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Science and Technology

Life cycle assessment of an offshore electricity grid interconnecting Northern Europe

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Submission date: July 2012
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Norwegian University of Science and Technology
Department of Energy and Process Engineering

NTNU
Norwegian University
of Science and Technology

Department of Energy
and Process Engineering

EPT-M-2012-68

MASTER THESIS

for

student Rasmus Nes

Spring 2012

Life cycle assessment of an offshore electricity grid interconnecting Northern Europe

Livssyklusanalyse av et Nordeuropeisk offshore kraftnett

Background and objective

The increasing use of variable renewable electricity sources in Northern Europe creates a need for changing the electric power infrastructure to store electricity, build fossil backup power, or extend electricity grids to even out the electricity generation across larger regions. Norwegian hydropower is seen as an important source for regulating power to countries around the North Sea. Power transfers across the North Sea will require substantial investments in grid expansion onshore and the development of an offshore electricity grid. Substantial financial requirements, material requirements and interventions in nature are the result.

Life-cycle assessment has been used to calculate the emissions and resource requirements associated with different types of energy production and to compare electricity sources. However, assessments of environmental impacts of energy supply technologies often neglect the differing requirements that different energy sources have in terms of the grid and in terms of backup solutions and balancing requirements. Large grids are a way to address the balancing and reduce the need for storage.

Life-cycle assessment is designed to take all production aspects into account. The problem is that LCA has system boundary issues (cut-off) and is not able to model downstream effects. Input-output analysis offers a more complete systems description and a way to address downstream effects, but it is usually based on an annual flow table and does not endogenize investments. Hybrid life cycle assessment is in theory better suited to include different types of inputs and avoid cut-offs; however, its implementation is not standardized yet and potentially has substantial data requirements.

The aim of this project is to produce a life cycle assessment of hypothetica offshore grid infrastructure for a future renewable power system in Northern Europe. The objective is to analyse the overall environmental impacts of renewable power and to assess the trade-offs of using an off-shore grid to address the balancing requirements.

The following tasks are to be considered:

1. What alternative electricity grid infrastructures will be potentially developed as part of a future Northern European electricity grid?

2. What is best life-cycle approach to assess such a grid? What combination of material, process-level and input-output methods provides reliable results at reasonable effort? Justify your methodological choice.
3. What are the environmental and resource impacts of different scenarios?
4. Break down these impacts by component and material or sector.
5. How does the cost of an off-shore grid compare to the benefit in terms of making renewable energy sources accessible and reducing the need for other balancing/storage options?

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Department of Energy and Process Engineering, 16. January 2012

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Preface and acknowledgements

This master thesis completes my MSc in Energy and Environmental Engineering at the Norwegian University of Science and Technology.

Many persons have supported me and contributed much to the completion of this thesis. I especially want to thank my co-supervisor Anders Arvesen for the amount of time he has spent on giving me quality guidance and letting me use his work as a starting point for mine. Without the framework basis borrowed by him, such a detailed analysis as was achieved would not have been possible. I also want to thank my supervisor Edgar Hertwich for his quality guidance throughout the year. Being in close contact with one of the main contributors to the WINDSPEED project have been essential for understanding all the assumptions made in the project and providing me with necessary additional data. Many thanks are owed to Daniel Huertas Hernando at SINTEF Energy Research for this. Some data used in this thesis are based on Christine Birkeland's work in her master thesis of spring 2011; I would like to thank her for that important indirect contribution.

In addition I would like to thank Anthony Pak for teaching me how to make nice graphs and constructive discussions, and Mari Nes, Dag Eide and Andreas Duckfoot Cappelen for valuable proofreading of my work.

Oslo, July 2012

Rasmus Nikolai Nes

Abstract

There is a growing demand for increased electricity transfer capacities between the countries surrounding the North Sea. The increased capacities will enable easier integration of intermittent renewable energy sources, decrease the need for balancing power, increase power trade and competition, and increase security of supply across the region. Interregional offshore grid connections are required if large scale deployment of deep sea, far from shore offshore wind energy in the North Sea is to take place. The WINDSPEED research project has resulted in proposals of realistic scenarios for large scale deployment of offshore grid and wind energy in the North Sea. In this study the environmental impacts of an interregional meshed offshore grid as proposed by WINDSPEED have been assessed. Environmental impacts of the offshore wind farms, which may be connected to the grid, have been included in the assessment as well, completing the system boundaries.

The methods used to quantify the environmental impacts are process-based life cycle assessment (LCA), input-output assessment (IOA) and tiered hybrid LCA, with main focus on the results of the latter. Four offshore grid scenarios have been assessed, with and without offshore wind farms connected. The offshore grid is primarily composed of 450 kV HVDC technology for long distance transmission, based on the HVDC cables used in the NorNed connection. Wind farms are deployed far from shore (requiring much sea transport and long distance grid connections) and at an average of 43.9 meters depth (requiring large bottom-mounted foundations for the wind turbines). These requirements make the environmental impacts of deep sea, far from shore offshore wind energy substantially higher than for both close to shore offshore wind energy and onshore wind energy.

The environmental assessment of the interregional meshed offshore grid found that the largest contribution to environmental impacts is from manufacturing and installation of HVDC cables. Sea transport required for installation of components and operation and maintenance contributes between 5 and 25 percent to most impact categories. The electrical equipment (converters, breakers and switchgear) required by the grid has a quite varying contribution, from almost none to some impact categories to about 35 percent to climate change impact. The environmental assessment of the deep sea, far from shore offshore wind energy, finds that the largest contributors to environmental impacts are the wind turbines. But the other components required – deep sea foundations, offshore grid and sea transport for installation, operation and maintenance – makes the environmental impacts caused by it around twice as high as for onshore wind energy installations. Total climate change impacts were found to be 42.9 g CO_2-Eq/kWh; the grid is responsible for 11, foundations 31 and sea transport 9 percent of that. The largest impacts of deep sea, far from shore offshore wind energy as compared to other relevant energy sources are to the impact categories freshwater ecotoxicity, human toxicity and metal depletion. The impacts to these categories are many times larger, up to almost 20 times, compared to other relevant fossil fueled energy sources. The impacts to the other impact categories are substantially lower.

The results indicate that the environmental impacts caused by an interregional meshed offshore grid in the North Sea are substantial; it needs to be considered an important part of an environmental assessment of deep sea, far from shore offshore wind energy. On the other hand, the environmental costs are probably not so high that they outweigh the potential benefits of such offshore grid connections. It may in fact lead to net environmental gains because of a decreased demand for fossil balance power. As for large scale deployment of deep sea, far from shore offshore wind energy the environmental benefits as opposed to relevant fossil alternatives are obvious, but, including the significant disadvantages of intermittent energy supply and high monetary costs, overall gain to society is harder to predict.

Sammendrag

Det er et voksende behov for økt overføringskapasitet av elektrisk energi mellom landene som ligger rundt Nordsjøen. Økt overføringskapasitet vil føre til enklere tilkobling av fornybare energikilder med diskontinuerlig produksjon, redusere behovet for balansekraft, øke krafthandel og konkurranseforhold og øke forsyningssikkerheten i regionen. Interregionale offshore krafttilkoblinger er nødvendig for å muliggjøre storskala utbygging av offshore vindkraft på dypt vann, langt fra land i Nordsjøen. Forskningsprosjektet WINDSPEED har resultert i realistiske forslag til storskala utbygging av offshore kraftnett og vindkraft i Nordsjøen. I dette studiet har miljøpåvirkningene som følge av utbygging av interregionalt «masket» offshore kraftnett blitt kartlagt. Miljøpåvirkninger forårsaket av offshore vindkraft som kan bli tilknyttet det offshore kraftnettet har også blitt kartlagt.

Metodene brukt for å kvantifisere miljøpåvirkningene er prosess-basert livssyklusanalyse (LCA), kryssløpsanalyse (IOA) og tiered hybrid LCA, med hovedfokus på resultatene fra den sistnevnte metoden. Fire offshore kraftnett scenarier har blitt kartlagt, med og uten vindparker tilkoblet. Det offshore kraftnettet er primært sammensatt av 450 kV HVDC-teknologi for overføring av kraft over lange distanser. Kabelen ar antatt å være lik den som er i bruk i NorNed-forbindelsen. Vindparkene bygges ut langt fra land (krever mye sjøtransport og lange kraftnett-tilkoblinger) på en gjennomsnittlig dybde på 43.9 meter (krever store fundamenter montert på havbunnen for vindturbinene). Disse kravene gjør at miljøpåvirkningene forårsaket av vindkraft på dypt hav, langt fra land er markant høyere enn både offshore vindkraft nærme land og vindkraft på land.

Resultater fra kartleggingen av miljøpåvirkninger forårsaket av et interregionalt «masket» offshore kraftnett viser at mesteparten av miljøpåvirkningene skyldes produksjon og installasjon av HVDC sjøkabler. Sjøtransport som er nødvendig for installasjon av komponenter og drift og vedlikehold bidrar med mellom 5 og 25 prosent til de fleste miljøpåvirkningskategorier. Det elektriske utstyret (omformer, brytere og fordelingsanlegg) som er nødvendig i kraftnettet har et varierende bidrag, fra nesten ingen utslipp til noen miljøpåvirkningskategorier og opptil 35 prosent til klimagassutslipp. Resultatene fra kartleggingen av miljøpåvirkninger av vindkraft på dypt hav, langt fra land viser at mesteparten av miljøpåvirkningene er forårsaket av vindturbinene. Men de andre nødvendige komponentene – fundamenter på dypt hav, offshore kraftnett og sjøtransport knyttet til installasjon, drift og vedlikehold – gjør at *miljøpåvirkningene er dobbelt så store som for vindkraft på land.* Totalt utslipp av klimagasser er på 42,9 g CO_2-Eq/kWh; kraftnettet er ansvarlig for 11, fundamenter 31 og havtransport 9 prosent av det. De største miljøpåvirkningene forårsaket av vindkraft på dypt hav, langt fra land er, sammenlignet med andre relevante energikilder, til miljøpåvirkningskategoriene forgiftning av ferskvann, forgiftning som når mennesker og utarming av metaller. Utslippene til disse kategoriene er mange ganger større, opptil nesten 20 ganger, enn utslipp forårsaket av relevante alternative fossile energikilder. Utslippene til de andre kategoriene er markant lavere.

Resultatene indikerer at miljøpåvirkningene forårsaket av et interregionalt «masket» offshore kraftnett i Nordsjøen er såpass markant at det bør anses som en viktig del av en kartlegging av miljøpåvirkninger forårsaket av vindkraft på dypt hav, langt fra land. På den andre siden, påvirkningene på miljøet er antakelig ikke så høye at det vil være vanskelig å rettferdiggjøre en utbygging offshore kraft-tilkoblinger. Faktisk kan det være netto miljøvinning ved en utbygging fordi behovet for fossil balansekraft på land vil minske. For storskala utbygging av vindkraft på dypt vann, langt fra land, miljøvinningene sammenlignet med relevante fossile alternativer er åpenbare. Men, hvis ulempene ved diskontinuerlig energiproduksjon og de høye kostnadene for en slik utbygging tas med i betraktningen, er total gevinst til samfunnet vanskeligere å estimere.

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Abbreviations

AC	Alternating Current
CSC	Current Source Converter
DC	Direct Current
HV	High Voltage
HVAC	High Voltage Alternating Current
HVDC	High Voltage Direct Current
IOA	Input-Output Analysis
IO	Input-Output
LCC	Line Commuted Converter (same as CSC)
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
NGO	Non-Governmental Organization
OWE	Offshore Wind Energy
TSO	Transmission System Operator
VSC	Voltage Source Converter
WINDSPEED	Spatial Deployment of offshore WIND Energy in Europe (research project)

1 Introduction

As the issues related to climate change and depletion of fossil fuels are becoming more and more pressing, it is deemed necessary to increase the share of renewable energy sources in the energy system. Offshore wind energy is by many considered to play an important role in the energy system of the future. To reach ambitious targets for offshore wind adequate grid connections to them needs to be built. It is that necessary offshore grid expansion and the accompanying environmental impacts that is the focus of this study.

The primary aim of this study is to find the environmental impacts from constructing an interregional offshore grid in the North Sea. An interregional offshore grid in the North Sea will have many potential benefits for the connected regions and wind farms, including increased power trading and competition, increased security of supply and less demand for new balancing power to mitigate the effect of intermittent renewable energy sources. To be able to see the results in a relevant context, the environmental impacts of deep sea, far from shore offshore wind energy attached to the grid have also been assessed.

The primary method used in the assessment is the tiered hybrid life cycle assessment method, which includes both physical inventory and monetary costs to be able to better include all impacts.

1.1 Objective and motivation

In recent years it has been conducted many life cycle assessments of wind energy, trying the find the total environmental impacts caused by this renewable energy technology. The majority of them have been of onshore wind turbines and using process-based LCA. It has not been conducted any life cycle assessments of an offshore grid (to this author's knowledge). By assessing the environmental impacts caused by ambitious interregional meshed grid scenarios and the far from shore wind energy that it enables, new aspects, as the increased amount of cabling, transport and large foundations needed, have been included in the assessment.

Three methods have been used to assess the environmental impacts. This is primarily because there is a large risk of serious system boundary cut-off issues when using process-based LCA for assessing renewable energy. Cut-off errors of process-based LCA studies of renewable energy systems can be higher than 50% for some impact categories [1], a claim that is supported by the results in this study. The two other methods used are input-output analysis (IOA) and tiered hybrid LCA, the last being a combination of process-based LCA and IOA trying to benefit from the two methods strengths and avoiding their weaknesses. The primary focus in this study will be on the results of the tiered hybrid LCA, as they are regarded as being the most accurate.

1.2 Previous Work

Previous studies assessing the environmental impacts of offshore wind farms have found that wind farms emit typically between 5 and 20 g CO_2-Eq/kWh [2]. Anders Arvesen finds in his study of the Havsul 1 wind farm outside the west coast of Norway that impacts are ranging from 20.7 to 32.2 g CO_2-Eq/kWh, varying with optimistic or pessimistic assumptions [3]. Much of this study is based on numbers obtained from Arvesen's Havsul 1 wind farm study. There is a hybrid LCA study of onshore wind power in the UK with results between 28.7 and 29.7 g CO_2-Eq/kWh, depending on hybrid method used [4]. Christine Birkeland conducted an environmental assessment of 33 kV cables and the NorNed offshore cable in her master thesis from 2011 [5]. Raquel Jorge has conducted an LCA of electricity transmission and distribution components [6], but cables assessed are smaller and emissions related to power losses are included and contribute much; the results are not really comparable to the ones obtained in this study.

As mentioned, there are no existing studies doing the exact same as in this study: assessing the environmental impacts of an interregional meshed offshore grid and deep sea, far from sea offshore wind energy. That is unfortunate as a comparison would have been valuable.

1.3 Structure of report

Chapter 2 describes the methods and frameworks used. LCA, IOA and tiered hybrid LCA are presented with all relevant nomenclature and equations. The background databases Ecoinvent and EXIOPOL are explained, as well as the ReCiPe characterization framework.

Chapter 3 explains the motivation for building an offshore grid and covers briefly the most important aspects of power trade and balance management. Most importantly, chapter 3 tries to explain all technological choices and assumptions made in this study to be able to complete the assessment. The WINDSPEED report, on which the analyzed scenarios in this study are based, is described and explained.

In chapter 4 the most relevant results are presented and discussed. The life cycle inventory and life cycle costs are listed. The life cycle impact assessment is presented in a concise way with brief descriptions of each figure. In the end there is a discussion of the results, aimed at pinpointing the most relevant tendencies and information that can be deduced, and an evaluation of data quality and uncertainty.

In chapter 5 the environmental impacts found are discussed in a broad context and compared to other energy sources. The economic costs of the assessed scenario is calculated and compared to other energy sources. Implications for grid balancing and storage are also discussed.

Chapter 6 is the conclusion and includes suggestions for further studies.

Throughout the text much important information may be repeated several times. This is deliberate, so that it is possible to read excerpts from the text and understand them without having to read the entire text from back to back.

2 Methods

The goal of this study is to conduct a life cycle assessment (LCA) of an offshore electricity grid interconnecting Northern Europe. Several approaches of LCA can be used for such an assessment. Deciding which one to use is dependent on many factors; with data availability, product[1] characteristics and time-frame being some of the most important. In this study the tiered hybrid LCA approach has been chosen. The tiered hybrid LCA method combines the bottom-up approach of process LCA and the top-down approach of the environmentally extended input-output analysis (IOA), seeking to combine the strengths and avoid the weaknesses of the two methods. A thorough discussion of the methods available for environmental assessments is given in this chapter.

The increased awareness of the importance of environmental protection, and the possible impacts associated with products, has created a demand for methods to better understand and address these impacts. Two of the techniques that have been developed for this purpose are life cycle assessment and input-output analysis. According to ISO 14040 [7] LCA can assist in

- Identifying opportunities to improve the environmental performance of products in various points in their life cycle.
- Informing decision-makers in industry, government and NGOs (e.g. for the purpose of strategic planning, priority setting, product or process design or redesign).
- The selection of relevant indicators of environmental performance, including measurement techniques.
- Marketing (e.g. implementing an ecolabeling scheme, making an environmental claim, or producing an environmental product declaration).

The points above are valid for the environmentally extended IOA method as well.

To make this chapter more graspable for a reader that's not familiar with environmental assessments, there will be references to an example product throughout the chapter. The product is a wind turbine gearbox manufactured in Europe. Its inventory is hypothetical and has fewer components than in reality.

Table 1: Life cycle inventory of a hypothetical wind turbine gear box. The cost is for a unit, ready for installation.

Components	Amount	Unit
Physical		
Steel	100	kg
Oil	20	kg
Electricity	1000	kWh
Monetary		
Cost	1	M€

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[1] In this chapter, the term product has a broad meaning. It may represent everything a study want to assess; from an entire economy to a small component of a microchip.

2.1 Life Cycle Assessment

Works in the field that would eventually be called life cycle assessment were first performed in the late 1960s. No common terminology existed, but many of the central elements of the established LCA framework of today were used. There was a growing realization that there was a need for a holistic perspective when considering the environmental aspects of products. In the early 1990s the field, as we know it today, was starting to take form [8].

The ISO 14040 "Environmental management – Life cycle assessment – Principles and framework" provides a generic framework for LCA. LCA comprise four phases: the goal and scope definition, inventory analysis, impact assessment, and interpretation.

In the goal and scope phase the study is defined. The goal of an LCA mainly states the intended application and the reasons for carrying out the study. The scope needs to include the product to be studied, system boundaries, assumptions and limitations. The scope should be sufficiently well defined to ensure that the breadth, depth and detail of the study are compatible and sufficient to address the stated goal.

The life cycle inventory analysis (LCI) involves data collection and calculation procedures to quantify relevant inputs to and outputs of a product system. Data collection can be one of the main challenges and may be constrained by publically available information. As a basis for the calculations a background data set is needed, like the Ecoinvent database, to link the inputs and outputs of a product system to all the processes and services involved in its complete production chain. The calculations generate the results of the inventory analysis.

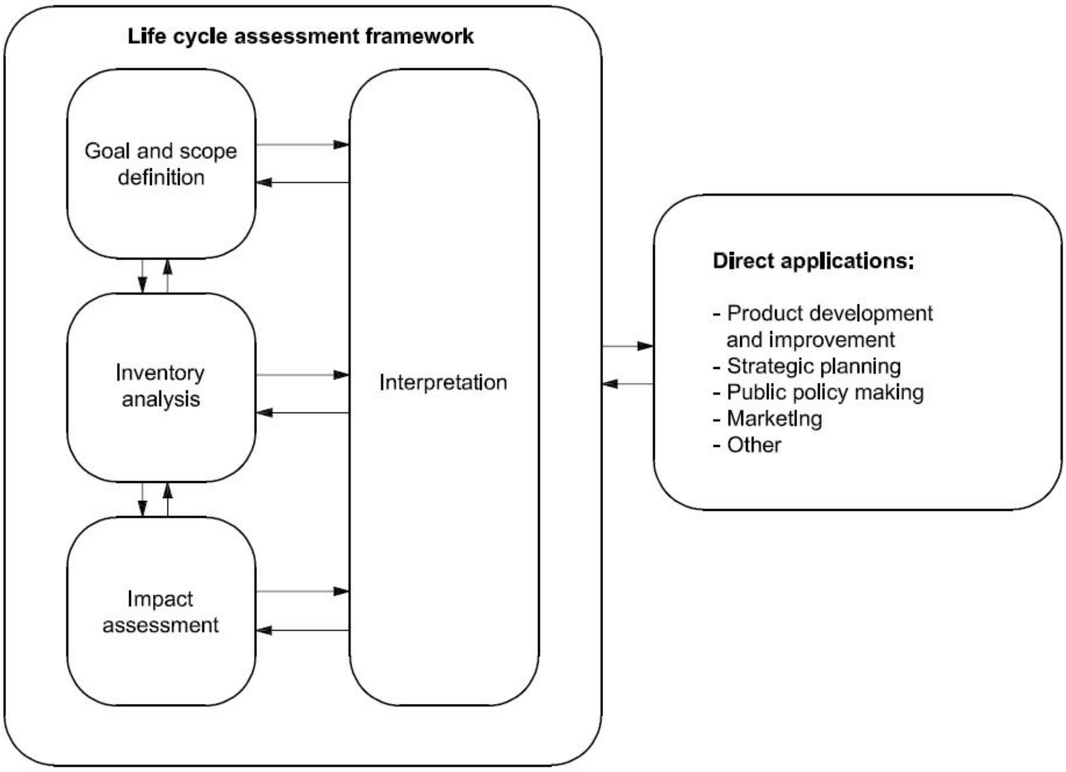


Figure 1: Stages of an LCA [7]

The life cycle impact assessment (LCIA) phase of LCA is aimed at evaluating the significance of the potential environmental impacts caused by the emissions calculated in the LCI phase. That is usually done by associating the emissions with specific environmental impact categories, e.g. by associating CO_2, SF_6, CH_4 etc. to global warming potential (GWP). ReCiPe is an example of a framework that makes such associations.

Interpretation is the phase of LCA in which the findings from the inventory analysis and the impact assessment are considered together with the goal and scope of the study to make conclusions and possibly recommendations.

