurations are according to fig. 5-18

Large amount of wind power can be absorbed in the system with a meshed offshore grid and potentially lead to a large reduction in production cost. With the chosen 2025 wind scenario the wind is already in the base case well integrated in the power system and the potential increase in benefits provided by a meshed offshore grid is in that way limited. However as the installed wind power capacity is increased with approximately 50 % the operational cost are reduced with almost 300%, even with large amounts of curtailed wind due to limitations in the existing network.

The meshed grid is further seen to accommodate both wind integration and trade. Hydro is in this context an important factor and this system is sensitive for changes in available hydro energy. With the occurring hydro-wind competition the large increase in wind production in the NO area will lead to waste of energy resources unless the interconnection capacity to and exchange with other areas is sufficient.

The benefits of having a meshed offshore grid are further largely depending on the generation portfolio of the connected systems. In this system almost all reduction in operational cost can be attributed to the GB area, mainly due to the large share of coal based units (see Table 5-1 for complete generation portfolio). Thus having more areas with similar production mix, the cost reductions and benefits will increase.

6.2 Recommendations

For a better representation of the North Sea area and consequently increased accuracy of the results it can be recommended for further or similar studies to increase the resemblance to the real power system by including representations of interconnected areas and interconnections which were simply excluded in this system. The simplifications related to the scheduling of hydro in the input data and the software may as well influence the validity of the results and it is recommended for further studies to treat the hydro scheduling in greater detail.

As this study assess the effect and relative benefits of different grid topologies. A further step, in order to give recommendations on the optimal structure to be built, is to better estimate the investment cost. A cost-benefit analysis can then be performed instead of the benefit- link utilisation trade-off considered in this thesis.

With raising fuel prices as fossil fuel resources are expected to decline and raising emission cost as environmental concerns are increasing, the benefits of wind integration can be expected to increase accordingly. Adding sensitivity analysis of fuel prices and emission cost should thus be included in further studies.

As final recommendations, more work can be done regarding the wind scenarios. The wind speeds and the corresponding wind power could firstly be better modelled by having correlated offshore and onshore wind resources based on actual or modelled wind speed time series. Another interesting aspect of wind is the variation in available wind energy for different years. As presented in this thesis, the results here are only based on one year of wind data. Evaluating the benefits over several years or even over the lifetime of the assets, with varying wind speed scenarios, may however add value to the results. In this context methods for creating artificial wind speed series can contribute with their capability of providing arbitrary amounts of wind speed data. The created wind speed series can thus represent a longer period of random wind years or even be filtered to isolate scenarios with high or low wind energy content. This can provide additional information about the studied cases sensitivity towards the wind and the possible yearly variations that may occur.

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Appendix A: Generation Scenario for the North Sea

Country	Wind Park Scenario 1 Included in the scenarios in the following steps of development: 1. Dark blue – 2. Green – 3. Pink	Capacity [MW]
The Netherlands	Beaufort (Katwijk)	279
	Borssele Development zone	1000
	Breeveertien	150
	Breeveertien II	349
	Brown Ridge Oost	282
	Bruine Bank	550
	Buitengaats (BARD NL1)	300
	Callantsoog West	245
	Callantsoorg Oost	245
	Callantsoorg Zuid	328
	Clearcamp (EP Offshore NL1)	275
	Cornelia	438
	Den Haag I	381
	Den Haag II	255
	Den Haag III	705
	Den Haag Noord	504
	Den Helder 1	450
	Den Helder 2	450
	Den Helder 3	430
	Den Helder I	468
	Den Helder I	500
	Den Helder II	500
	Den Helder III	500
	Den Helder IV	500
	Den Helder Noord	798
	Den Helder Zuid	435
	Egmond aan Zee	108
	Eurogeul Noord	275
	Favorius	129
	FLOW - Turbine Demonstration Facility	300
	Helder	225
	Hoek van Holland 1	300
	Hoek van Holland 2	450
	Hoek van Holland 3	450
	Hoek van Holland 4	450
	Hopper	400
	HoriWind	270
	Horizon	275