2.1.1 Formal framework

Table 2: Nomenclature for the LCA framework

Sets	**pro**		**Processes**
	str		**Stressors**
	imp		**Impact categories**
Matrices and variables	A	*(pro x pro)*	Matrix of inter-process requirements
	y	*(pro x 1)*	Vector of external demand
	x	*(pro x 1)*	Vector of outputs for a given external demand
	L	*(pro x pro)*	The Leontief inverse. Matrix of outputs per unit of external demand
	F	*(str x pro)*	Matrix of stressor intensities per unit output
	e	*(pro x 1)*	Vector of total emissions generated for a given external demand
	E	*(str x pro)*	Matrix of emissions generated from each process for a given external demand
	C	*(imp x str)*	Characterization matrix
	d	*(imp x 1)*	Vector of impacts generated for a given external demand
	D_{pro}	*(imp x pro)*	Matrix of impacts generated from each process for a given external demand
	D_{str}	*(imp x str)*	Matrix of impacts generated from each stressor for a given external demand

The aim of an LCA study is to find all the direct and indirect emissions induced by the specific product studied. The first step in such a process is to map all the direct requirements demanded by the product. For instance, the wind turbine gear box requires 100 kg steel, 20 kg oil and 1000 kWh of electricity to be made. After mapping all requirements, the requirements matrix can be established:

$$A = \begin{pmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{pmatrix} \tag{2.1}$$

In the requirements matrix each column represents a process and the quantities required from the other processes to produce one unit output of this process. In the simple A-matrix shown above, the first column may represent the gearbox. Then a_{11} would tell how many gearboxes a gearbox requires, a_{21} how much steel, and a_{31} how much electricity it requires. The general balance for each process in the production system becomes

$$x_{11} = a_{11}x_1 + a_{12}x_2 + a_{13}x_3 + y_1 \tag{2.2}$$

where x_{11} is the total output induced by component 1 in the system and $a_{11}x_1 + a_{12}x_2 + a_{13}x_3$ is the intermediate demand component 1 has from component 1, 2 and 3, and y_1 is the external demand for component 1.

The production system can now be represented by a set of linear equations and handled as a set of matrices and vectors, giving

$$x = Ax + y \qquad 2.3$$

This equation can be solved for x by

$$x = (I - A)^{-1}y = Ly \qquad 2.4$$

where the L-matrix is known as the Leontief inverse. The Leontief inverse is an alteration of the requirements matrix to include the requirements of the entire production chain of the product, not just the direct requirements. By using the Leontief inverse for further calculations both direct and indirect outputs (and emissions) caused by the product will be found.

Basic contribution analysis

This part will briefly show the equations and calculation steps that are available when doing an LCA.

To find the vector of total emissions e, the stressor matrix F first has to be determined. F associates all product outputs to emissions. For instance, it associates how much emissions a given amount of steel produced in Europe will cause: x kg CO_2-emissions, y kg SO_2, z kg NO_x etc. When this has been mapped, total emissions can be found by

$$e = Fx = FLy = F(I - A)^{-1}y \qquad 2.5$$

By diagonalizing x the E-matrix can be found. It shows how much the various processes contribute to the total stressor load.

$$E = F\hat{x} \qquad 2.6$$

The vector of total impacts for a given external demand, d, can be calculated by including the characterization matrix, C. The characterization matrix associates how much each emission contributes to each impact category, for instance how much emissions of SO_2 contributes to climate change, acidification, eutrophication etc. Total impacts can then be found by

$$d = Ce = CFx = CFLy \qquad 2.7$$

Finally, one may be interested in how the different processes and the different stressors contribute to the environmental impacts:

$$D_{pro} = CE = CF\hat{x} \qquad 2.8$$

$$D_{str} = C\hat{e} \qquad 2.9$$

$$d = \sum D_{pro} = \sum D_{str} \qquad 2.10$$

Modeling with foreground and background systems

For some products it may be beneficial to model the requirements matrix with a foreground and background system. It will then look like

$$A = \begin{pmatrix} A_{ff} & 0 \\ A_{bf} & A_{bb} \end{pmatrix} \qquad 2.11$$

where A_{ff} represents the foreground requirements matrix, A_{bf} the foreground to background requirements matrix and A_{bb} the background requirements matrix. The main benefit of such modeling is the added aspect of foreground inter-requirements. The product being analyzed may be a wind farm that is composed of 120 wind mills each demanding 3 rotor blades, and that relationship may be modeled in A_{ff} so that when changing the demand for wind farms (y), the total output (x) will tak into account all requirements modeled in the foreground.

When modeling with a foreground and background system another equation may be of relevance:

$$D_{pro,ff} = CFL\hat{y} \qquad 2.12$$

which finds how much the different processes in the foreground system contribute to each impact category. Equation 2.7 will, with this modeling approach, find how much each background process contributes to each impact category. All other equations above are still valid.

2.1.2 Ecoinvent

LCA is a very data intensive framework. The requirements matrix ideally needs to contain *all* requirements for *all* processes in the products entire production chain. Fortunately, it is not necessary to map all this data for every study, since a lot of processes have already been mapped. For example, the process of making steel in Europe can be generalized into one “standard” process which would be almost always correct, regardless of what the steel is used for. Since the early 90’s much data has been collected and organized into different databases. For European purposes, Ecoinvent is recognized as the best quality and most complete LCA database [8]. It has a wide range of process categories included. Some examples are electricity generation, metal extraction, metal production, paper production, transport and heat production. The Ecoinvent database v2.2 contains 4087 processes.

Depending on how the LCA is modeled, the Ecoinvent database can represent either the entire A-matrix or it can represent only the background matrix in A, A_{bb}. A stressor matrix F is also part of the Ecoinvent database. It contains 1613 emissions, e.g. aldehydes, CO_2 and uranium [9].

2.1.3 ReCiPe

A characterization matrix, C, has the purpose of associating emissions to impact categories. The most established and common characterization method for European purposes is called ReCiPe. ReCiPe has impact categories at midpoint level (e.g. global warming potential and eutrophication) and endpoint level (e.g. damage to human health and damage to ecosystem quality) [10]. It may be argued that the midpoint indicators are a more accurate and objective measure than endpoint indicators [11]. Still, there are uncertainties related to the conversion and aggregation process and as result the ReCiPe method offers three different perspectives:

- The **individualist** perspective is based on the short-term interest. Only impact types that are undisputed are present. Technological optimism is rated highly.

- The **hierarchist** perspective is based on the most common policy principles with regards to time-frame and other issues.
- The **egalitarian** perspective is the most precautionary perspective. It has the longest time-frame and substances that are not yet fully proven to have an impact are included.

The hierarchist perspective with midpoint indicators is chosen in this study. ReCiPe contains 18 impact categories, shown in the table below.

Table 3: ReCiPe midpoint impact categories

Abbreviation	Impact Category	Unit
ALO	Agricultural Land Occupation	m2a
CC	Climate Change	kg CO2-Eq
FD	Fossil Depletion	kg oil-Eq
FET	Freshwater Ecotoxicity	kg 1,4-DCB-Eq
FE	Freshwater Eutrophication	kg P-Eq
HT	Human Toxicity	kg 1,4-DCB-Eq
IR	Ionising Radiation	kg U235-Eq
MET	Marine Ecotoxicity	kg 1,4-DCB-Eq
ME	Marine Eutrophication	kg N-Eq
MD	Metal Depletion	kg Fe-Eq
NLT	Natural Land Transformation	m2
OD	Ozone Depletion	kg CFC-11-Eq
PMF	Particulate Matter Formation	kg PM10-Eq
POF	Photochemical Oxidant Formation	kg NMVOC
TA	Terrestrial Acidification	kg SO2-Eq
TET	Terrestrial Ecotoxicity	kg 1,4-DCB-Eq
ULO	Urban Land Occupation	m2a
WD	Water Depletion	m3

2.2 Input-Output Analysis

Input-output analysis was originally an economic method used to analyze the industry relationships in an economy. The framework was developed by Professor Wassily Leontief in the late 1930s, work for which he received the Nobel Prize in Economic Science in 1973 [19]. By mapping all monetary flows in an economy, both from industry to industry and from industry to consumers, the framework makes it possible to find all the economic activity induced (output) by a given final demand. Table 4 below shows how a general input-output accounting framework, like EXIOPOL, looks like.

	Industries	**Net final demand**	**Total output**
Industries	Z	y	x
Value added	v		
Total input	x		

Table 4: Simplified table of components of a general input-output accounting framework

The output induced a given final demand can further be used to find the environmental impacts of this demand. That method is called the environmentally extended input-output analysis and is what the abbreviation IOA refers to in this study. The environmentally extended version of input-output analysis is summarized in the following sections.

IOA enables us to calculate both direct and indirect impacts from our economic activities [12]. The direct emissions correspond to the emissions induced by the production of the final product. The indirect correspond to the sum of all emissions caused by the intermediate products necessary to produce the final product, throughout the entire production chain.

2.2.1 Formal framework

Table 5: Nomenclature for the IOA framework with established Z-matrix

Sets	**prod**		**Products**
	ind		**Industries**
	str		**Stressors**
	imp		**Impact categories**
Matrices and variables	Z	*(prod x prod) or (ind x ind)*	Inter-industry flow matrix
	y	*(prod x 1) or (ind x 1)*	Vector of external demand
	x	*(prod x 1) or (ind x 1)*	Vector of total output of the economy
	v	*(prod x 1) or (ind x 1)*	Vector of value added
	A	*(prod x prod) or (ind x ind)*	Matrix of inter-industry requirements
	L	*(prod x prod) or (ind x ind)*	The Leontief inverse. Matrix of outputs per unit of external demand
	F	*(str x prod) or (str x ind)*	Matrix of stressor intensities per monetary output
	e	*(pro x 1)*	Vector of total emissions generated for a given external demand
	C	*(imp x str)*	Characterization matrix
	d	*(imp x 1)*	Vector of impacts generated for a given external demand

In general, the frameworks of LCA and IOA are quite similar. The main difference is that the requirements matrix has to be made by dividing the inter-industry flow matrix (Z) with total output of the economy (x). Mathematically that is written like

$$A = Z\hat{x}^{-1} \qquad 2.13$$

which now means that the framework can be treated the same way as process based LCA mathematically.

The biggest difference between IOA and LCA is that IOA is based on monetary flows and LCA on physical. That implies two different ways of mapping data; with IOA only costs of the related products are of interest as compared to all physical processes in LCA. The connection between the monetary units of costs and the actual physical emissions may be hard to grasp at first. But as long as costs are homogenous the monetary flows are just as representative as physical flows [21]. In this case, homogenous costs mean that the product costs are representative of the amount of physical flows the product is composed of. This is an ideal situation, and is generally not the case, but the assumption is considered good enough to make decent estimations of environmental impacts. EXIPOL costs are in so-called basic prices, which mean that no taxes, fees or subsidies are included. Thus, the monetary flows (costs) of the products to be analyzed should also be in basic price. What kind of prices the relevant costs are given in is information that is often lacking, and may be a source of uncertainty.

But the resolution of an LCA database like Ecoinvent is much higher than IOA databases, providing basis for more detailed analysis. Process based life-cycle assessment is according to Edgar G. Hertwich "based on detailed modeling of production, distribution, use and disposal processes of a specific product" while IOA "represents links among all industry sectors of an economy" [22]. The system boundaries of IOA are broader and thus more fully include the downstream effects.

2.2.2 EXIOPOL

The EXIOPOL ("A New Environmental Accounting Framework Using Externality Data and Input-Output Tools for Policy Analysis") database project was recently completed, and is the most up to date and accurate environmental accounting framework for Europe [13]. The database contains data for the entire world economy (44 countries: mainly Europe + certain large economies in the rest of the world (e.g. US, China), compiled in the same way as in Table 4. The database has 129 sectors, which covers all sectors in an economy; everything from cultivation of rice to manufacturing of steel to banking. It is modeled in such a way that the European economy can easily looked at in isolation, by separating the inter-industry flow matrix into a column for Europe (EU) and a column for rest of the world (ROW), resulting in

$$Z = \begin{array}{cc} & \begin{array}{cc} EU & \text{ROW} \end{array} \\ \begin{array}{c} EU \\ ROW \end{array} & \begin{pmatrix} z_{11} & z_{12} \\ z_{21} & z_{22} \end{pmatrix} \end{array} \qquad 2.14$$

which makes it easy to model a vector of external demand (y) for Europe only.

The Z-matrix is available in the industry by industry format (how much each industry requires from itself and all other industries) or the product by product format (how much each product requires from itself and all other products). Both are in monetary units. The product by product matrix has been used in this study.

The stressor matrix (F) in EXIOPOL is much smaller and simpler than the one in Ecoinvent. It only contains 28 stressors and all are emissions to air. Among them are CO_2, CH_4 and N_2O, some of the most important contributors to GWP – the impact category that is often of most interest when doing an environmental assessment of power production technologies. I.e. IOA can yield as relevant results as LCA for some, but not all, impact categories. All stressors in the EXIOPOL stressor matrix are listed in Table 6.

Table 6: EXIOPOL emissions/stressors

Ammonia (NH3)	Indeno[1,2,3-cd]pyrene
Arsenic (As)	Lead (Pb)
Benzo(a)pyrene	Mercury (Hg)
Benzo(b)flouranthene	Methane (CH4)
Benzo(k)flouranthene	Nickel (Ni)
Benzene, hexachloro- (HCB)	Nitrogen oxides (NOx)
Cadmium (Cd)	NMVOC
Carbon dioxide (CO_2)	PAH
Carbon monoxide (CO)	Particulates, > 10 um (TSP)
Chromium (Cr)	Particulates, < 2.5 um
Copper (Cu)	Particulates, > 2.5 um, and < 10um
Dinitrogen monoxide (N2O)	Polychlorinated biphenyls (PCB's)
Dioxins	Selenium (Se)
Sulfur oxides (SOx)	Zinc (Zn)

2.2.3 IOA characterization matrix

In contrast to in LCA, there is no established characterization framework, like ReCiPe, that associates the emissions calculated to specific impact categories. The process of associating emissions to impact categories can be done manually, by linking each emission to its appropriate impact category in an established LCA characterization framework.

2.3 Hybrid LCA

Life cycle assessments can suffer from incomplete system boundaries which may result in an underestimation of the environmental impacts found. Incomplete system boundaries generally mean that the system modeled does not include *all* indirect impacts. For example, to accurately assess all impacts from the production of steel in Europe, ideally even the energy that is used for the imported rice, which is cultivated in China, that feeds the workers at the steel factory should be included. This is not included in established LCA databases like Ecoinvent, and will result in an underestimation of environmental impacts.

IOA does not suffer from incomplete system boundaries, since the entire world economy is included. Assuming EXIOPOL is accurate implies that *all* background processes are included, i.e. the system boundaries are complete. IOA, on the other hand, suffers from low resolution and detail. By mapping the entire world economy into only 129 sectors, the level of accuracy of the results may be relatively low. For example, the manufacturing of HVDC cable and the manufacturing of electrical transformers, two quite different products, will yield the same impacts per monetary unit in an IOA because they are both allocated to the same sector called 'Manufacture of electrical machinery and equipment' in EXIOPOL.

As a result of the inherent weaknesses of LCA and IOA it has been developed methods that seek to combine their strengths and avoid their weaknesses. These methods are often referred to as hybrid LCA. Hybrid LCA, if done properly, can be the method that will calculate the environmental impacts most accurately. In this section the different types of hybrid LCA will be briefly explained and the method of choice in this study, the tiered hybrid LCA, will be explained in detail.

2.3.1 Hybrid LCA approaches

As previously explained, the idea of hybrid life cycle assessments is to combine the strengths of LCA and IOA in order to achieve an improved method for environmental system analysis. There are different ways of doing this. The three most common approaches are the tiered hybrid-, the input-output (IO) based- and the integrated hybrid- LCA. They all have their different strengths and weaknesses, and the most appropriate approach is often dependent on data availability and product characteristics [8].

The tiered hybrid LCA is performed as a conventional process based LCA, but with an additional IO background system. The background system can easily be introduced to already existing LCAs and is thus regarded as the easiest approach. The approach requires both physical and monetary values for all components of the product studied. The basic idea is that purchases from the input-output system shall cover that which is missed out in the process based LCI data and therefore minimize the truncation error. The biggest weakness of the approach is double counting, but the problem can be avoided by some manipulations of the applied matrices. The expression double counting addresses the issue of overestimated impacts because of *both* the IO and LCA part of the model will calculate *all* impacts caused by the product or system being studied. To avoid this the model should allocate some of the processes to the LCA part and some to the IO part. An ideally modeled tiered hybrid LCA will, for the example of steel production in Europe, allocate the process-related emissions (from heat, electricity, steel production, etc.) to the LCA part and the emissions from processes farther downstream (from energy use for cultivation of crops and mining of iron in Asia etc.) to the IO part. To allocate the different processes to the LCA part and removing them from the IO part is cumbersome and very dependent on the LCA practitioners understanding of the product studied and his/hers judgment.

The IO based approach does not add a background system based on IO data, instead it *replaces* the process based LCA background data set. The boundary issues of LCA are then avoided, but there may be loss in aggregation resolution and detail. The approach requires a well developed foreground system in order to outweigh the issues of aggregation error related to the IO data. The approach is only recommended if the product flows analyzed are so small that they are negligible compared to flows at a national level, i.e. they do not take up a big part of the economy. The approach avoids the issue of double counting.

The last approach, called integrated hybrid LCA, is the most advanced and data intensive. It has much in common with the IO based hybrid approach, but because it requires that we apply flow matrices to establish the A-matrix it allows for modeling systems where the foreground system is of such magnitude that it is not negligible with respect to the background economy [8].

In this study the method tiered hybrid LCA has been used. This is mainly because of the availability of both physical and monetary data and a belief that the problem with double counting can be avoided properly for the system studied.

2.3.2 Tiered Hybrid LCA

With the motivation of obtaining the most accurate assessment of environmental impacts of an offshore grid in the North Sea, the tiered hybrid LCA method has been chosen in this study. By using both monetary and physical data for the environmental assessment, it will not suffer from low resolution nor incomplete system boundaries. If, at the same time, double counting is avoided properly, the tiered hybrid LCA is one of the most accurate methods for assessing environmental impacts.

Formal framework

In general, the formal framework is similar to the one of process based LCA. The main difference is that the requirements matrix includes both a background IO system and background LCA system. In this study they are represented by EXIOPOL and Ecoinvent, respectively. The requirements matrix takes the following form:

$$A = \begin{pmatrix} A_{ff} & 0 & 0 \\ A_{pf} & A_{pp} & 0 \\ A_{nf} & 0 & A_{nn} \end{pmatrix} \quad 2.15$$

The different submatrices are explained in Table 7 below. It is assumed that the IO table is in products by products format, which is the case in this study.

Table 7: Nomenclature for the tiered hybrid LCA framework

Sets			
	pro		**Processes**
	prod		**Products**
	str		**Stressors**
	imp		**Impact categories**
Matrices and variables	A_{ff}	*(pro x pro)*	Matrix of foreground system inter-process requirements, physical units
	A_{pf}	*(prod x pro)*	Matrix of requirements from foreground to background IO data set, in monetary units
	A_{pp}	(prod x prod)	Background IO data set/matrix of inter-industry requirements, in monetary units
	A_{nf}	*(pro x pro)*	Matrix of requirements from foreground to background LCA data set, in physical units
	A_{nn}	*(pro x pro)*	Background LCA data set/matrix of inter-process requirements, in physical units
	A	*varies*	Complete requirements matrix, mixed units
	L	*varies*	The Leontief inverse. Matrix of outputs per unit of external demand
	F	*(str x pro, prod)*	Matrix of stressor intensities per unit output
	e	*(pro x 1)*	Vector of total emissions generated for a given external demand
	E	*(str x pro)*	Matrix of emissions generated from each process for a given external demand
	C	*(imp x str)*	Characterization matrix
	d	*(imp x 1)*	Vector of impacts generated for a given external demand
	D_{pro}	*(imp x pro)*	Matrix of impacts generated from each process for a given external demand
	D_{str}	*(imp x str)*	Matrix of impacts generated from each stressor for a given external demand

To avoid double counting, some sectors in the IO system have to be modified or set to zero. Modifying means to subtract the monetary values represented by the physical flows in the LCA system. This task may not be easy because the relationship between monetary and physical units is often not that easy to determine. Costs are usually given for a complete product and not for the specific parts that product is made of, and the intangible asset of value added may vary from product to product. To do this, very good physical and cost data is required. The option of setting some sectors to zero in the IO system avoids this issue, because it assumes that *all* physical flows are entirely covered by the LCA system. The zero-sector approach has been used in this study, that is, some sectors in Apf are set to zero. Following is a quick step-by-step procedure for creating the Apf matrix:

1. **Cost allocation step.** The cost of each component of the product has to be allocated to their appropriate sectors in the IO system. For example, the total cost of the wind turbine gear box is allocated to the sector 'Manufacture of machinery and equipment'. Some components may have costs allocated to several sectors, for instance HV cables offshore: 70% to 'Manufacture of electrical machinery and apparatus', 20% to 'Construction' and 10% to 'Sea and coastal water transport'. It may be difficult to find data for how component costs should be allocated appropriately; in that case the allocation process is left to the LCA practitioner's judgment. This step may involve much uncertainty, but this step is also necessary for a "stand-alone" IOA and is thus not unique for the tiered hybrid LCA.

2. **Distribute component costs across the economy.** The symmetrical Z-matrix has to be normalized and multiplied with the allocated costs from step 1 to create Apf. Mathematically this gives

$$\bar{Z} = Z\hat{x}^{-1} \tag{2.16}$$

$$A_{pf} = \bar{Z}y \tag{2.17}$$

where x is the vector of total output of the economy and y is the vector of allocated costs created in step 1.
3. **Setting appropriate sectors to 0 to avoid double counting.** The challenge now is to find all the corresponding sectors in Apf that the LCA processes in Anf is "taking care of" and set them to zero. Referring to the example again; as the gearbox contains the three physical components steel, oil and electricity, the sectors 'Manufacture of basic iron and steel and ferro-alloys and first products', 'Manufacture of other petroleum products' and all electricity production sectors (coal, gas, hydro etc) are set to zero. This is done for all the different components of the product analyzed. There is much uncertainty involved in this step as it is pretty much left to the LCA practitioner's judgment to decide which sectors in the economy that corresponds to the physical sectors covered by the LCA system.

How costs are allocated (step 1) and what sectors that are set to 0 to avoid double counting (step 3) in this study is given in appendix B.

A stressor matrix needs to be made so that the environmental impacts from both the IO- and the LCA system are accounted for. If the background data sets are EXIOPOL and Ecoinvent, as in this study, the easiest way to do this is to "link" the 28 emissions in EXIOPOL to their corresponding emissions in the Ecoinvent stressor matrix. For example, CO_2 emissions to air from EXIOPOL is linked to the Ecoinvent emission called 'Carbon dioxide, fossil, to air, at unspecified location'. After doing this for all of the 28 emissions in EXIOPOL, the ReCiPe characterization matrix can be used as is to categorize the impacts from the complete hybrid system.

When the tedious job of assembling the A-matrix properly and linking the F-matrices is complete the matrices can be treated like regular process based LCA matrices, i.e. the mathematical framework is the same as for process based LCA (see section 2.2.1). When calculating total output by doing

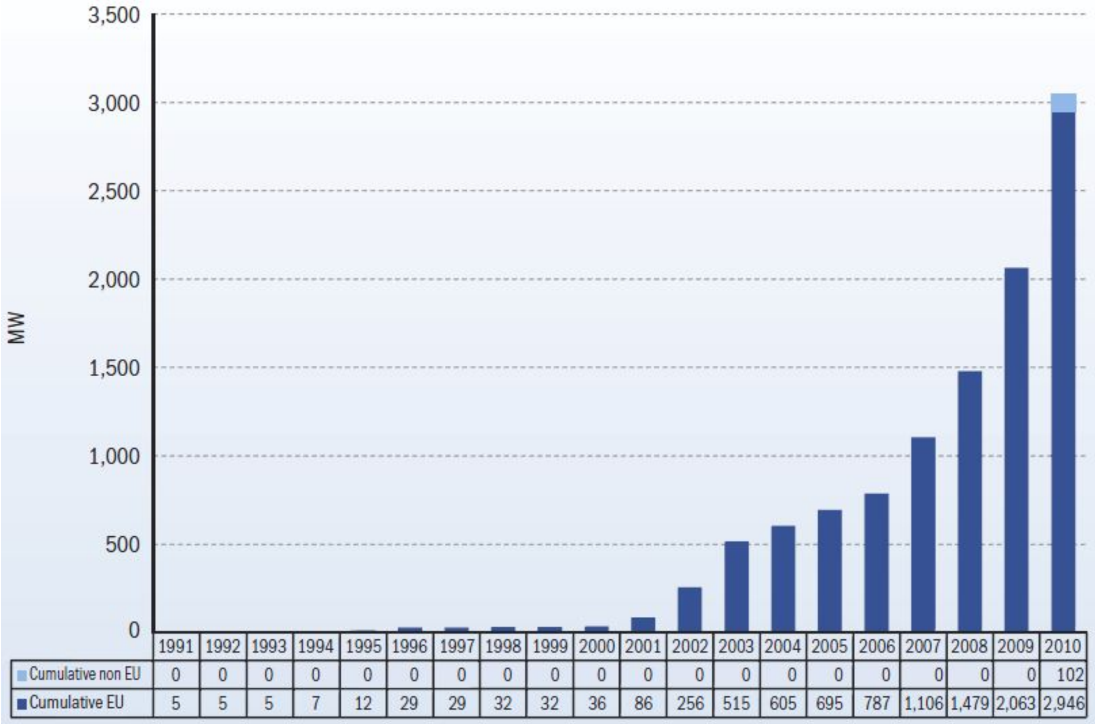
$$x = (I - A)^{-1}y \tag{2.18}$$

the y-vector now "speaks" correctly with A_{ff}, A_{pf} and A_{nf} and should at the same time avoid double counting.

To summarize, the tiered hybrid LCA method may be a very accurate environmental impact assessment method, *but* there is much uncertainty related to the process of avoiding double counting. Arguably, the method is quite vulnerable to the LCA practitioner's judgment, at least in comparison to regular process based LCAs.

3 Background

The first offshore wind farm was opened in 1991 in Denmark, 2.5 km off the east coast at Vindeby. It featured eleven turbines of 450 kW, totaling 4.95 MW for the wind farm. Until 2001 offshore wind development was irregular and mainly dependent on a handful of small near-shore projects in Danish and Dutch waters featuring less than 1 MW turbines. Since the beginning of the last decade, offshore wind has grown substantially every year, see Figure 1below [14].



	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
■ Cumulative non EU	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	102
■ Cumulative EU	5	5	5	7	12	29	29	32	32	36	86	256	515	605	695	787	1,106	1,479	2,063	2,946

Figure 2: Cumulative offshore wind capacity - EU and non EU 1991-2010 [14]

The majority of the offshore wind farms that have been completed by today are located 20 km or less from the shore and in up to 20 m of water depth. Clearly visible from shore and affecting near-shore wildlife habitat and coastal activities, the wind farms are not always wanted by the local communities. Because of the rapid growth in Northern Europe, the number of suitable places for deployment of near-shore offshore wind at low depths has decreased. Thus, the trend today is to move farther from shore and into deeper water [14].

This trend leads to new challenges, with one of the biggest being the transport of the electricity produced to shore. At the same time there is also a growing demand for increased power transmission capacity between countries in the North Sea. As a result of these two main drivers there has been an increasing amount of research with focus on offshore grid development in the North Sea. One research project that has tried to develop likely future scenarios for an offshore grid in the North Sea is called WINDSPEED. It is the environmental impacts of the scenarios developed in WINDSPEED that are assessed in this study.

3.1 Electricity and power markets

Wind power produces energy in the form of electricity. Electricity is one of the highest quality energy carriers, with energy content equal to exergy content, i.e. 100% of the energy is recoverable as work [15]. But electricity has certain features that leads to challenges related to its distribution. Most notably are [16]:

- **Instant generation and consumption.** Electricity is consumed at the moment of time it is generated. Electricity travels with the speed of light.
- **Non-storability.** Electricity cannot be stored in significant quantities in an economic manner.
- **Consumption variability.** Electricity consumption is variable with characteristic patterns for day/night, week, year and regions.
- **Non-traceability.** There is no physical means by which a unit of electricity delivered to a consumer can be traced back to the producer that actually generated the unit.
- **Flows to where it is needed.** In every moment, electricity will flow to points where it is needed, independent of where it may be produced.

The points above are important when assessing the motivation for building an offshore grid. There are many advantages in making interregional offshore electricity connections, all of which are related to the points above.

The price aspect of electricity is also important, when trying to assess the motivation for making interregional connections. But the relationship between the physical commodity and the price is not straight forward, mostly because of the (usually) low elasticity of demand for electricity, especially in Norway. I.e. most Norwegian households do not think much about the electricity bill at the moment they turn on the lights or a heating oven. This has mostly to do with the cheap and stable electricity prices in Norway and a lack of information about the price available to the customer. Larger customers, like industry, adjust their consumption (somewhat) to the electricity price. Information about prices is expected to improve this decade as smart metering will be implemented [17].

The point of mentioning elasticity of demand is that if the demand for electricity were to be completely elastic, the relationship between the physical commodity and the price would be straight forward. If all customers were at all times aware of the electricity price and adjusted accordingly *and* there were no bottlenecks in the distribution, electricity would always flow to the point where the customer is willing to pay the highest price (i.e. the highest demand)! But since there are both bottlenecks in distribution grids and a varying elasticity of demand, the relationship between the physical commodity and the price of electricity is more complex and varies from region to region. See Figure 3 for an illustration of the price variance in Norway and Germany, showing, among other things, that there is more price variation and a higher elasticity of demand in Germany than in Norway. If the transfer capacity between the two price areas were to be increased, the two curves would become more similar; the price variation in Germany would decrease whereas it would increase in Norway. With no transfer constraint the curves would meet and become identical.

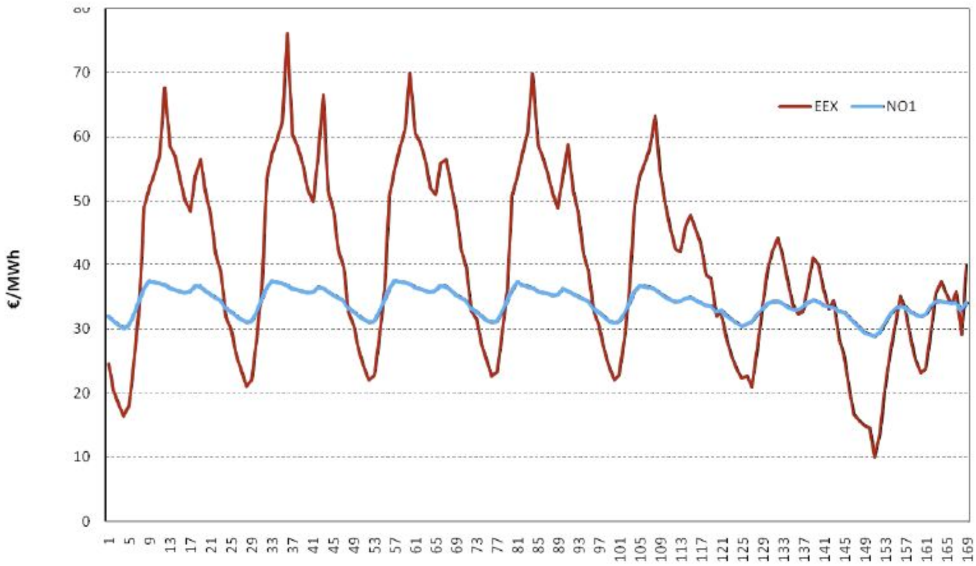
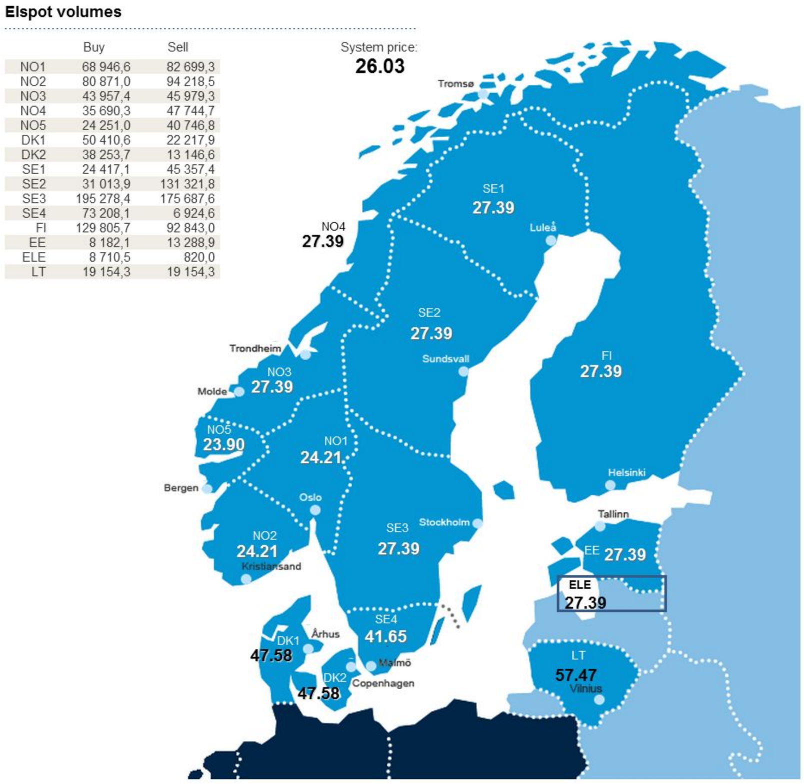


Figure 3: Average price structure over the week in Germany and southern Norway, 2002-2009. X-axis in hours. [18]

Power markets are divided into different price areas. Price areas are a simplification of the real world by assuming that the grid capacity across the price area is unconstrained and thus have a uniform electricity price for all consumers in the area. See Figure 4 for an illustration of the different price areas in the NordPool spot market.


Elspot volumes

	Buy	Sell
NO1	68 946,6	82 699,3
NO2	80 871,0	94 218,5
NO3	43 957,4	45 979,3
NO4	35 690,3	47 744,7
NO5	24 251,0	40 746,8
DK1	50 410,6	22 217,9
DK2	38 253,7	13 146,6
SE1	24 417,1	45 357,4
SE2	31 013,9	131 321,8
SE3	195 278,4	175 687,6
SE4	73 208,1	6 924,6
FI	129 805,7	92 843,0
EE	8 182,1	13 288,9
ELE	8 710,5	820,0
LT	19 154,3	19 154,3

System price:
26.03

Figure 4: NordPool area prices (€/MWh) 18.06.12. [19]

The reason for the different area prices are limited transfer capacity between the areas. Transfer capacity is a constraint on an ideally free market and thus implies socioeconomic losses. By increasing transfer capacity between price areas, prices will be more even and there will be a welfare gain to society.

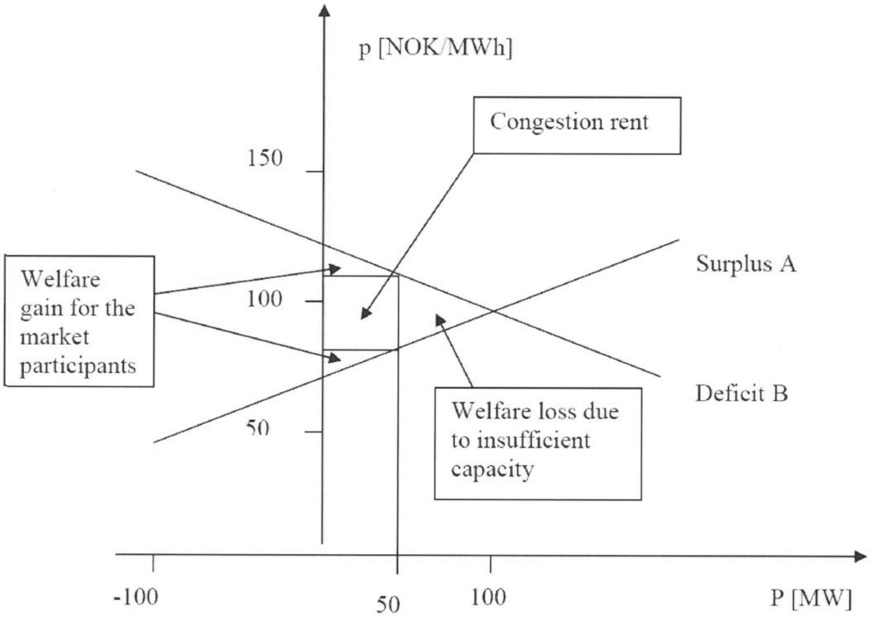


Figure 5: Welfare loss due to insufficient transfer capacity. [16]

Figure 5 illustrates how limited transfer capacity creates an imperfect market and leads to welfare loss. The downward sloping curve is the demand curve of price area B and the upward sloping curve is the supply curve of area A. They meet at 100 MW, which would be the transfer between the areas if there was no transfer constraint present. But transfer capacity is constrained to 50 MW and there is a welfare loss, which can be seen as the triangle in between 50 MW and the demand and supply cross.

To summarize, there are several solely economic reasons for increasing transfer capacity between the countries surrounding the North Sea.

3.2 Intermittent energy sources and balance power

The European Union has a goal stating that 20% of the energy supply will be produced by renewable energy sources by 2020 [20]. With the potential for expansion of hydropower being limited by few feasible waterways left and strict regulation of those that exist, intermittent renewable energy sources like wind and solar will necessarily have to make up a large share of the targeted 20%. Since the wind doesn't always blow and the sun doesn't always shine, the power intermittent energy sources produce may not be available at the times it is needed. A major goal of recent energy research has been to find ways to smooth out these irregular supplies.

As of today there is no technology that is able to store enough electricity to smoothen the supply from intermittent energy sources adequately, and so the implementation of intermittent energy sources to the electricity grid has to be more carefully planned than for the implementation of thermal and hydro power plants.

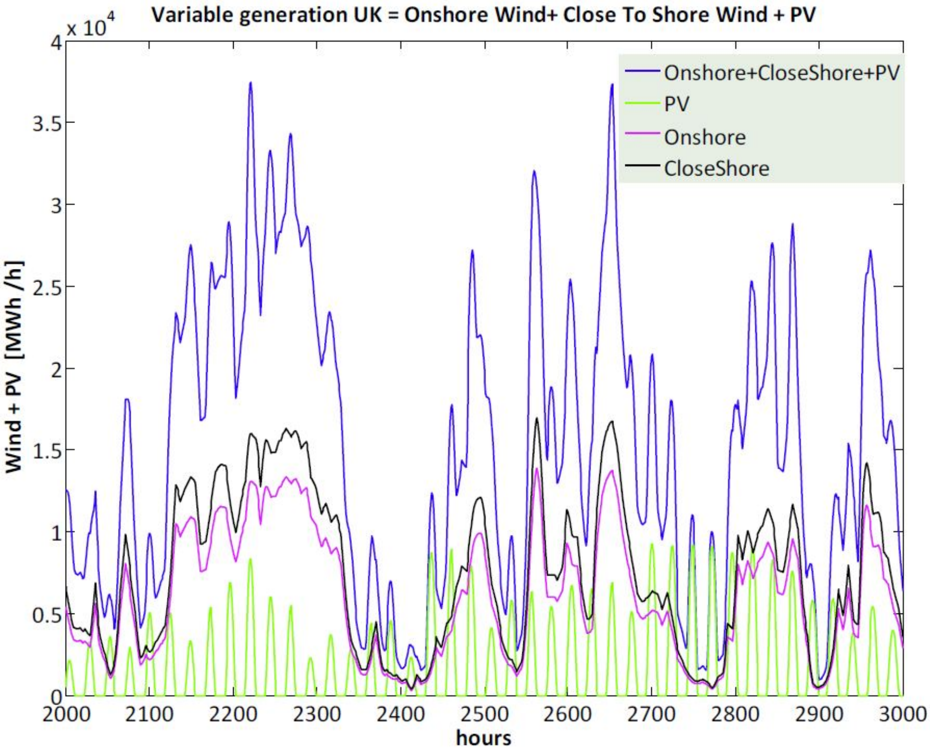


Figure 6: Effect variation of intermittent energy sources in the UK [21]

There is one noteworthy grid storage technology: pumped-storage hydropower. Pumped-storage hydropower basically means the capability of some hydropower plants to pump water into reservoir when the demand for electricity is low. This technology is able store quite large amounts of energy, but is not that common and those that exist today are designed to deal with seasonal variations of the grid, not day to day or hour to hour variations (which is needed for smoothing the supply intermittent energy sources) [22].

Some people are advocating the idea that Norway should take the position of becoming a storage battery for Europe because of Norway's exceptional amount of hydropower. The idea may be good, but there are several obstacles to overcome before it can be realized, most notably: upgrading the existing pumped-storage technology to handle short time variations, building new pumped-storage capability to many hydropower plants in the south of Norway and a vast expansion of transfer capacity between the south of Norway to mainland Europe and the UK. Regardless of whether the hydropower plants in southern Norway are of the pumped-storage type or not, it will be beneficial for mainland Europe and the UK with increased transfer capacity to Norway, especially if a large scale deployment of intermittent energy sources is realized. The main benefits are connecting to a price area with relatively low prices and being able to utilize the unique characteristics of hydropower that makes it a "perfect match" for intermittent energy sources:

- Close to zero costs for starting and stopping power production
- Close to zero delay for starting and stopping power production. I.e. demand can be met immediately.

This is what is meant by the term 'balance power', one energy technology's capability of balancing another's variability. In this context hydropower is unique and could play an important role in the development of intermittent energy sources in Northern Europe. But to play an important role, sufficient transfer capacity is prerequisite.

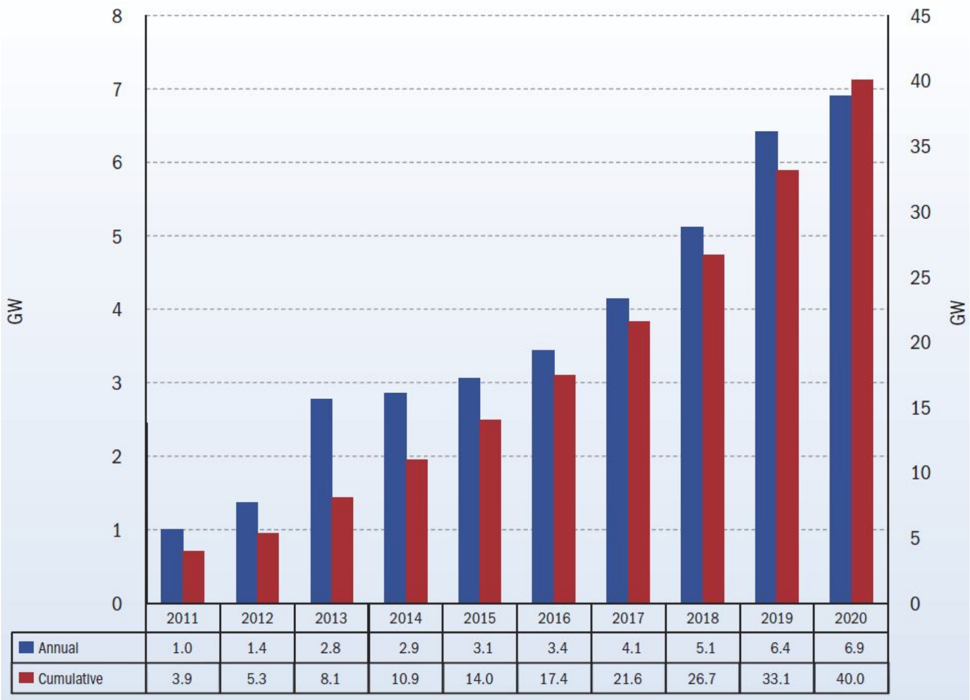
The other most noteworthy ways of handling intermittency (with today's technology) are

- **Diversifying the energy mix.** Combining many types of energy sources reduces the impact of each source's intermittency.
- **Increase long distance transmission.** By interconnecting regions, all regions will be less vulnerable to regional intermittency.
- **Implementing smart metering.** The grid becomes "smarter" if consumers get real-time price information and household's power consumption can be programmed and remote controlled, increasing demand response.
- **Thermal reserve.** Thermal power plants may operate below full effect (e.g. 70%) to be able to quickly compensate for unexpected intermittency. The efficiency of thermal plants not running at full effect decreases substantially, leaving this option as a non-optimal solution.

Other technologies that have the potential of smoothing the supply of intermittent energy sources are batteries, compressed air, flywheel, hydrogen, supercapacitor and thermal (e.g. molten salt). These technologies may one day revolutionize grid storage, but at present the two main problems are that they either cannot store enough energy (batteries, compressed air, flywheel, supercapacitor) or that the conversion process involves so substantial losses that is not worth it (hydrogen, thermal) [23].

3.2.1 Offshore wind

In northern Europe offshore wind may be one of the most important energy sources for reaching the ambitious 2020 targets. That is what the European Wind Energy Agency (EWEA) believes, as seen in Figure 7. In WINDPSEED the scenarios start in 2020, using NREAP (National Renewable Energy Action Plans (EU)) 32 GW offshore wind energy projection as a starting point.