	Ijmuiden	153
	Ijmuiden 1	450
	Ijmuiden 2	450
	Katwijk Buiten	325
	Maas West Buiten	175
	Noord Hinder	400
	Noord Hinder 1	400
	Noord Hinder 2	400
	Okeanos	158
	Oost Friesland	450
	Osters Bank 1	450
	Osters Bank 2	310
	Osters Bank 3	450
	Osters Bank 4	450
	Prinses Amalia Wind Park	120
	P12	141
	P15 - WP	219
	Q10	153
	Q4	78
	Q7 - West	245
	Riffgrond	500
	Rijnveld Zuid	150
	Rotterdam Noord-West	180
	Ruyter Oost	259
	Ruyter West	259
	Schaar	328
	Scheveningen Buiten	212
	Scheveningen 1	450
	Scheveningen 2	450
	Scheveningen 3	450
	Scheveningen 4	450
	Scheveningen 5	450
	Thetys	159
	Tromp Binnen	295
	Tromp Oost	367
	Tromp West	385
	West Rijn	259
	Wijk aan Zee	200
	WindNed Noord	60
	WindNed Zuid	150
	ZeeEnergie (GWS Offshore NL 1)	300
	Total Capacity [MW]	**25960**
Great Britain	2-B Energy Prototype	S6
	Aberdeen	115
	Beatrice	920
	Beatrice Demonstraition	S10
	Blyth	S4

	Britannia 10MW Turbine Project	S10
	Docking Shoal	540
	Doggerbank	6000
	Doggerbank Project One	1400
	Doggerbank Tranche A	1600
	Dudgeon	560
	East Angelina One	1200
	East Angelina Two	1200
	East Angelina Three	1200
	East Angelina Four	1200
	East Angelina Five	1200
	East Angelina Six	1200
	Firth of Forth Phase 1	1075
	Firth of Forth Phase 2	1435
	Firth of Forth Phase 3	955
	Galloper Wind Farm	504
	Greater Gabbard	504
	Grundfleet Sands	173
	Grundfleet Sands 3 - Demonstration Project	S6
	Hornsea	2800
	Hornsea Project One Block 1	600
	Hornsea Project One Block 2	600
	Humber Gateway	230
	Hywind Demonstration	S2,3
	Inch Cape	905
	Inner Dowsing	97
	Kentish Flats	90
	Kentish Flats 2	51
	Lincs	270
	London Array phase 1	630
	London Array phase 2	370
	Lynn	97
	Moray Firth Eastern Development Area edward MacColl	380
	Moray Firth Eastern Development Area Robert Stevenson	380
	Moray Firth Eastern Development Area Thomas Telfort	380
	NaREC Offshore Wind Demonstration Project	100
	Near na Gaoithe	420
	NOVA (Novel Offshore Vertical Axis) Project	S10
	Race Bank	620
	Scorby Sands	60
	Sheringham Shoal	317
	Teesside	62
	Thanet	300
	Triton Knoll	1200
	Westermost Rough	240
	Total Capacity [MW]	**34180**
Belgium	Belwind Phase 2	165

B	Belwind Phase 1	165
	Eldepasco	216
	North Sea Power	360
	RENTEL	288
	Seastar	246
	Thornton Bank phase I	30
	Thornton Bank phase II	148
	Thornton Bank phase III	148
	Zone 7	2000
	Total Capacity [MW]	**3766**
Norway N	Ægir Havvindpark	1000
	Idunn energipark	1200
	Karmøy Wind Turbine Demonstration Area	S8
	Rennesøy Wind Turbine Demonstration Area	S8
	Siragrunden	200
	Sørlige Nordsjø I	1500
	Sørlige Nordsjø II	500
	Sørlige Nordsjøen	1000
	SWAY	S5
	SWAY 10 MW test turbine	S10
	Testområde Bukketjuvane	S10
	Testposisjon Fure	S5
	Testposisjon Kvalheimsvika	S5
	Utsira nord	1500
	Utsira Phase 1	S25
	Utsira Phase 2	280
	Total Capacity [MW]	**6180**
Germany G	Aiolos	985
	Albatros	400
	Alpha Ventus (test)	60
	Amrumbank West	400
	Aquamarin	400
	Area C I	400
	Area C II	400
	Area C III	400
	Austerngrund	400
	BARD Offshore 1	400
	Bernstein	520
	Bight Power I	400
	Bight Power II	400
	Borkum Riffgrund	277
	Borkum Riffgrund II	480
	Borkum Riffgrund West	400
	Borkum Riffgrund West II	215
	Borkum West II phase 1	200
	Borkum West II phase 2	200
	Butendiek	288