	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
🟦 Annual	1.0	1.4	2.8	2.9	3.1	3.4	4.1	5.1	6.4	6.9
🟥 Cumulative	3.9	5.3	8.1	10.9	14.0	17.4	21.6	26.7	33.1	40.0

Figure 7: EWEA projections for offshore wind power, annual (blue) and cumulative (red) installations 2010-2020. [14]

The intermittent nature of wind power makes the supply of energy hard to predict as it varies with seasons, from day to day and hour to hour. Wind power is at some times able supply the entire grid demand, while at other times it will have zero contribution.

The implications are that wind power has unusual requirements for grid connection capacity. The example of an offshore 600 MW wind farm is used to illustrate the requirements. Assuming the capacity factor[2] is 35%. The average effect over a year will be 600 MW*0.35=210 MW. Then, how much must the transfer capacity to the grid be? The obvious answer is that the cables need to be dimensioned to peak production 600 MW, so that no energy is lost when the wind farms operate at full capacity. But that leaves most of the grid connection capacity (600*(1-0.35)=390 MW) unused over the year, which basically means a overdimensioning of the grid connections from wind farms.

It is with this unused capacity that the grid scenarios in WINDSPEED seeks to hit two birds with one stone, by utilizing it for interregional power trading when available. The idea may be good, but the unpredictability of wind power will then make power trading unpredictable and sometimes constrained. This issue will be mentioned again when describing the OffshoreGrid project in section 3.4.2.

WINDSPEED meshed grid scenarios do not have cables dimensioned in such a way that all energy can reach the closest shore during peak production. A meshed grid design has this advantage, since the power produced may flow in multiple directions to multiple countries at the same time. Ideally, wind power connected to a meshed grid will supply whatever region that needs the power the most at any given moment.

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[2] Capacity factor is the ratio of the actual output of a power plant over a period of time. It is calculated by dividing the actual energy produced over a period by the amount of energy the plant would have produced at full capacity. For wind power it is usually in the range 30-35%.

3.3 Electrical power transmission offshore

Offshore power cables may serve three purposes:

1. Connecting offshore power producing units, like wind parks, to the onshore electricity grid.
2. Connecting the electricity grids of different power markets which are separated by sea, enabling power trade and balance management.
3. Connecting to power consuming facilities offshore, like oil drilling platforms.

Ideally, a grid should have the ability to serve all three purposes at the same time. It should also be future proof, meaning that new uses and connections in the future should be able to join the established grid, or at least coexist. Obviously it is very difficult to accurately plan and dimension such a grid.

There are basically two different ways, or approaches, of building an interregional offshore grid with wind farms and oil drilling platforms connected:

- **Radial.** Each wind farm/platform is connected to the shore of the country they are built in. The interregional cables are then made from shore to shore of each country.
- **Meshed grid.** A meshed offshore grid connected to all wind farms/platforms/regions enables power to flow directly from where it is produced to where it is needed.

Both approaches have their pros and cons, which will be discussed more in detail in section 3.4. See Figure 8 for an illustration of the two approaches.

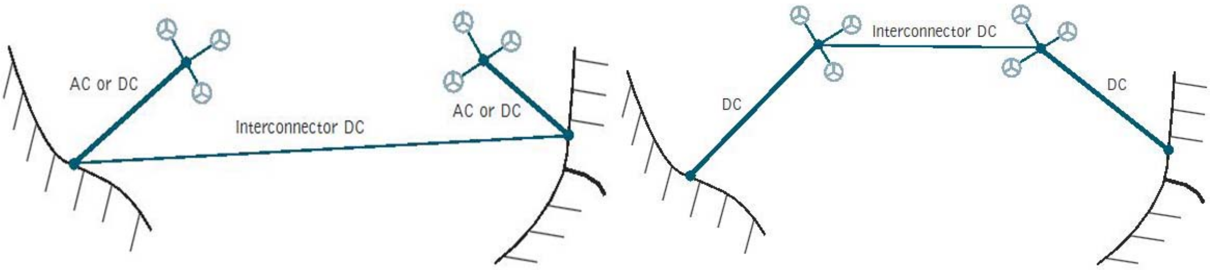

Figure 8: Radial (left) and Meshed grid (right) approaches [24]

There are already several offshore HVDC cables in Europe, all based on the radial approach. See Figure 9 for a map of existing, under construction and proposed cables in Europe. The primary purposes of the existing cables are power trading, security of supply and supplying power to remote regions, like islands. The longest offshore cable built to date is the NorNed cable between Feda in southern Norway and Eenshaven in the Netherlands. It is a 580 km 700 MW HVDC cable built as a joint project between the TSOs (Transmission System Operator) of each country, Statnett and Tennet [25]. It was built mainly for trading purposes, and the revenue of trade so far has been higher than expected [26].

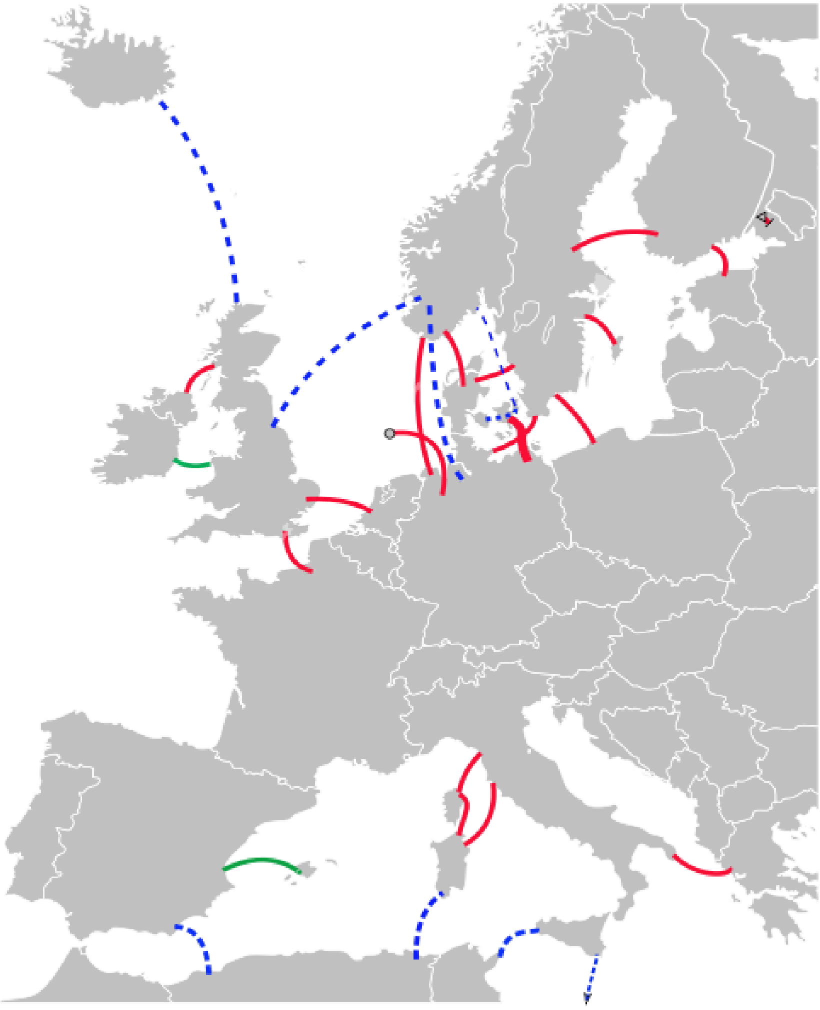

Figure 9: Offshore HVDC cables in Europe. Red: existing, Green: under construction, Blue: proposed. [27]

In Figure 9 a red line in the north-west of Germany “ends” in the middle of the North Sea. This is the BARD Offshore 1 wind farm. It is the first connection to an offshore wind park realized with HVDC technology. The 200 km connection is the longest connection to an offshore wind farm in the world. It is planned to be completed in 2013 [28].

This study is focusing on the ambitious interregional meshed grid scenarios in WINDSPEED, which may only be achieved if there is interregional cooperation in the planning phase. Countries surrounding the North Sea need to make collaborative efforts for deciding where to situate and how to dimension the wind farms and the interconnecting cables. Detailed and reliable predictions for future energy developments in each country are also necessary to make a sound basis for the necessary decision-making. This means that much research is still needed before such a grid can be realized.

3.4 Relevant research projects

The offshore grid scenarios that are environmentally assessed in this study are obtained from a research project named WINDSPEED. Much of the technical and cost data assumed in WINDSPEED is available to the public, which is one of the main reasons for choosing this project as a basis for the assessment. In addition, this study has benefited from the OffshoreGrid research project, especially in the context of comparing two independent projects with two different approaches.

The hybrid LCA of the Havsul 1 wind farm (from now on referred to as 'the Havsul 1 project') is the data basis for windmills and transport, and it also provides much of the framework for the hybrid method.

All three research projects are described briefly in the sections below.

3.4.1 WINDSPEED

WINDSPEED (Spatial Deployment of offshore WIND Energy in Europe) is a collaborative European research project, with SINTEF Energy Research being an important contributor, aimed at producing a roadmap to the deployment of offshore wind energy (OWE) in the Central and Southern North Sea from 2020 to 2030. The countries surrounding the Central and Southern North Sea – the UK, Belgium, the Netherlands, Germany, Denmark and Norway – share the sea basin which has a big potential for offshore wind energy. With this potential as a starting point, WINDSPEED has produced a set of possible scenarios for future development of offshore wind energy in the region. The project concludes that, if the most ambitious scenario is realized, a total capacity of more than 120 GW is possible by 2030 [29].

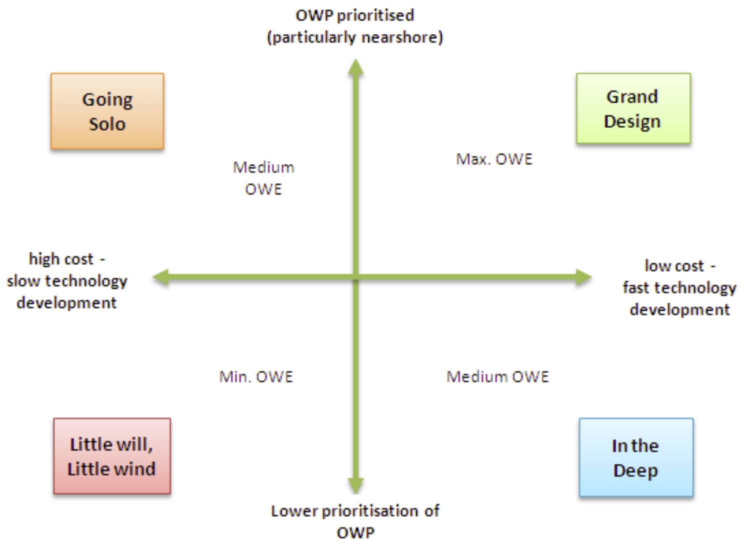

Figure 10: Overview of the four scenarios considered in WINDSPEED. [29]

The different scenarios are based primarily on two factors: technology development and offshore wind energy prioritization. Slow technology development does in effect mean that only radial grid connections close to shore wind farms are built and that an interregional grid will not be realized. Thus, *only* the two scenarios with fast technology development are focused on in this study. In the scenarios In The Deep and Grand Design a large scale deployment of offshore wind energy is expected, of which a significant share will come from areas far from shore, meaning that building a meshed grid interconnecting countries and wind farms may be a good solution. By using the phase-wise approach explained below, WINDSPEED has come up with possible interregional meshed grid scenarios.

WINDSPEED approach and methods

The project was developed in four primary phases [29]:

- **Phase I: Sea uses mapped and analyzed.** The North Sea is a sea area already preoccupied with many activities and uses. These had to be mapped and analyzed in order to find suitable areas for offshore wind energy deployment. Sea uses include fishing, oil and gas extraction, shipping, cables and pipelines, existing and planned OWE, military activities, nature conservation, and marine wildlife preservation. Current and future sea uses have been assessed in order to find suitable areas for building offshore wind farms.
- **Phase II: DSS analysis.** A so-called Decision Support System (DSS) was used in order to analyze offshore wind energy development in relation to costs and the presence of non-wind sea use functions. The prioritization of costs and sea uses were weighted differently to produce estimates for suitable areas to install OWE, and produces the basis for the four scenarios developed in phase III. See appendix E for the spatial and economic potential found for each scenario as found by the DSS tool.
- **Phase III: Scenario development and Net-Op optimization.** Four different scenarios were developed to model how OWE might develop within 2030. The scenarios were created on the basis of how much OWE is prioritized and the speed of technology development. A tool called Net-Op was used to optimize the investments in the offshore grid, reaching all locations and adequately cover the installed capacities of wind power. It is the grid scenarios created by the Net-Op simulation that are environmentally assessed in this study.
- **Phase IV: Creating the final roadmap.** Based on all results, a final roadmap for realizing ambitious goals for OWE is created. The final roadmap shows ambitious but realistic targets for OWE development in the North Sea and recommendations to policymakers on how to reach them.

WINDSPEED scenarios

The two relevant scenarios (fast technology development) have been considered in two different case studies[21]:

- **In The Deep 20% (ITD20).** This case assumes a finite minimum production constraint for non-renewable/conventional generation units: oil, gas, nuclear as well as for biomass.
- **In The Deep 0% (ITD).** This case assumes the same input as the 20% case but considers a zero minimum production constraint for non-renewable/conventional units: oil, gas, nuclear as well as for biomass. This scenario shows a higher utilization of the offshore wind farms located at the clusters far from shore, showing a higher share of wind penetration.
- **Grand Design v05 (v05).** In this case, the maximum possible potential (~88 GW) for the installed capacity at the offshore clusters is assumed as being obtained from the DSS +Resolve-E (a techno-economic renewable electricity market simulator) analysis.
- **Grand Design v06 (v06).** In this case, a reduced potential of ~81 GW for the installed capacity at the offshore clusters is considered. The 7 GW reduction in installed capacity in case v06 compared to case v05 reflects both the competition with other sea uses as well as the high grid investments needed for the development of all available economic potential found in the DSS + Resolve-E analysis.

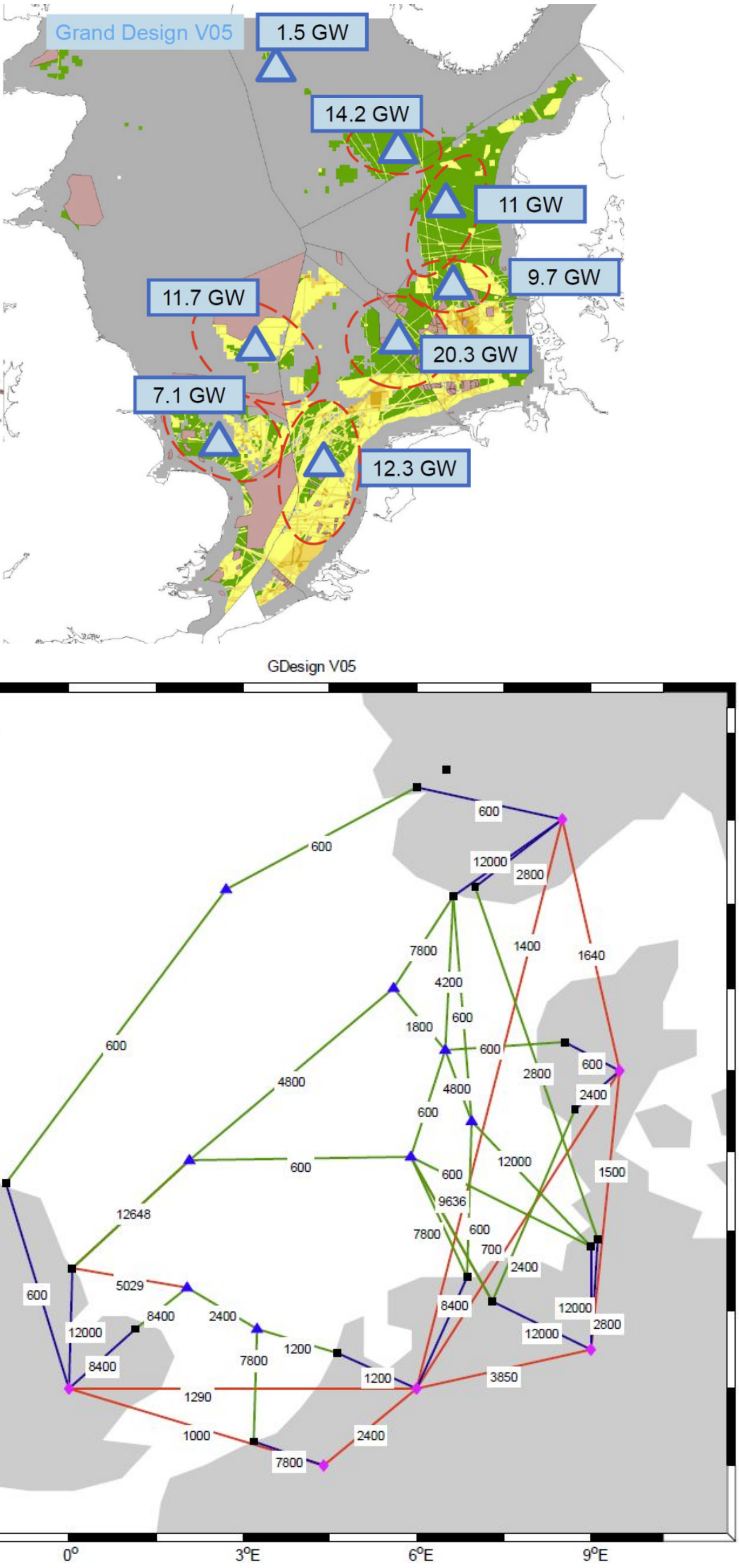

Figure 11: Top: Total effect from wind farm clusters in the Grand Design v05 scenario. Bottom: Cable capacities in the Grand Design v05 scenario. Triangles represent wind farm clusters and squares represent onshore connection points. [21]

All of the four case studies have been environmentally assessed in this study, but for practical reasons this study will only focus on the results of one of them. Even though the scenarios may be quite different in absolute terms, the environmental impacts per unit energy produced are so similar that focusing on one scenario (case study) seems reasonable. It is the *Grand Design v05* scenario that has been chosen, principally because of the motivation of finding the environmental impact of the most ambitious scenario. Results comparing the scenarios can be found in appendix C.

WINDSPEED technology and design assumptions

The objective of this study is to assess the environmental impacts of the grid scenarios created by WINDSPEED. The approach taken to achieve this as accurately as possible is to start with the technology and design assumptions made in WINDSPEED as a basis. Unfortunately, the assumptions in WINDSPEED are not detailed enough to provide all the data necessary for the assessment, so other sources have been used as well. The details of the actual grids assessed are given in section 3.5. Below is a list of all relevant technology and design data, mostly obtained from WINDSPEED delivery 2.2 (D2.2) [30].

Wind farm. A collection of windmills producing electrical energy, connected to one substation.

- Discrete 600 MW clusters consisting of 120 x 5 MW windmills. All components listed below are also considered as discrete units, i.e. export cables, array cables, substations etc. are only be seen as integer multiples of 600 MW.
- Because of wake effects between turbines, the distance between them is a design problem. In reality the distance will vary from wind farm to wind farm. In D6.1 2MW/km^2 is claimed to be a conservative but justifiable overall average and is thus chosen in this study (this only affects the length of array cables).
- No concrete specifications for the wind mills beside installed effect are given.

Wind farm cluster. A collection of adjacent wind farms in a given area.

- The combined effect of the wind farms in each cluster vary from scenario to scenario. For the effects of each cluster in the Grand Design v05 scenario, see Figure 13 above.

Array cables. Transports the power produced by the windmills in the wind farm to the offshore substations.

- 33kV AC 3-phase cables.
- Two conductor sizes, 630 mm^2 and 240 mm^2, depending on proximity to substation. See Figure 18 in section 3.5.1 for more details.
- Capacity dependent on conductor size and voltage, but both have a minimum requirement of being able transport all energy from each array of windmills to the substation. That gives >25 MW for the 240 mm^2 and >40 MW for the 630 mm^2 cable.
- Total cable length per array is 177.2 km, composed of 82.9 km 240 mm^2 and 94.4 km 630 mm^2 cables. Calculated by using equation given in D2.2 and 2MW/km^2 density as input.
- No information given about
    - Losses
    - Composition

Export cables. Transports power from offshore substations to shores, and from shores to shores.

- 400kV HVDC cables.
- 1600mm^2 conductor size.

- 600MW capacity.
- Total lengths vary from scenario to scenario and are all listed in section 4.1.
- No information given about
    - Losses
    - Composition

Offshore substation. Substation containing the power converter and other electrical equipment, like switchgear and breakers.

- Converter: three, triple wound 33kV AC to 150kV DC, 240/120/120MVA. (Possible design flaw[3])
- Breakers and switchgear for AC side, power transformers, standby generator, ancillary systems and 'workshop, accommodation and Fire & Protection' are regarded as parts of the substation.

Offshore substation structure. The structure required to support the equipment in the substation. Consists of topside and foundation.

- Foundation: Bottom-mounted. Three possible technologies listed; monopole, jacket and concrete gravity structures, but no choice made. See appendix D for illustrations of the different foundation types.
- In the scenarios there is a sea depth constraint of maximum 70 meter. 70 meter is regarded as the maximum sea depth for bottom-mounted structures. I.e. all wind farms are bottom mounted, floating turbines are not considered.
- The specific sea depth at each wind farm cluster is not given, except that is less than 70m (because of the constraint).
- The topside serves as a frame and enclosure to the electrical equipment. Material composition and weight is not given.

Onshore substation. Substation containing the power converter and other electrical equipment, like switchgear and breakers.

- Connection voltage to onshore AC grid is 400kV.
- Does the same as the offshore substation, but in the "opposite direction" and to a higher voltage, meaning conversion of 150kV DC to 400kV AC. Specifics for the converter are not given.

DC breakers and switchgear (offshore and onshore).

- Attached to substations on the DC side.
- Not regarded as parts of the substations due to cost uncertainties related to the technology, and difference in costs offshore and onshore.

The list above is a starting point for the technology assumptions made in this study. Depending on data availability and comparison to other sources and existing technology, some components "stick to" WINDSPEED specifications and some are changed considerably. The final technology specifications and assumptions in this study are given in section 3.5. Component capital costs in the grid are obtained

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[3] 240+120+120=480MVA. The relationship between MW and MVA for converters can usually be simplified to MW=0.8*MVA, meaning that the combined effect of the three converters should be 600MW/0.8=750MVA and not 480MVA. It could be that the relationship is assumed the other (wrong) way, 480MVA/0.8=600MW, but that might as well be a coincidence.

from WINDSPEED, for all of the components listed above. The specific numbers used in the assessment are listed in the section 4.1. WINDSPEED provides no information about operation and maintenance costs for the grid, so this is obtained from the Havsul 1 project.

For more information about the WINDSPEED project visit http://www.windspeed.eu/. Most relevant for this project have been delivery 2.2 and 6.3, but the other deliveries have also been relevant.

3.4.2 OffshoreGrid

OffshoreGrid is a techno-economic study of possible future offshore grid scenarios in Europe. The study was coordinated by the Dutch consultancy firm 3E with several project partners, including EWEA and SINTEF Energy Research. In comparison to WINDSPEED, which has a broad approach for creating a roadmap to deployment of offshore wind energy in the North Sea, OffshoreGrid has a more narrow focus on grid development. The grid scenarios produced by OffshoreGrid are possibly more realistic and feasible than the ones produced by WINDSPEED, but unfortunately detailed technical and cost data could not be obtained. The OffshoreGrid project is noentheless considered to be of relevance, mainly because of the radial vs meshed grid discussion and that some of the technical and design choices made in it justifies some of the technical choices made in this study. The relevant parts of the project are presented briefly in this section.

Project results

The goal of the study was to make an estimate of investment costs necessary to realize possible grid solutions that satisfy OffshoreGrid’s stated three main advantages of an offshore grid: security of supply, improving competition and market conditions, and integration of renewable energy (in particular offshore wind). Two main approaches were used, the radial and hub approach. The radial approach connects all wind farms to shore with a single designated cable for *each* wind farm. The hub approach cluster together adjacent wind farms into hubs, connecting *several* wind farms to shore with one connection, saving costs and materials. In a second step based on the hub approach, two interconnected grid designs were drawn up – the ‘Direct Design’ and the ‘Split Design’. In the Direct Design, interconnectors are built to promote unconstrained trade between countries and electricity markets. The Split Design is essentially designing an offshore grid around the planned offshore wind farms, which is the same approach as in WINDSPEED and is thus the most relevant scenario for this study [24]. The final results of OffshoreGrid can be seen in Figure 12 below.

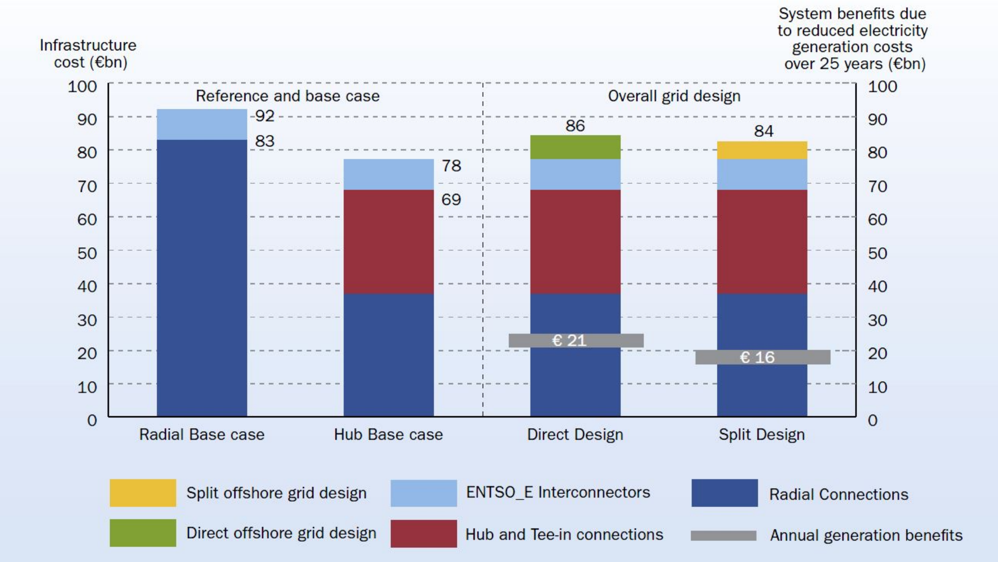


Figure 12: Total investments for OffshoreGrid overall grid designs [24]

Split Design is the lowest cost alternative at 84000 M€, which seems reasonable since prioritizing unconstrained trade (Direct Design) would increase the number of installed cables. The geographical scope of OffshoreGrid is larger than WINDSPEED's, encompassing all of northern Europe and not only the Central and Southern North Sea. In Figure 13 below the relevant North Sea section of the Split Design is shown with cable voltages and technology. See appendix F for an overview map of the entire Split Design offshore grid design.

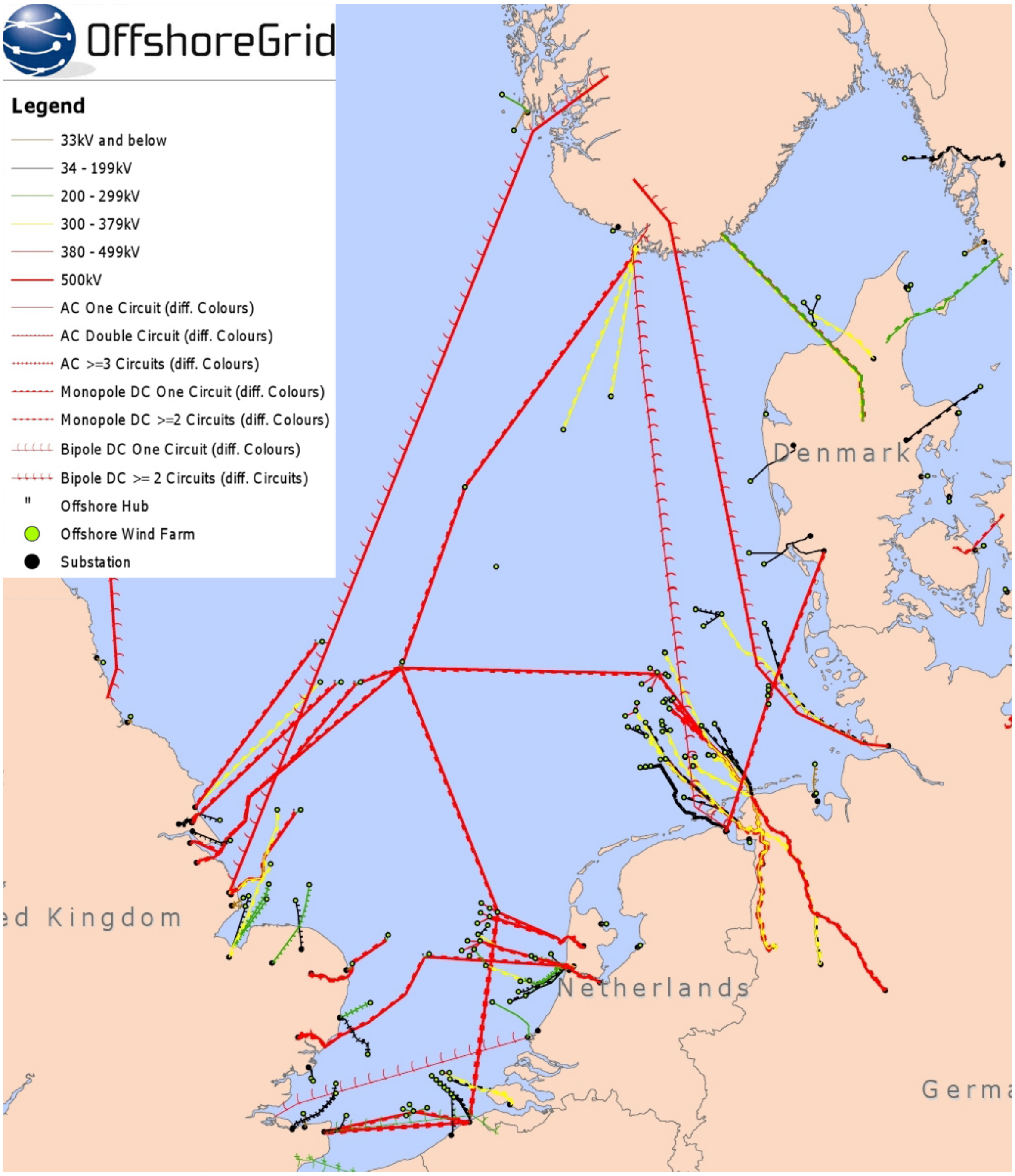


Figure 13: Split Design offshore grid in the Central and Southern North Sea. [31]

Figure 13 shows existing, under construction, planned and possible cables. For example, the planned NorBrit cable is the 500 kV cable with a 'Bipole DC One Circuit' configuration connecting Norway and the UK. The cables of relevance for this study are the cables connected to offshore wind farms. As seen, there are several different connection technologies utilized depending on the distance from shore. In general the wind farms relatively close to shore are connected with HVAC technology, with voltage increasing with distance. At a certain threshold (see section 3.5) the technology changes from HVAC to HVDC, and again the tendency of voltage increase with wind farm distance to shore is present. Superimposing the wind farm clusters present in WINDSPEED on to the OffshoreGrid map indicates that all wind farm clusters in WINDSPEED would be connected with ‘Monopole DC One Circuit’ configuration in the voltage range 300-500 kV. Further, this indicates that the WINDSPEED design choice of 150 kV in the DC export grid may be lower than what is optimal. OffshoreGrid does not give any data on cable capacities or conductor sizes.

One other important aspect to take notice of in Figure 13 is the extensive use of radial connections. The vast majority of the wind farms are connected, either via hubs or independently, only to the closest shore, and not to a meshed grid. The meshed grid present only connects to some of the wind farms farthest from shore, i.e. a very different approach from WINDSPEED. In the OffshoreGrid final report there is a thorough discussion on radial vs meshed grid solutions, which will be explained briefly in the next paragraph. In WINDSPEED there is no discussion on this matter.

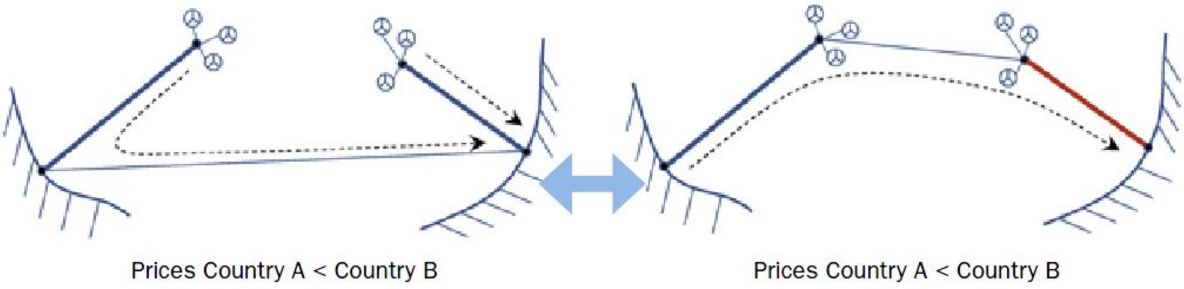


Figure 14: Schematic explanation of reduction of system benefits of a meshed grid. The cable in red shows where the system constraints may be increased. [24]

Figure 14 above illustrates how the system constraints may increase with a meshed grid solution. For instance, on a cold windy day where the wind farms operate at maximum effect and the demand for electricity is high in country B, trade capacity between the two countries may be constrained by the capacity of the cable connecting wind farm B to country B (in red). Even though the demand for electricity is higher in country B, most of the electricity produced in wind farm A has to be transported to and used in country A. Because of capacity constraints the radial solution to the left shows how system constraints are reduced and the free flow of electricity is increased.

The discussion of which solution to choose is primarily about economics. One could dimension the transfer capacities in a meshed grid to handle both max wind power and trade *at the same time,* but that would be an (expensive) oversizing of the system for the average situation. The radial solution, on the other hand, requires an increase of total cable length which also leads to increased costs. The discussion can be broken down to: how much are we willing to pay for the increased benefits of a less constrained power market? OffshoreGrid claims that it is dependent on wind farm capacity and its distance to shore. For the wind farm size relevant to this study (600MW), OffshoreGrid estimates the threshold distance to be around 160 km, meaning that if the wind farm is closer than 160 km to shore a radial connection is recommended and a meshed grid connection is recommended for distances over 160 km. See appendix F for a graph showing the threshold distance for different wind farm capacities. This recommendation is “violated” for several of the clusters in WINDSPEED, suggesting a non-optimal design of the grid in WINDSPEED. Interestingly, if the wind farm *clusters* (all adjacent wind farms in one area) in WINDSPEED were to be considered as a wind farm, all wind farm connections would then be recommended as radial connections, i.e. there would be no meshed grid! The objective of this study is to conduct an environmental assessment of possible ambitious grid scenarios in the North Sea, and not to benchmark the different design possibilities, but there are indications that the grid scenarios proposed by OffshoreGrid are more carefully considered and realistic than the ones by WINDSPEED. As mentioned, it was not possible to assess the OffshoreGrid scenarios due to lack of data.

Table 8: OffshoreGrid and WINDSPEED compared

	OffshoreGrid Split Design	WINDSPEED Grand Design v05	
Total cost	84000	60519	M€ (2010)
Total export cable length	~30000	39804	km
Total effect	126000	88122	MW
Cost per installed effect	666667	686764	€/MW

On the other hand, the total outputs of the two projects are not very different, as Table 8 illustrates. This gives reason to believe that the environmental impacts caused by the two grid proposals would probably not be very different either. The assessment of the WINDSPEED meshed grid will probably give good indications for the environmental impacts caused by the OffshoreGrid solutions as well.

3.4.3 Havsul 1 hybrid LCA

Havsul 1 is the first planned offshore wind project in Norway. It got a license in 2009 and may be completed by 2017 [32]. It will be located 5-13 km off the north-western coast of Norway (Sandøy municipality, Møre og Romsdal county), and will consist of 70x5 MW wind turbines, resulting in a total of 350 MW. The total investment cost for the park is estimated to be around 750-900 M€ [33].

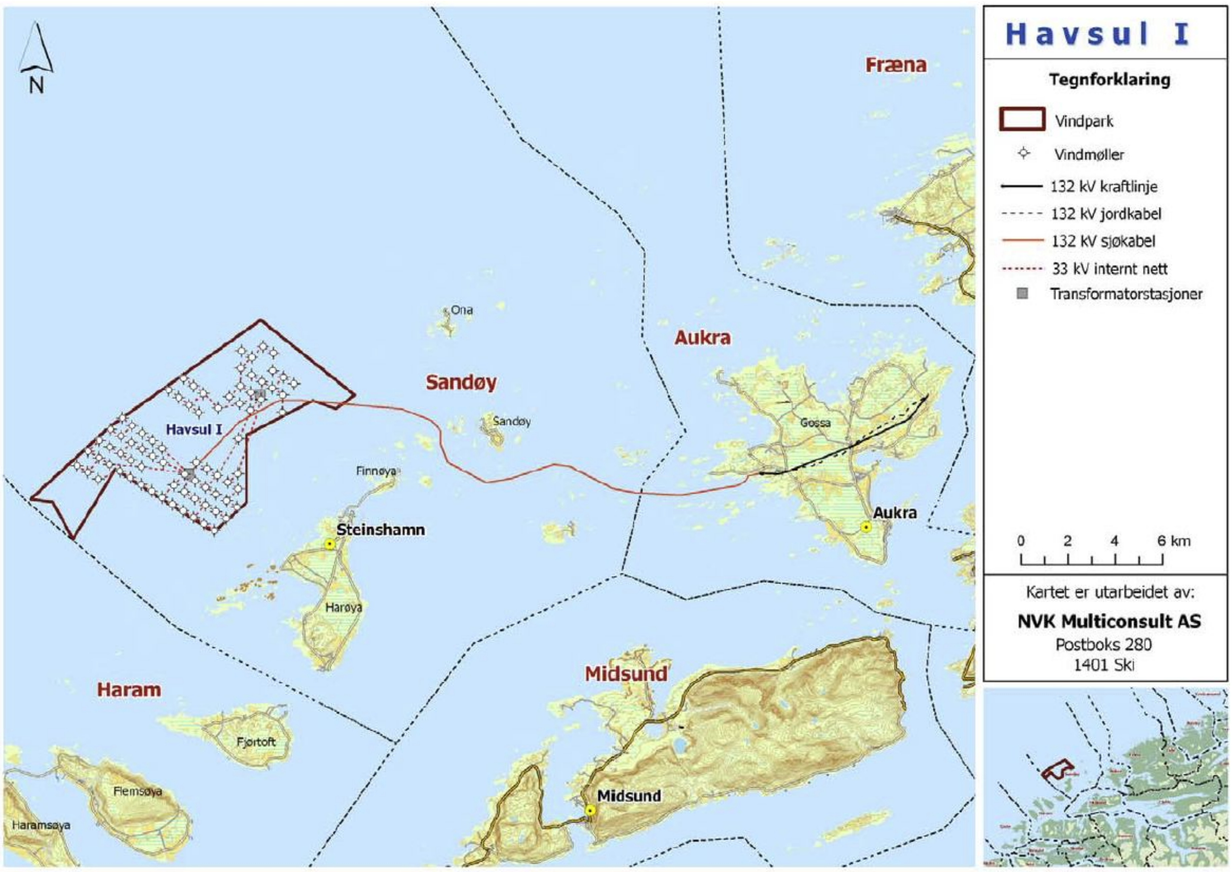


Figure 15: Havsul 1 offshore wind park overview map [34].

The planned export cable will be an approximately 30 km long 133 kV AC cable, reaching shore in another municipality where the grid connection is stronger. The sea depth varies from 4 to 30 meters. Compared to WINDSPEED's 2 MW/km2, the wind farm density is quite high at 7.14 MW/km2. This may suggest that WINDSPEED's wind farm density is very low, but there are some major differences between the cases. Firstly, the wake effects increase with the size the wind farm (600 vs 350 MW) as the number of windmills increase. Secondly, in clusters there will also be wake effects caused by the entire *wind farms* being close to each other. Thirdly, there are fewer constraints when it comes to wind farm size in the middle of the sea, as the visual impact and the influence of wild life habitat and sea uses are not as important. Based on these three main reasons a density of 2 MW/km2 seems reasonable for wind farm clusters far from shore.

In this study much of the technological assumptions are based on Anders Arvesen's hybrid LCA study of Havsul 1 (Havsul 1 project) [3]. Both physical and monetary data for the offshore windmills are mostly obtained from the Havsul 1project, with the main difference being the foundation which has increased significantly in size and cost due to the increased sea depth. The physical data for the array cables are also obtained from the Havsul 1 project. Using this data mostly unmodified seems reasonable, because they will not change much whether the windmills assessed are close to or far from shore.

Transport is, on the other hand, likely to be quite different. There will indeed be a higher demand for transport for wind farms far from shore, but the energy produced also increases with wind farms being farther from shore. Using the same functional unit as in the Havsul 1 project, total transport has, with some modifications on the export cable transport, been modeled the same way. Arguably this transport should have been modeled differently to better take into account the wind farm's increased distance from shore. Not contradicting this point, transport processes are complex to map, implying that there is much uncertainty even though a large amount of time is spent on trying to map it accurately. Having this in mind, the simplification of using the same data for transport in this study might not be very unreasonable.

The technology assumptions and choices made in this study are based on a combination of the data and assumptions from WINDSPEED, OffshoreGrid and the Havsul 1 project. By doing so, the combined system has likely become more realistic and the assessment probably more reliable than if everything was based on data and assumptions from *one* project. A description of the technology actually assessed in this study is given in section 3.5.

3.5 Technology assessed

The main objective of this study is to conduct an environmental assessment of an offshore grid in the North Sea. That is possible by using the grid modeled by WINDSPEED as a basis. Due to lack of data given in the project and some seemingly non-optimal technical solutions, data and assumptions have also been obtained from other sources, mainly OffshoreGrid and the Havsul 1 project. In this section the technology that takes part in the offshore grid assessed is described briefly.

Before getting into the specifics of an offshore HVDC grid, it is necessary to explain a bit about the onshore HVAC transmission grid. The transmission grid is the part of the grid that is used for long distance transmission between regions and between power plants and customers. High voltage is used since transmission losses decrease with higher voltage. The technology that an onshore distribution grid utilizes is established and well known. Standards vary somewhat with distances and countries, but generally the transmission voltage is between 132 and 400 kV [35]. Most importantly, the transmission grid uses alternating current, and that is the standard for onshore power distribution. The natural thing when expanding the grid would be to stick to the standard, being cheaper and making connections points easier. Unfortunately that is not possible (explained more in detail below) for long distance transmission offshore (~>70 km), the losses in HVAC cables becomes so high that converting the power to HVDC is deemed necessary.

3.5.1 Cables

The grid is composed of two different kinds of cables: the 33 kV AC array cables (connecting the windmills to the offshore substation) and the 450 kV DC export cables (connecting the offshore substations to each other and onshore substations).

WINDSPEED specifications for the export cable are quite different from the cable that is assessed in this study. The export cable assessed in this study is based on the flat cable in the NorNed HVDC cable. The array cables are based on WINDSPEED specifications for conductor sizes, with materials and composition from the Havsul 1 project.

HVDC vs HVAC

Wind farms generate alternating current (AC) electricity and the mainland grid is AC. The benefits of connecting the two with AC connections are obvious. But the problem with AC connections is that it is unsuitable for long distance transport. A characteristic of AC cable circuits is the charging current induced in the cable due to the capacitance between each phase conductor and earth. This charging current effectively reduces the ability of the cable to transfer useful power from one end to another [36]. When distances from shore becomes more than 70 km, distinct power losses will occur, and DC cable systems are generally preferred [21]. In fact, after some hundred kilometers HVAC will not be able to transfer *any* useful power, it is all gone because of self-capacitance. See Figure 16 below for a comparison between HVAC and HVDC cable losses with distance.