	Breitling	S3
	Citrin	400
	DanTysk	288
	Delta Nordsee 1	240
	Delta Nordsee 2	160
	Deutche Bucht	273
	Diamant	800
	EnBW He Dreiht	595
	EnBW Hohe See	400
	ENOVA Offshore NSWP 4	486
	ENOVA Offshore NSWP 5	510
	ENOVA Offshore NSWP 6	504
	ENOVA Offshore NSWP 7	570
	ENOVA Offshore project Ems Emden	S5
	Euklas	800
	Gaia I	400
	Gaia II	200
	Gaia III	400
	Gaia IV	340
	Gaia V	400
	Gannet	400
	Global Tech I	400
	Global Tech II	380
	Global Tech III	105
	Gode Wind I	400
	Gode Wind II	400
	H2-20	400
	He dreiht II	140
	Heron	400
	Hochsee testfield Helgoland	95
	Hooksiel	S5
	Horizont I	325
	Horizont II	380
	Horizont III	355
	Innogy Nordsee 1 Phase 1	332
	Innogy Nordsee 1 Phase 2	332
	Innogy Nordsee 1 Phase 3	332
	Jules Verne	800
	Kaikas	415
	KASKASI	320
	Meerwind Ost	144
	Meerwind Süd	144
	Meerwind West	805
	MEG Offshore I	400
	Nautilus	675
	Nemo	680
	Nordergründe	90

	Nordlicher Grund	320
	Nordpassage	400
	Nordsee Ost	295
	Notos	265
	OWP West	400
	Petrel	400
	Riffgat	108
	Sandbank24	288
	Sandbank24 extension	200
	Seagull	400
	Sea Storm I	400
	Sea Storm II	190
	Sea Wind I	220
	Sea Wind II	300
	Sea Wind IV	390
	Sea Wind III	285
	Skua	400
	Veja Mate	400
	Witte Bank	400
	Total Capacity [MW]	**31101**
Denmark	DanTysk DK	1200
	Horns Rev 1	160
	Horns Rev 2	209
	Horns Rev A	200
	Horns Rev B	200
	Horns Rev C	200
	Horns Rev D	200
	Horns Rev E	200
	Jammerbugten K	200
	Jammerbugten L	200
	Jammerbugten M	200
	Jammerbugten N	200
	Ringkøbing F	200
	Ringkøbing G	200
	Ringkøbing H	200
	Ringkøbing I	200
	Ringkøbing J	200
	Rønland	S17
	Total Capacity [MW]	**3169**

Appendix B: Generation Portfolio, incl. SAF values

	GENERATION TYPE	SAF [MW]	EXCL. OFFSHORE WIND [MW]	INCL. OFFSHORE WIND [MW]
NL	Nuclear power	500	500	500
	Coal	7500	7350	7350
	Gas Total	*33800*	*30186*	*30186*
	Offshore Wind			6000
	Onshore Wind		5400	5400
	System Capacity	34900*	**43436**	**49436**
	Peak load:		24926	24926
	Load	22600		
	Gen/Load- Ratio	**1,54**	**1,59**	**1,66**
GB	Nuclear power	11870	11940	11940
	Coal	20030	22000	22000
	Gas Total	*31960*	*34193*	*34193*
	Offshore Wind			23000
	Onshore Wind		14000	14000
	System Capacity	62700*	**82133**	**105133**
	Peak Load:		67165	67165
	Load	58300		
	Gen/Load - Ratio	**1,08**	**1,08**	**1,18**
NO	Ccgt	930	986	986
	Hydro	28800	28800	28800
	Offshore Wind			2500
	Onshore Wind		5000	5000
	System Capacity	26600	**34786**	**37286**
	Peak Load:		28704	28704
	Load	24530		
	Gen/Load - Ratio	**1,08**	**1,09**	**1,12**
	*)Reliable Available Capacity			