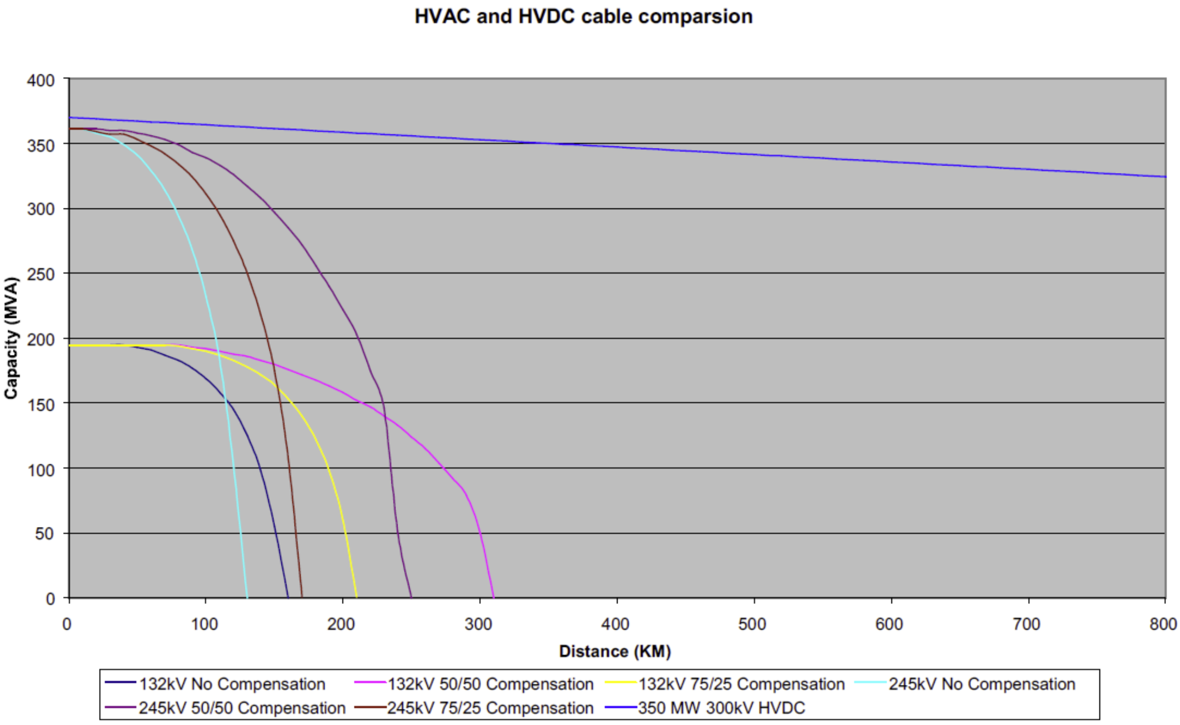
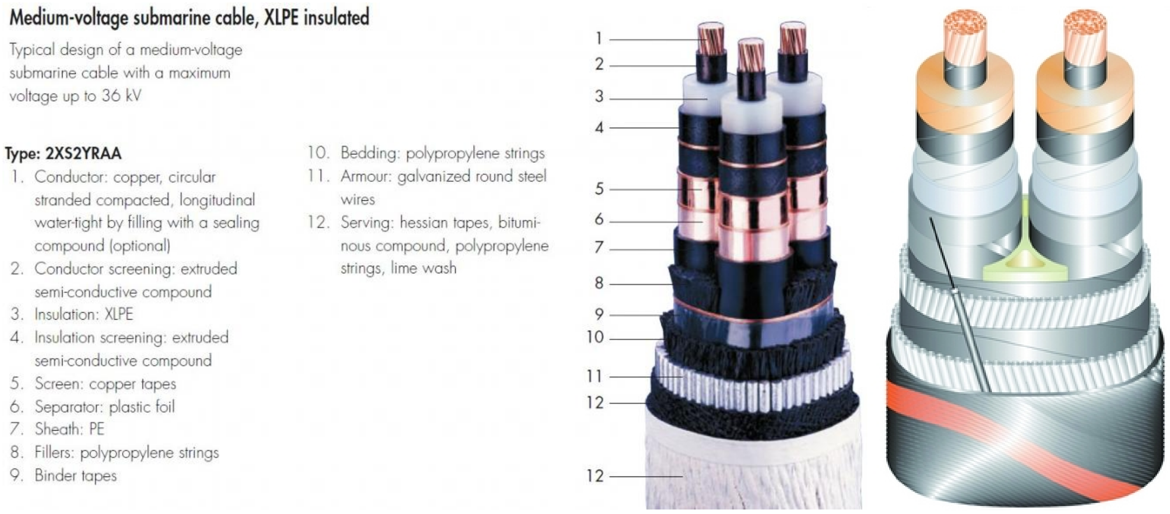


Figure 16: HVAC & HVDC cable losses with distance. [36]

Composition, sizes and voltages

Since no specifications for the composition of the cables in WINDSPEED are given, it has been assumed that the composition of the cables is based on the most common technology today. Both cables have copper conductors, but insulation materials are different.

The internal cables use cross-linked polyethylene (XLPE) as insulation, which is most common for cables at 33 kV today. The cable composition is obtained from the Havsul 1 project. It is a 3-phase cable with three conductors. Two conductor sizes are utilized: 630 mm^2 closer to the substation and 240 mm^2 farther away from it. The increase in conductor size is necessary because the total current increases with the number of wind turbines attached.



Medium-voltage submarine cable, XLPE insulated

Typical design of a medium-voltage submarine cable with a maximum voltage up to 36 kV

Type: 2XS2YRAA

1. Conductor: copper, circular stranded compacted, longitudinal water-tight by filling with a sealing compound (optional)
2. Conductor screening: extruded semi-conductive compound
3. Insulation: XLPE
4. Insulation screening: extruded semi-conductive compound
5. Screen: copper tapes
6. Separator: plastic foil
7. Sheath: PE
8. Fillers: polypropylene strings
9. Binder tapes
10. Bedding: polypropylene strings
11. Armour: galvanized round steel wires
12. Serving: hessian tapes, bituminous compound, polypropylene strings, lime wash

Figure 17: Cable compositions. Left: XLPE three-core 36 kV AC cable [37]**. Right: the NorNed flat mass-impregnated HVDC cable** [25]**. Except for the insulation, the materials are more or less the same.**

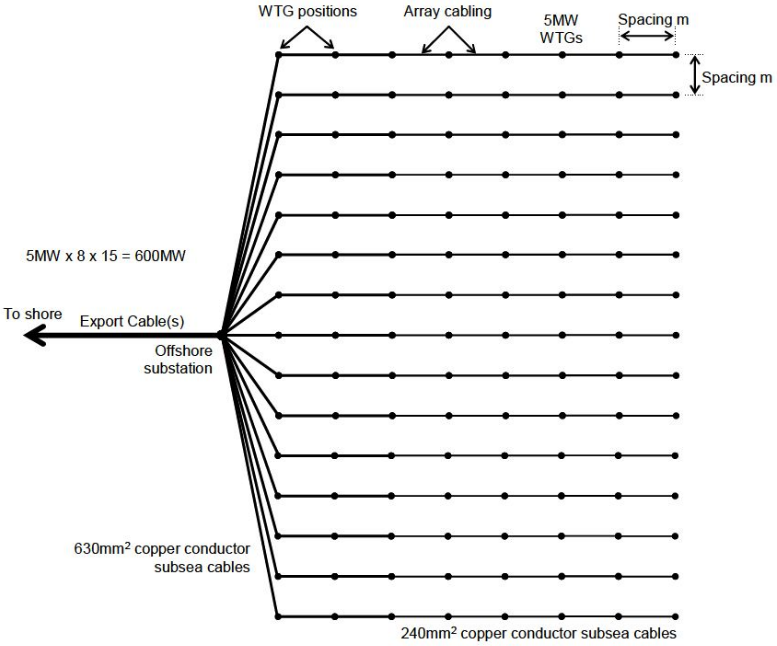


Figure 18: Array cables as modelled by WINDSPEED. Notice the two different conductor sizes. 'Spacing' is 0.98 km when a density of 2 MW/km2 is assumed, giving a total cable length of 177 km. [30]

The distance between the windmill farthest away in the wind farm and the substation is less than 12 km, meaning a 33 kV AC connection system is appropriate. The distance between the substations and shore are more than 70 km, resulting in all export cables in the grid being HVDC.

The specifications of the export cable used in the grid is based on the flat cable in the NorNed transmission cable (NorNed is composed of two types of cables), with two 700 mm^2 conductors and mass-impregnated paper (MIP) as insulation. This choice seems reasonable when looking at the HVDC cables suggested by OffshoreGrid, which are all in the range between 300-500 kV as opposed to the lower voltage (150 kV) suggested by WINDSPEED. In addition, HVDC cable data is company confidential and very hard to obtain, i.e. one have to use one of the few data sources available. NTNU has received a sample of the NorNed flat cable, which Christine Birkeland measured by hand in her Mater Thesis [5]. Those measurements are the basis for the physical inventory of the HVDC cable assessed in this study.

XLPE is considered a better insulating material than mass-impregnated paper, but as of today there are no cables with XLPE insulation available that can handle as high voltages as 450 kV. With the voltage capacity for XLPE cables continuously increasing, it is possible that 450 kV XLPE cables are available within the start of WINDSPEED (2020) [36]. That could change some environmental impact categories considerably, as paper and plastic are two quite different materials.

The materials used in the cables are given in the life cycle inventory, section 4.1. For more information about cable composition, see [25] [37] .

3.5.2 Substations

A substation comprises everything that is needed for electricity conversion, most importantly the power converter, switchgear and circuit breakers for the AC and DC side of the converter. In WINDSPEED the components of the substations are assumed to be similar offshore and onshore; the same is assumed in this study. The substation substructures, on the other hand, are very different onshore and offshore. The offshore substructure is made of a bottom-mounted foundation and the topside. For the onshore substation it is assumed that there is no substructure, all components are placed on the ground in open air.

Voltage Source Converters

Line Commuted Converter (LCC, or Current Source Converter (CSC)) and Voltage Source Converter (VSC) are basically two different technologies for transforming currents from AC to DC or vice versa. LCC is older than VSC and is an established technology. It is the technology used in existing interregional HVDC connections today, for example NorNed. LCC requires a strong AC network to be able to control the reactive power injected to or absorbed from the AC network, so LCC is only suited to connect to strong points on existing AC networks. In contrast, VSC converter stations are able to form their own AC voltage waveform and act as a true voltage source. This enables the converters to be connected to weak AC systems giving total flexibility regarding the location of the converters, for example offshore and connected to a wind farm AC array [36].

In addition VSC has the possibility of flexible multi-terminal operation, meaning that any number of connections to a VSC converter station is possible, making a meshed grid possible. DC multi-terminal connections and operations are technically complex and is still under development, but is likely possible by the end of this decade [36].

The two major downsides with voltage source converters are that they are expensive, mainly because it is a young technology compared to LCC, and that the losses are higher than for LCC. Grid losses are discussed more in detail in section 3.4.4.

The physical data for the converter assessed in this project is based on a 500 MVA, up to 600 kV, AC/AC line commuted converter from abb.com [source: abb.com LCA]. This converter has been upsized to a 750 MVA (600 MW=0.8*750 MVA) using the relation

$$m = s^{3/4} \tag{3.1}$$

where m is total converter mass and s is converter capacity. This relation gives a 36% increase in mass for a 750 MVA converter compared to a 500 MVA. Thus, all inventory components (including electricity and heat) of the 500 MVA converter are multiplied with 1.36 to get a reasonable estimate of a 750 MVA converter. This relationship is obtained from professor Arne Nysveen at the electrical power engineering department at NTNU [38]. He also claimed that the difference in inventory components and mass between LCC and VSC and AC/AC and AC/DC converters is not that big, which justifies the simplification of using a LCC AC/AC converter in the assessment. Obtaining data for a 750 MVA VSC was not possible, mostly due to the fact it does not (yet) exist.

In contrast to the design suggested by WINDSPEED, where *three* smaller converters in series handle the 600 MW conversion, it is assumed that *one* large converter does the same thing. This may not be an ideal design since much of the time the converter will not operate at full capacity, possibly resulting in higher conversion losses than necessary. But, since an LCA only requires material and process inputs, the difference between the sum of three smaller converters and one large is probably not that big. To summarize, the assumption of using a 750 MVA line commuted converter for the environmental assessment seems a like a reasonable simplification.

The converter components make up the physical inventory in the sectors called ‘Offshore substation’ and ‘Onshore substation’ in the assessment. See section 4.1 for inventory details.

Gas insulated switchgear and breakers

Except for the costs, no information is given about the switchgear and breakers in the substations in WINDSPEED. The costs are somewhat lower for the onshore substations mainly because of lower installation costs.

Spatial concerns have a high priority for all equipment in an offshore substation; keep it as small as possible. Due to this it has been assumed that gas insulated switchgear (GIS) has been used on the DC side of the converter. By insulating the electrical circuits with SF_6 gas as opposed to air, much space is saved due to the higher resistivity of SF_6. SF_6 is a very potent greenhouse gas, and some leakage over the lifetime of the GIS has been included in the assessment (small contribution, about 0.06% of total climate change impact). The inventory of a 420 kV GIS from ABB has been used in the assessment. 420 kV is a bit lower than the cable voltage of 450 kV, but it is assumed to be close enough to be used without any size modifications. The inventory data for the 420 kV GIS can be found at abb.com [39].

For circuit breakers on the DC side of the converter, the most suitable circuit breaker available at abb.com was used [40]. It is called a pantograph disconnector and has a voltage range of 123-550 kV.

The switchgear and circuit breakers on the array side (33 kV) of the converter offshore are not included. This simplification can be justified with the fact that switchgear and breakers for medium voltage are much smaller (~0.8%[4]) than for high voltage; meaning that the impact of these components will contribute very little to the total impacts of the grid. The inventory of medium voltage switchgear and breakers is quite much the same as for higher voltages, thus it has been assumed in this study that it is covered by the sector called 'Offshore substation breakers and switchgear'.

The switchgear and breakers on the AC grid side onshore is outside the scope of this study and is not included.

It is the two components, the 420 kV GIS and the pantograph disconnector, that make up the physical components of the sectors called 'Offshore substation breakers and switchgear' and 'Onshore substation breakers and switchgear'. See section 4.1 for inventory details. Even though spatial concerns are less important onshore, meaning that air-insulated switchgear may be used, gas insulated switchgear has been assumed there as well. This is mainly because data for high voltage air-insulated switchgear were not found, but the inventory is possibly not very different (with the exception of SF_6).

Offshore substation substructure

The sector 'Offshore substation substructure' consists of foundation and topside. The topside is built of steel and its main function is to serve as a frame and enclosure to all the electrical equipment. The foundation is bottom-mounted and it is mainly built of concrete, see Figure 20 for an illustration. Illustrations of the two other common foundation designs are given in appendix D.

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[4] Found by dividing total mass of medium voltage switchgear [59] with total mass of the HV GIS.

Figure 19: Offshore substation. The topside (grey) and the beginning of the foundation (yellow) can be seen. [41]

The sea depth assumed in this study is 43.9 meters. It was found by using the coordinates of the wind farm clusters in WINDSPEED and the average sea depth at each coordinate as given by http://4coffshore.com/offshorewind/. Then the average sea depth at each coordinate was weighted by the effect of each cluster, to find the overall average sea depth. Building foundations, that reach 43.9 meters deep, support more than 1000 tons and are able to withstand heavy wind and waves, naturally requires a lot of materials and is expensive. The contribution of the foundations to the total environmental impacts is significant.

Since no foundation type was specified in WINDSPEED, the same technology as in Havsul 1, concrete gravity structures (CGS), have been used as foundation for both substations and windmills. The amount of concrete was found in Figure 4.5 in WINDSPEED D2.2 (where concrete volume is given as function of sea depth) by assuming the most robust design due to the cluster location far from shore (i.e. much wind and waves). The amount was found to be 2425 m^3 per foundation. The amount of the other materials in the foundation and the topside is obtained from the Havsul 1 project.

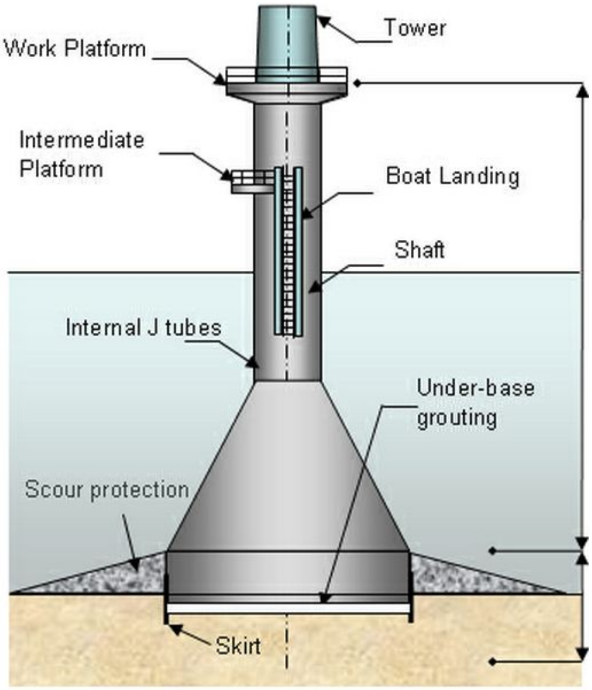

Figure 20: A Concrete Gravity Structure foundation. (Indicative only: actual implementation may be different) [42]

3.5.3 Windmills

WINDSPEED does not include costs or physical inventory for windmills, so that had to be obtained elsewhere. The windmills included in this study are based on the 5 MW models used in the Havsul 1 project, for both physical inventory and costs. The windmill components will only be briefly described because assessing windmills is not the main goal of this study. It is included to be able to model a system with a larger scope: the entire offshore grid system, meaning grid + all the offshore windmills (from now on referred to as 'complete system'). WINDSPEED and OffshoreGrid only look at the cost of grids that make it *possible* to deploy offshore wind on a large scale, and not the cost of the offshore wind in itself. For a detailed description of the physical inventory and costs used for the windmills in the Havsul 1 project, please contact Anders Arvesen [43].

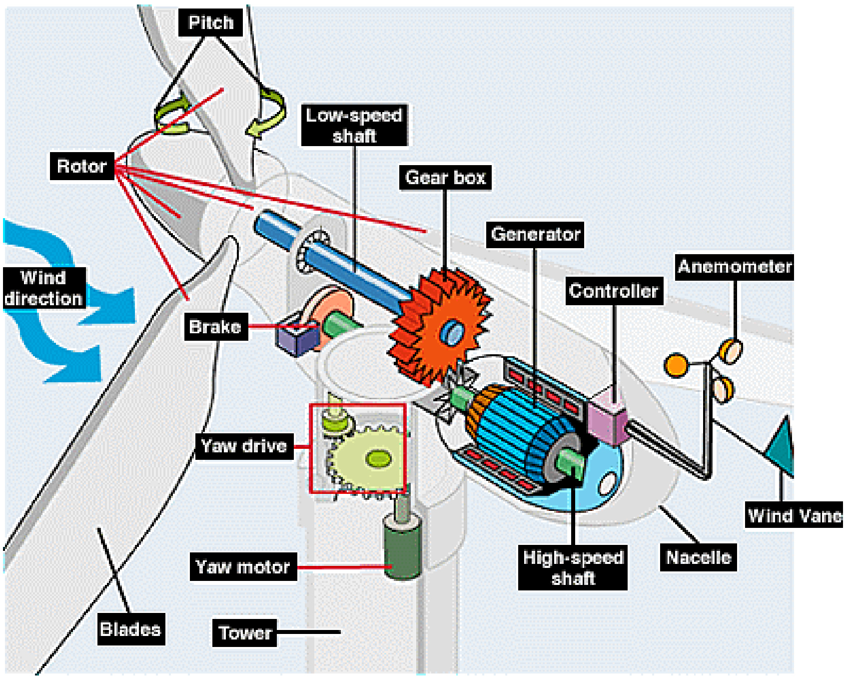

Figure 21: Generic components of a wind turbine.[44]

Figure 21 above shows the main components of a modern wind turbine. It consists of a rotor with blades, gear box, generator, low voltage transformer – all encompassed by the nacelle. The tower lifts the turbine close to 100 meter above sea, standing steady on the bottom-mounted foundation. The term windmill is used to describe the entire unit: wind turbine, tower and foundation.

The data for the foundation obtained by the Havsul 1 project has been modified to account for the increased average sea depth of 43.9 meters. The physical inventory is the same as for the substations the costs are obtained from a Norwegian Water Resources and Energy Directorate (NVE) report [source: NVE report], at 8.2 million euro per foundation at 40 meter sea depth. This is an important modification; the wind turbine foundations now make up almost 30% of the total climate change impacts for the complete system. Other foundation designs than CGS do exist, see appendix D for illustrations of jacket design and monopole. But, regardless of what foundation design that is chosen, the material and energy requirements would be extensive, only shifting from less concrete to more steel if one of the other designs were chosen.

3.5.4 Losses

Grid losses have been included by making some simple estimations. Converter and export cable losses have been found from two different sources and added together. Losses in array cables have not been included. See Table 9 below for details.

Table 9: Grid component losses

VSC Converter 500 MW	1,76	% per conversion [45]
NorNed cable	0,003569	% per km [25]

Converter losses are easily included: one conversion offshore and one conversion onshore, resulting in a total loss of 2*1.76=3.52%. One of the major disadvantages of VSC is the increased losses in the conversion process, which is remarkably higher than for LCC technology.

Total export cable losses, on the other hand, are not that straightforward to calculate. The problem is that the distance the electricity travels before it reaches an onshore substation is very complex to estimate accurately. In a meshed grid like the one assessed, the power produced in wind farms in Norwegian waters might just as well flow directly to the UK or the Netherlands as to Norway. To make good estimations of where the electricity travels requires complex simulations, which is beyond the scope of this study. Some simulations for electricity flows have actually been conducted in WINDSWPEED, but even the results are too complex to use to make any simple estimations.

A simple algorithm has been used to estimate where the electricity flows to from each wind farm cluster:

- It is assumed that the electricity produced will flow in the direction of where there is the most transfer capacity. The greater part will then flow to the shore closest to the wind farm cluster.
- If the wind farm cluster capacity is larger than the transfer capacity to the closest shore (which is the case for *all* wind farm clusters), it is assumed that the *remaining* electricity produced travels the route with the second highest transfer capacity, meaning the electricity will only travel to two destinations. The electricity that travels to the second destination is found by subtracting the transfer capacity to the closest shore from the total cluster production.
- To find the total travel distance, the distances to the two destinations have been weighted by the amount of the electricity that travels to each destination and summed together.
- In the end the overall average travel distance is found by a weighted average of all travel distances.

By using the simple algorithm above the average travel distance for the electricity in the Grand Design v05 scenario was estimated to be 162 kilometers, giving a total loss of 4.1%. The more ambitious scenario the shorter the average travel distance is, which seems reasonable. The simple algorithm probably gives a conservative estimate of losses, since it assumes that most of the electricity always travels to the closest onshore connection point. In reality this would probably not be the case. See Table 10 below for total losses in each scenario.

Table 10: Total losses for each scenario.

In The Deep 20%	In The Deep 0%	Grand Design v05	Grand Design v06
4,39 %	4,29 %	4,10 %	4,12 %

The amount of energy produced in each WINDSPEED scenario does not include losses; it is the sum of energy produced by each windmill at site, and not the energy that reaches the shores. Losses have been included in this study by multiplying the losses found for each scenario with the total energy produced in each scenario.

In some life cycle assessments of grid components, losses in the use face have been included when assessing environmental impacts. That may be reasonable when the electricity mix includes fossil power plants, grid losses can then be regarded as a contributing factor to emissions from the use phase of the power plants. Wind power does not create any emissions during its use phase, so this aspect is not considered relevant in this study.

4 Results

In this chapter the results from this study are presented, discussed and evaluated.

Four terms will be used for describing the two scopes assessed in this chapter. The terms ‘grid’ and ‘interregional meshed offshore grid’ mean the exact same thing. This is also the case for ‘complete system’ and ‘deep sea, far from shore offshore wind energy’. The point of introducing the longer terms is that the results may be relevant to use in a generic context, as opposed to the terms ‘grid’ and ‘complete system’ that only makes sense in the context of this thesis. The terms will be used interchangeably throughout this chapter.

The ‘grid’ scope is that of the offshore grid only, with its boundaries reaching from the end of the array cables to the AC side of the onshore substation, ready for onshore grid connection, at the other. The ‘complete system’ scope is simply the ‘grid’ *plus* windmills (wind turbines and foundation).

4.1 Life Cycle Inventory and Costs

This section presents all the relevant data obtained for completing the life cycle impact assessment. The data is presented in a concise table-oriented way with little explanation about where the data are obtained from and what assumptions that are used. For a more detailed description of this see chapter 3 Background.

4.1.1 Technical data for the interregional meshed offshore grid

Below the most relevant data and assumptions for the grid components are listed. For more details on how this data was obtained, see chapter 3 Background.

Array cables

Outer cables conductor size	240	mm^2
Outer cables total length	82,9	km
Inner cables conductor size	630	mm^2
Inner cables total length	94,4	km
Total cable length (three conductors)	177,3	km
Current type	AC	
Cable voltage	33	kV
Conductor material	Copper	
Cable insulation	XLPE	
Losses	0	%

Export cables

Conductor size	700	mm^2
Total cable length (two conductors) (GD v05)	39804	km
Current type	DC	
Cable voltage	450	kV
Conductor material	Copper	
Cable insulation	MIP	
Losses	0,00357	%/km

Offshore substation substructure

Foundation type	CGS	
Average sea depth	43,9	m
Topside material	Steel	

Offshore and onshore substation

Converter type	VSC	
Converter capacity	750	MVA
Converter voltage	<600	kV
Conversion losses	1,76	%
# of onshore substations (GD v05)	153	
# of offshore substations (GD v05)	147	

Breakers and switchgear

Switchgear type	GIS	
Switchgear voltage	420	kV
# of switchgear units	1	per substation
Breaker type	Pantograph Disconnector	
Breaker voltage	123-550	kV
# of breaker units	1	per substation

4.1.2Scenario data

Below the most relevant scenario data are listed and discussed briefly.

Table 11: Scenario data. All data are from WINDSPEED, except grid losses.

	ITD 20%	ITD 0%	GD v05	GD v06
Installed capacity [MW]	53259	53259	88122	81122
Capacity factor, before losses	37,92%	42,39%	38,84%	40,81%
Energy produced per year, before losses [TWh/y]	176,9	197,8	299,8	290,0
Windfarm to shore losses	4,39%	4,29%	4,10%	4,12%
Capacity factor, with losses	36,25%	40,57%	37,24%	39,13%
Energy produced per year, after losses [TWh/y]	169,1	189,3	287,5	278,0
Energy produced over lifetime (25 y), after losses [TWh]	4228,3	4732,0	7187,8	6951,1
Total investment costs (M€)	36290	36687	60519	56562
Investment costs per unit effect (€/MW)	681387	688841	686764	697246
# of wind farms	89	89	147	135
# of windmills	10652	10652	17624	16224
# of substations onshore	95	105	153	147
# of substations offshore	89	89	147	135
Export cable total length [km]	28600	29546	39804	37989

All the data, except for losses, are obtained from WINDSPEED. The losses in the scenarios are calculated by using losses data from two sources and some simple assumptions, for details see section 3.5.4. Many of the rows above represent the final demand for each scenario. Due to the independent variation of km export cable, number of onshore substations from scenario to scenario it has not been possible to model the system with *one* functional unit for all components. The functional unit used for most sectors is 'MW'. The y-vector, which contains the final demand for each scenario for both scopes, is given in appendix B.

The capacity factors are not given in WINDSPEED, but the total energy produced in each scenario is, hence it is easy to calculate. Interestingly, the calculated capacity factor of the two In The Deep (ITD) scenarios are different even though the installed effect is the same. According to WINDSPEED this is due to constraints in the offshore grid and a lower demand for offshore wind energy because a higher amount of other energy sources in use onshore, not allowing the wind energy produced to be fully utilized. The capacity factors in ITD 20% are marked in orange, because the numbers calculated are strictly speaking not the capacity factor. It is reasonable to assume that the capacity factor is the same as in ITD 0%, but with some of the energy produced failing to be utilized.

The choice of focusing on the Grand Design v05 scenario is primarily due to it being the most ambitious scenario, but also because it has the least optimistic capacity factor (see section 4.1.6 for a discussion on capacity factors). In addition, the scenarios have an almost similar environmental impact per unit energy produced. Impacts calculated for the other scenarios are given in appendix C.

4.1.3 Life Cycle Inventory for the interregional meshed offshore grid

All inventory processes that are inputs to the Ecoinvent background database are listed in Table 11. All inventory components are allocated to the Ecoinvent process that is similar, or most similar, to the processes given by the respective sources. All processes are given per functional unit: export cable has 'km' as functional unit, the others have 'unit', which means that the processes listed are what is necessary to build one complete unit of the given component.

Some specific points that should be clarified:

- Electricity demand has been allocated to the process called 'electricity, production mix RER', which basically means an average European production mix. The average European production mix involves much fossil fueled power generation, which will lead to significant impacts (especially to climate change) from this process.
- Heat demand has been allocated to the process called 'natural gas, burned in industrial furnace' for all components.
- Electricity and heat demanded to produce the offshore substation substructure were not found, so these two processes have been covered by the IO system for this component.
- Onshore transport is calculated by simply assuming the total mass of each component's functional unit has to travel 100 km with lorry. For example, the export cable has a mass of 310 ton per kilometer, which gives 31000 tkm transport necessary for every km of cable produced.

More transport processes are included than what is given in Table 11. Sea transport has been modeled as foreground processes on their own, as obtained from the Havsul 1 project. Some changes to transport have been made to better account for the grid only scope, and some transport processes have been altered for the complete system as well to better account for the increased amount of transport necessary for export cable laying. See appendix B for more details on sea transport and how transport demand has been altered.

The column called 'Included in LCA?' is related to the issue of double counting. In the rows where there is a 'NO', the process in that row has not been included in the LCA part of the assessment but instead in the IO-part. The two processes 'other' and 'porcelain' does not exist in Ecoinvent, thus it is naturally a part of the IO-system. The processes 'nickel' and 'silver' exist in Ecoinvent but because of the very small contribution to the sectors (3 and 1 kg per unit breakers and switchgear, respectively) they are not included. If the sectors were to be included, the corresponding sectors in the IO-part would have to be set to zero. To exclude the foreground demand for broad economic sectors because of such small process demands, is considered inferior to letting the IO-sectors handle nickel and silver contribution.

Table 12: Life Cycle Inventory of interregional meshed offshore grid per component. The functional units are listed in the second row.

Ecoinvent process		Array cables	Export cables	Offshore substation substructure	Offshore substation	Offshore substation breakers and switchgear	Onshore substation	Onshore substation breakers and switchgear	Included in LCA?
		unit	km	unit	unit	unit	unit	unit	
sulphur hexafluoride, liquid, at plant/ RER/ kg	kg					534		534	
lubricating oil, at plant/ RER/ kg	kg				85390		85390		
gravel, unspecified, at mine/ CH/ kg	kg			5151000					
concrete, normal, at plant/ CH/ m3	m3			2425					
electricity, production mix RER/ RER/ kWh	kWh	4450179	86469		406621	7578	406621	7578	
aluminium, production mix, at plant/ RER/ kg	kg					9746		9746	
aluminium, production mix, cast alloy, at plant/ RER/ kg	kg				2310		2310		
cast iron, at plant/ RER/ kg	kg					108		108	
chromium steel 18/8, at plant/ RER/ kg	kg					435		435	
copper, at regional storage/ RER/ kg	kg	1889080	13000		54162	1146	54162	1146	
lead, at regional storage/ RER/ kg	kg	1284990	23000						
nickel, 99.5%, at plant/ GLO/ kg	kg					3		3	NO
reinforcing steel, at plant/ RER/ kg	kg			560000					
silver, at regional storage/ RER/ kg	kg					1		1	NO
steel, low-alloyed, at plant/ RER/ kg	kg	2011220	65480	630000	216447	2885	216447	2885	
zinc coating, pieces/ RER/ m2	m2	71211	512						
natural gas, burned in industrial furnace >100kW/ RER/ MJ	MJ	4450179	59293		406621	7578	406621	7578	
alkyd paint, white, 60% in H2O, at plant/ RER/ kg	kg				2982		2982		
polyester resin, unsaturated, at plant/ RER/ kg	kg					80		80	
kraft paper, unbleached, at plant/ RER/ kg	kg		5500		8810	10	8810	10	
epoxy resin insulator (Al2O3), at plant/ RER/ kg	kg				219	1096	219	1096	
polycarbonate, at plant/ RER/ kg	kg					5		5	
polyethylene, HDPE, granulate, at plant/ RER/ kg	kg	344730				22		22	
polypropylene, granulate, at plant/ RER/ kg	kg	211890	3000						
synthetic rubber, at plant/ RER/ kg	kg					65		65	
transport, lorry >32t, EURO5/ RER/ tkm	tkm	1163338	15500	2432200	78849	3804	78849	3804	
sawn timber, softwood, planed, air dried, at plant/ RER/ m3	m3				45,18	2,69	45,18	2,69	
other (not in Ecoinvent)	kg					175		175	NO
porcelain (not in Ecoinvent)	kg				3592	1500	3592	1500	NO

4.1.4 Life Cycle Costs for the interregional meshed offshore grid

In this section all costs that are inputs to the EXIOPOL background database are listed in Figure 12 and briefly explained. The O&M demand is in orange because MW, strictly speaking, is not a demand.

Table 13: Life Cycle Costs of interregional meshed offshore grid, in 2000 M€.
Second last row contains total demand, given in each component's functional unit.

EXIOPOL sector	Array cables	Export cables	Offshore Structure	Offshore Substation	Offshore B&S	Onshore Substation	Onshore B&S	O&M
	unit	*km*	*unit*	*unit*	*unit*	*unit*	*unit*	*MW*
Manufacture of cement, lime and plaster			3,57					
Manufacture of fabricated metal products, except machinery and equipment			1,79	7,05		6,88		
Manufacture of electrical machinery and apparatus	27,84	0,19		59,95	27,49	58,46	22,41	0,0088
Construction	7,96	0,14	7,15	3,53		3,44		0,0221
Sea and coastal water transport	3,98	0,09	3,57					0,0044
Other business activities		0,05	1,79					0,0088
SUM	39,78	0,47	17,87	70,53	27,49	68,78	22,41	0,044
GD v05 Demand	*147*	*39804*	*147*	*147*	*147*	*153*	*153*	*88122*
GD v05 Total Cost	5842	18468	2624	10359	4038	10546	3436	3895

All costs except for operation and maintenance (O&M) are obtained from WINDSPEED. In WINDSPEED the costs are given as supply and installation costs, with supply costs being the same as manufacturing costs. Decommissioning costs are not given, but have been included based on the assumption made by Kaiser and Snyder claiming that decommissioning costs can be assumed to be 50% of installation costs [46]. 'Other business activities' includes all relevant engineering services. The method used for adjusting and allocating the costs properly can be summarized as follows:

- **Component costs summed together.** All the different costs; supply, installation and decommissioning are summed together for each component.
- **Adjust for technology learning and economies of scale.** The technology used in the offshore grid is modern and expensive as of today, but it is reasonable to expect that there will be cost reductions until 2020 and over the period for which the grid is completed (2030). It has been assumed a total cost reduction of 37.7% for all scenarios, which have been distributed equally over all component costs.
- **Adjust costs for inflation.** WINDSPEED costs are given in 2010 €, so it has to be adjusted to 2000 € (which EXIOPOL is given in). The average European inflation rate for the period has been used, obtained from Eurostat [47]. The numbers in the row 'SUM' in Table 12 are now obtained.
- **Allocate costs to EXIOPOL sectors.** The costs are allocated to the sector in EXIOPOL that is most appropriate, primarily based on how the costs were allocated to supply and installation by WINDSPEED initially. Decommissioning costs are allocated the same way as installation

costs. How the costs are allocated is given in Table 12. The fractions used for allocation to each sector are given in appendix B, and the original costs as obtained from WSP are given in appendix E.

- **Distribute component costs across the economy.** The costs are now ready for the first step of the tiered hybrid LCA, the 'Distribute component costs across the economy' step as it is called in the methods chapter. It distributes the allocated costs over all economic sectors that take part in the production of the component. See chapter 2 Methods for more details.
- **Setting sectors covered by the LCA processes to zero.** The last step is to set all production/manufacturing sectors covered by the LCA processes to zero to avoid double counting. For example, the sectors related to electricity and heat production are all set to zero, with the exception of the component 'offshore substation substructure'. This is because electricity and heat production is not included as processes for that component (see Table 11). The sectors that are set to zero are given in appendix B.

The costs are then ready for calculations, i.e. the Apf-matrix is ready for inclusion in the A-matrix.

Operation and maintenance costs for the grid are not given in WINDSPEED. It has been a futile effort to try to obtain O&M costs for an interregional meshed offshore grid, which is not surprising since no such grid exist today. One could perhaps have used the O&M costs for NorNed, but as it only has onshore substations the costs would probably be quite much lower. Another option would be to use O&M costs for the onshore transmission grid, but this would probably also be lower. In the end it was chosen to base it on the Havsul1 project's O&M costs. Since the O&M costs for the Havsul 1 project is for the entire wind farm including grid connection, it is necessary to estimate what fraction of those costs that is spent on the *grid*. No such fraction exists, so it has been made by using the crude assumption of allocating the O&M costs the same way as the resulting climate change impacts of the project are distributed. In the Havsul 1 project the grid contribution to total climate change impacts is ~10%. So, the O&M costs used in the assessment of the interregional meshed offshore grid is equal to 10% of the Havsul 1 project O&M costs. A crude assumption indeed, but probably better than including no O&M costs at all.

4.1.5 Technical data, Life Cycle Inventory and Costs for windmills

The technical data, LCI and LCC of the windmills are obtained from the Havsul 1 project and has been used mostly unmodified. Because these data is not the work of this study, but has just been "borrowed", it has been decided that listing all the data would not be appropriate. The data is the work of Anders Arvesen at the Department of Industrial Ecology at NTNU, please contact him for interest in or questions about the data [43].

An important modification that has to be made to the Havsul 1 project data is to modify the windmill foundations to account for the increased average sea depth of 43.9 meters. The foundation is of the type concrete gravity structure (Figure 20 in section 3.5), meaning the main component is concrete. The amount of concrete was found in WINDSPEED D2.2 figure 4.5, the rest of the inventory was used unmodified. See column 'offshore substation substructure' in Table 11 for the complete inventory, but not including the 630000 kg 'steel, low-alloy, at plant' that represents the topside of the offshore substation structure. The cost of 8.23 M€ (after inflation adjustment and cost reduction) [48] has been allocated the same way as the offshore substructure substation, as can be seen in appendix B.

Transport sectors that are most likely to change significantly have been modified as best possible. The grid and windmill installation and maintenance is now farther from shore as compared to close to shore in the Havsul 1 project. For the grid assessment, all transport sectors involving are not included and the transport sectors related to export cables have been modified to account for the functional unit ‘km’. For more details on transport data and the demand for it, see appendix B.

4.1.6 Capacity factor and lifetime

In this section the important concepts of capacity factor and lifetime are discussed briefly. The reason is that the capacity factor and lifetime chosen when calculating impacts per unit energy produced are very significant for the results.

The capacity factor of a wind farm can be found using statistics for how much energy it produces over a year. That amount is divided by the theoretical maximum energy a wind farm can produce, which is maximum capacity (e.g. 5 MW as for the turbines in this study) times the 8760 hours in a year. In other words, the true capacity factor can only be found after the wind farms have been installed. Thus, the capacity factors used in this study are *estimated*, primarily based on wind statistics for the geographical area that the wind farms will be installed. Following are some examples illustrating that the capacity factor varies quite a bit with location, technology and wind farm design:

- According to EWEA a 40% capacity factor for offshore wind may be possible in the future [49].
- The existing North Hoyle offshore wind farm in the UK reports of an annual capacity factor of 35% [50].
- In the Havsul 1 project a capacity factor of 32.04% has been assumed.
- The average capacity factor for onshore wind in the UK today is 27.2% [51]

EWEA claims in their report ‘Economics of wind energy’ [52] that “For an onshore installation utilization, the energy production indicator is normally around 2000-2500 full load hours per year, while for a typical offshore installation this figure reaches up to 4000 full load hours per year, depending on the site.” It is thus not unreasonable to assume that the capacity factors for offshore wind farms are higher than those for onshore; it is more wind (especially far from shore) and the conditions are more stable. Wind turbine technology is also likely to continue to improve until 2030. Based on this and the examples above, it seems fair to claim that the capacity factors given in WINDSPEED are not unrealistic, but they are definitely tending towards the optimistic. The capacity factor used in the scenario of primary focus (GD v05) is 38.84% before losses, which seems perfectly realistic.

The lifetime of an entire system consisting of components with different lifetimes is a bit difficult to determine. Below is an overview of the lifetimes listed for the most important components, from their respective sources:

Table 14: Lifetimes for the different components, in years.

Converter	Export cable	Windmill	WINDSPEED grid
35	40	25	30

In this study the reasoning of the lowest common denominator has been used; meaning that the component with shortest lifetime is chosen as the lifetime for the entire system. One could then argue that the lifetime used for assessing the grid only should be the one given by WINDSPEED. But the main focus of the WINDSPEED grid scenarios is the transport of wind energy from the windmills to the mainland and not interregional trading. The lifetime chosen for all scenarios and scopes are 25 years.

The main reason for including this section is that the capacity factor and lifetime actually utilized severely affects how much energy that is produced over the lifetime of the system. If the results are presented as environmental impacts per unit energy produced over the lifetime of the system, like in this study, the results are affected just as much Below are three examples of how much it can change the results:

- A decrease of the lifetime assumed to 20 years would increase impacts per kWh with 25/20-1=25%.
- An increase of the lifetime assumed to 30 years would decrease the impacts per kWh with 1-25/30=16.6%.
- A decrease of the capacity factor from 37.2% (WINDSPEED GD v05, after losses) to 32.04% (Havsul 1 project) would increase the impacts per kWh with 1-32.04/37.2=13.9%.

As explained, there is much uncertainty related to these two parameters. However, to compare the impacts caused by offshore wind energy with other energy sources, dividing with total energy produced over the lifetime is probably the best way to do it.

4.2 Life Cycle Impact Assessment

In this section the most relevant results of the life cycle impact assessment are presented and discussed briefly. Only the results from the scenario Grand Deisgn v05 are presented, results from the other scenarios are available in appendix C.

A selection of what is considered the most relevant impact categories has been made. That is mostly due to practical reasons related to the presentation of the results, but also because some impact categories are not considered to be important in the context of this study. Results for the remaining impact categories are given in appendix C. See Table 15 below for the impact categories included.

Table 15: ReCiPe impact categories included in the presentation of the results.

Abbreviation	Impact Category	Unit
CC	Climate Change	kg CO2-Eq
FET	Freshwater Ecotoxicity	kg 1,4-DCB-Eq
HT	Human Toxicity	kg 1,4-DCB-Eq
ME	Marine Eutrophication	kg N-Eq
MD	Metal Depletion	kg Fe-Eq
PMF	Particulate Matter Formation	kg PM10-Eq
POF	Photochemical Oxidant Formation	kg NMVOC
TA	Terrestrial Acidification	kg SO2-Eq
TET	Terrestrial Ecotoxicity	kg 1,4-DCB-Eq

Impacts are shown as allocated to components and emission sources. Components are basically *foreground* processes either presented as they are modeled (in the case of grid, with some few modifications) or aggregated (in the case of complete system, where ‘wind turbines’ etc. are the sum of many processes). The emission sources are sums of the different processes in the *background* that can be attributed to the sources given. The background processes with no obvious allocation have been placed in the categories: ‘Other’ (for the LCA part), ‘IO Europe region’ and ‘IO ROW region’ (for the IO-part). All results are represented per kWh delivered to the AC onshore grid, with 25 years lifetime and 37.24% capacity factor (after losses) assumed.

4.2.1 LCIA of interregional meshed offshore grid

Hybrid assessment, all impact categories, impacts allocated to components

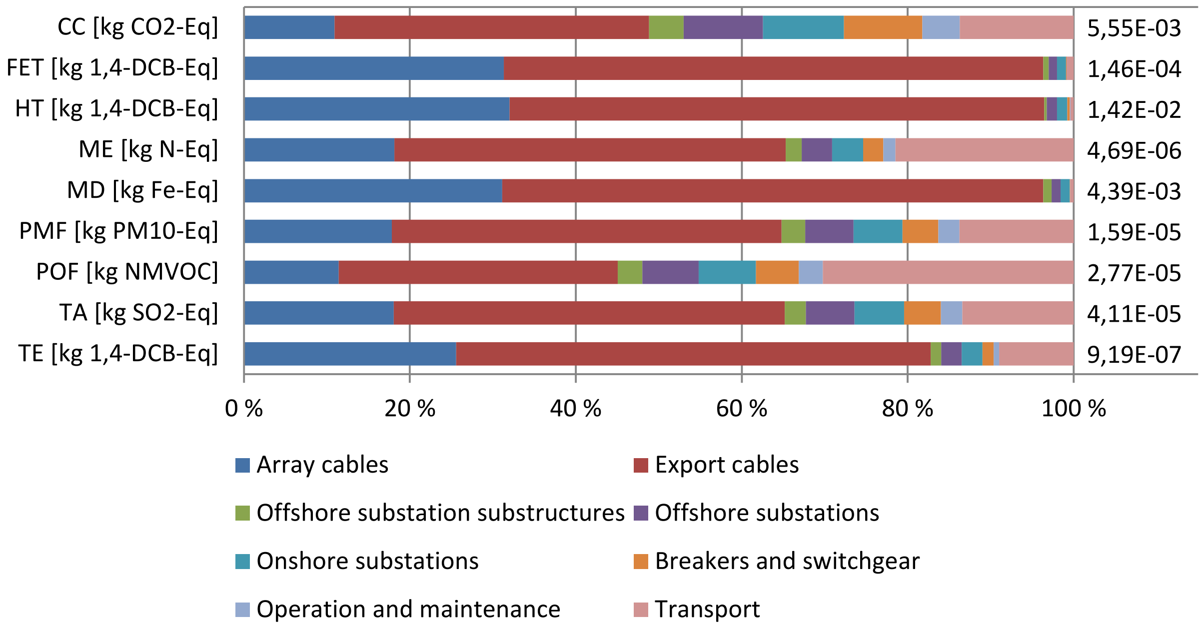

Figure 22: Hybrid LCA results for interregional meshed offshore grid. All impact categories, impacts allocated to components.

The hybrid assessment of the grid allocated to components is shown in Figure 22 above. For every 1 kWh produced, some impacts caused by the grid are 5.55 g CO_2-equivalents to climate change, 0.17 g 1,4-DCB-equivalents to freshwater ecotoxicity, 14.2 g 1,4-DCB-equivalents to human toxicity, 4.39 g Fe-equivalents to metal depletion and 15.9 mg PM10-equivalents to particulate matter formation.

Impacts are allocated to the different components included in the foreground system. Offshore and onshore breakers and switchgear have been added together for the sake of presentation, with impacts being close to equal. Transport is the sum of all foreground transport sectors, the majority of it being sea transport for installation, maintenance and decommissioning of the grid, but also some onshore transport sectors. Foreground transport processes is only modeled with physical values, thus its contribution is solely from the process-LCA part of the hybrid assessment. For more details on the foreground transport sectors included, see appendix B. Operation and maintenance is only modeled with monetary values, so its contribution is solely from the IO-part of the hybrid assessment. All other components have both a process-LCA part and an IO part contribution.

Export cables are the largest contributor to all impact categories, perhaps not surprising when there is a demand for more than 39000 kilometers of it. The second largest contributor varies between array cables and transport, depending on impact category. The dominance of cables in the toxicity categories (FET, HT and TE) is striking. Notice the almost similar graphs for FET, HT and MD, suggesting high correlation between the impact categories. Transport is a fairly large contributor to climate change, ME, PMF, TA and TE, but has the largest contribution to photochemical oxidant formation. The remaining components (electrical equipment and substructure) impact shares vary considerably: from almost none in the toxicity categories to about 30% to climate change.

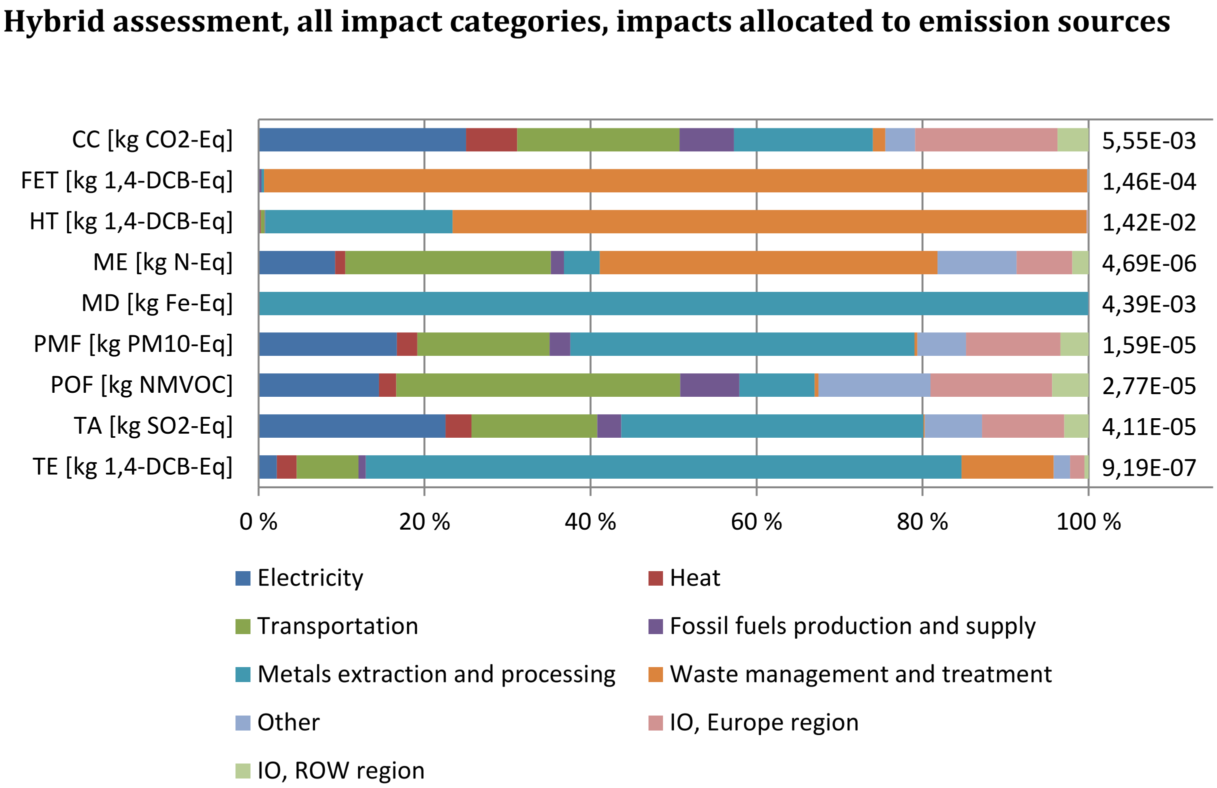

Figure 23: Hybrid LCA results for interregional meshed offshore grid. All impact categories, impacts allocated to emission sources.

The hybrid assessment of the grid, allocated to emission sources, is shown in Figure 23 above. The emission sources are the sum of different background processes, both from the process-LCA part and IO part, that fits in the emission source categories defined. The sectors ‘Other’, ‘IO, Europe region’ and ‘IO, ROW region’ are the sum of the background processes that cannot be attributed to any of the defined emission source categories. Transportation is the sum of all transport processes in the background, i.e. transport processes that are happening *because of* the foreground demand.

Climate change impact is quite evenly distributed across the different emission sources, with electricity production being the largest at more than 20%. Freshwater ecotoxicity, human toxicity and marine eutrophication are dominated by waste management and treatment. Terrestrial ecotoxicity, terrestrial acidification and particulate matter formation is dominated by metals extraction and processing. Metal depletion is, naturally, entirely due to metals extraction and processing. Photochemical oxidant formation has its largest contribution from transport, which is in accordance with Figure 22, where the second largest contributor to POF is the foreground transport processes.

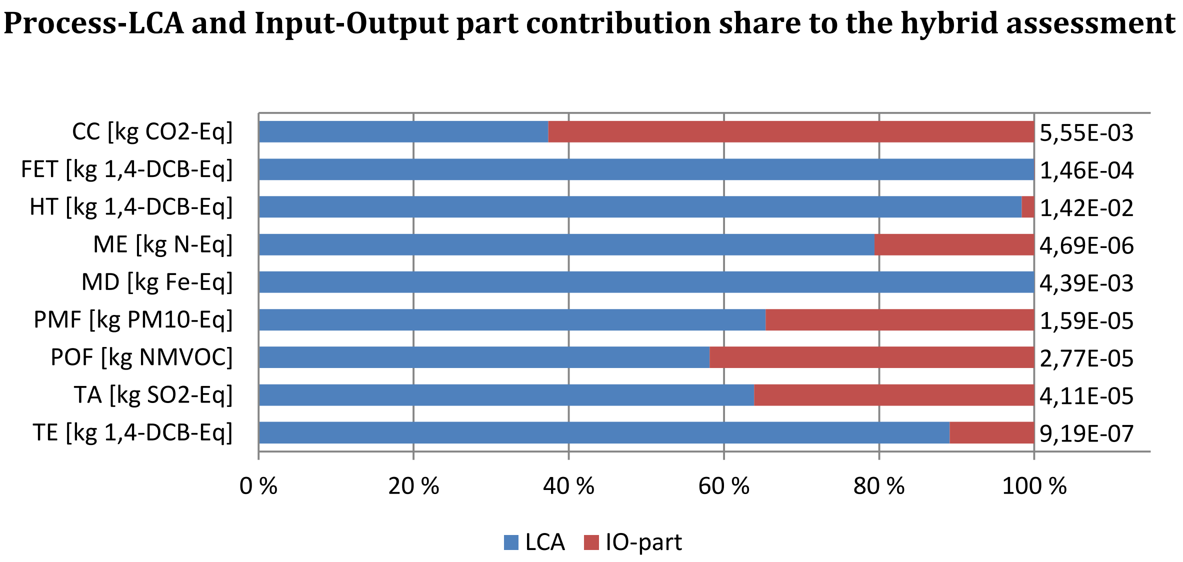

Figure 24: Process-LCA and Input-Output part contribution share to the hybrid LCA results. Interregional meshed offshore grid scope, all impact categories.

The contribution share to the impact categories of each of the two parts in the tiered hybrid LCA method, the process-LCA part and the IO part, is shown in Figure 24 above. It is included mainly to illustrate how much the inclusion of an IO part may increase total impacts. It is evident, at least in the case of climate change, that the system boundaries of LCA fail to account for all the emissions caused by the grid.

The IO part contributes the most to climate change impacts, with its share being more than 63%. That corresponds to an increase of 168% to a process-based assessment only. There are also significant contributions from the IO part to marine eutrophication, particulate matter formation, photochemical oxidant formation and terrestrial acidification. There is no contribution to metal depletion, and close to none to freshwater ecotoxicity and human toxicity. Terrestrial ecotoxicity has a noticeably contribution of about 8%.

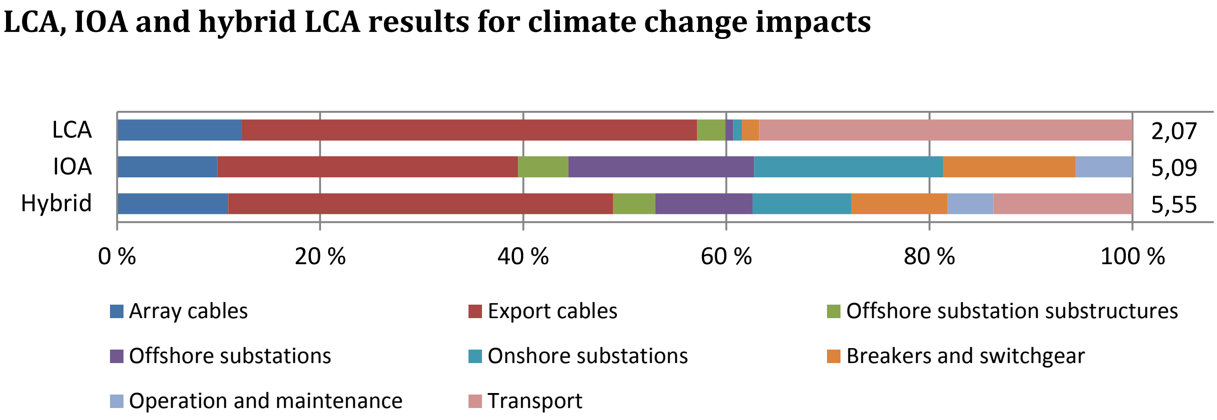

Figure 25: LCA, IOA and hybrid LCA climate change impact results for interregional meshed offshore grid. Impact (g CO2-Eq/kWh) allocated to components.

The climate change impact results of the three different methods used to assess the grid are shown in Figure 25 above, allocated to components. The hybrid LCA gives the highest results: 168% higher than LCA and 9% higher than IOA. The hybrid LCA impact shares sort of become an average between the LCA and IOA, which makes sense since it is a sum of LCA and IOA with double counting avoided.

Export cables have the largest impact contribution to all three methods, with 0.93 g/kWh for LCA, 1.51 g/kWh for IOA and 2.1 g/kWh for hybrid LCA. Impact shares for array cables are almost identical, at around 11%. Transport is the second largest contributor to the LCA, with more than 36%. Operation and maintenance contribute 4% to the hybrid assessment. The remaining grid components (substructures, substations, and breakers and switchgear) have a remarkably different contribution share, varying from 5% for the LCA to more than 50% for the IOA. This very large difference may be related to some of the main weaknesses of IOA: with costs as inputs to broad aggregated sectors the method may fail to differentiate between products of different composition and size. And with VSC converters being an expensive technology today, the IO system may treat it as a "normally priced" item, which will correspond to material and resource use per unit cost being inflated. For more on this, see section 4.4 on uncertainties related to methods.

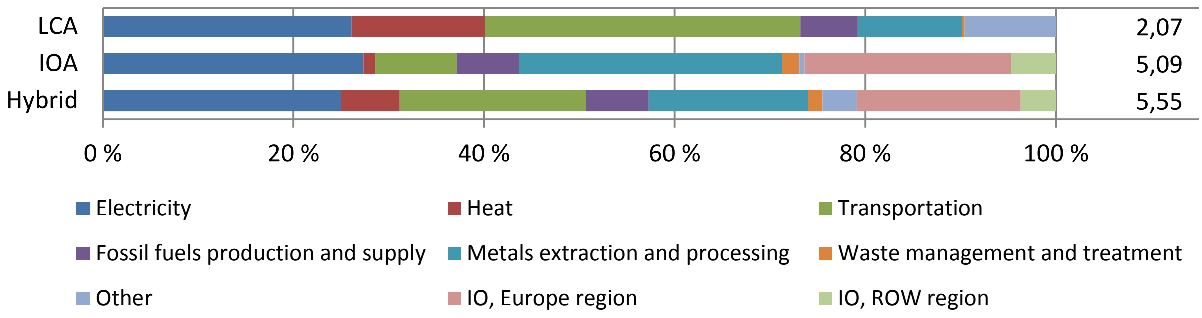

Figure 26: LCA, IOA and hybrid LCA climate change impact results for interregional meshed offshore grid. Impact (g CO2-Eq/kWh) allocated to emission sources.

The climate change impact results of the three different methods used to assess the grid, allocated to emission sources, are shown in Figure 26 above. Again, hybrid becomes a sort of average between the LCA and IOA.

Impacts due to electricity production have about the same contribution share for all three methods, at around 25%. Heat contribution share is quite much larger in the LCA than in the IOA, this is mainly due to IOA not having any obvious sector(s) that covers heat production. The share is probably larger, but the way the sectors in EXIOPOL are composed makes it hard to allocate properly to. Transportation has a quite much larger contribution share in the LCA than in the IOA. Metals extraction and processing has an almost twice as high contribution share in the IOA as in the LCA. This may be due to the more complete system boundaries of IOA, taking into account the entire production chain in the economy related to this activity. The "other-sectors" of IOA, namely 'IO, Europe region' plus 'IO, ROW region', make up a quite much larger contribution share than 'Other' does in the LCA. This seems reasonable, as IOA better account for services and other intangible activities than LCA.

Based on the reasoning in the paragraph above, it may be fair to suggest that it seems like the two methods of LCA and IOA tend to complement each other; one method's weakness in an area may be mitigated by the other method's strength in that area, making the" average" of a hybrid LCA possibly the most realistic assessment, but this is quite speculative. For more on discussion on methods, see chapter 2 Methodology and section 4.4 in this chapter.

4.2.2 LCIA of deep sea, far from shore offshore wind energy

Hybrid assessment, all impact categories, impacts allocated to components

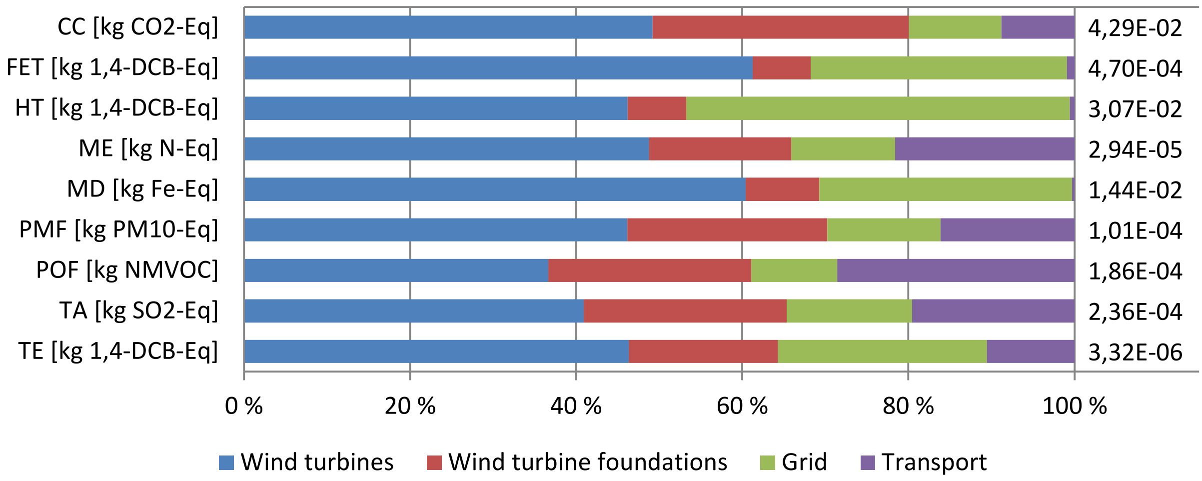

Figure 27: Hybrid LCA results for deep sea, far from shore offshore wind energy. All impact categories, impacts allocated to components.

The hybrid assessment of the complete system, allocated to components, is shown in Figure 27 above. For every 1 kWh produced, some of the impacts caused by the complete system are 42.9 g CO_2-equivalents to climate change, 0.47 g 1,4-DCB-equivalents to freshwater ecotoxicity, 30.7 g 1,4-DCB-equivalents to human toxicity, 14.4 g Fe-equivalents to metal depletion and 101 mg PM10-equivalents to particulate matter formation.

The impacts are allocated to different aggregated components. Wind turbines are the sum of all components that take part in a wind turbine (rotors, gearbox, LV converter, tower etc.) plus all the economic sectors directly related to the turbines (operation and maintenance, replacement of parts etc.). Wind turbine foundations correspond to the component called wind turbine foundation in the foreground system, containing both monetary and physical values. Grid is the sum of all components the interregional meshed offshore grid is made of (substations, export cables, array cables etc.) plus its required operation and maintenance costs. Transport is the sum of all foreground transport sectors, the majority of it being sea transport for installation, maintenance and decommissioning of the complete system, but also some onshore transport sectors.

Wind turbines have the largest contribution share to all impacts except human toxicity, at around 40-50%. That is not surprising, considering the large amount of material and work that goes into each wind turbine. What may be more surprising are the large contribution of the foundations and the grid to some categories. The foundations contribute more than 30% to climate change impact, and more than 20% to particulate matter formation, photochemical oxidant formation, and terrestrial acidification impacts. The grid has a large contribution to toxicity categories, especially to human toxicity at more than 46%. The grid has a large requirement for metal, contributing 30 % to metal depletion. Transport has a substantial contribution to marine eutrophication, particulate matter formation, terrestrial acidification and its largest contribution at more than 28% to photochemical oxidant formation. Transport contributes more than 8% to climate change impact.

Hybrid assessment, all impact categories, impacts allocated to emission sources

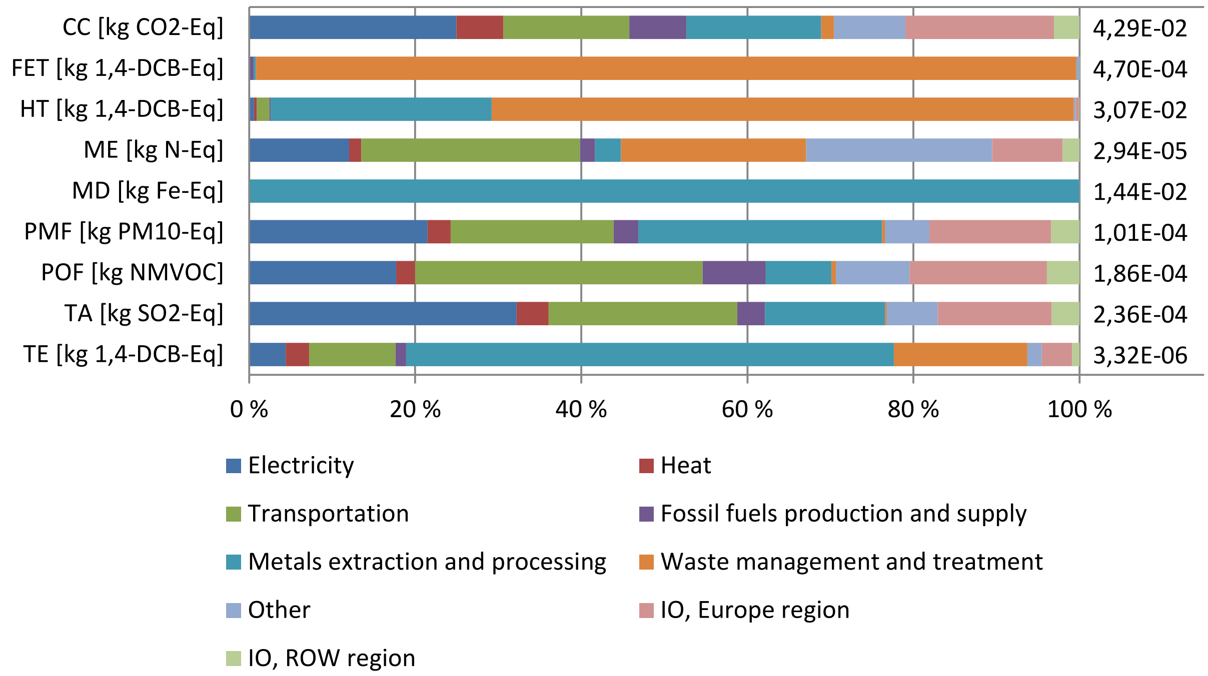

Figure 28: Hybrid LCA results for deep sea, far from shore offshore wind energy. All impact categories, impacts allocated to emission sources.

The hybrid assessment of the complete system, allocated to emission sources, is shown in Figure 28 above. The emission sources are the sum of different background processes, both from the process-LCA part and IO part, that fits in the emission source categories defined. The sectors ‘Other’, ‘IO, Europe region’ and ‘IO, ROW region’ are the sum of the background processes that cannot be attributed to any of the defined emission source categories. Transportation is the sum of all transport processes in the background, i.e. transport processes that are happening *because of* the foreground demand.

The contribution shares are remarkably similar to those for the offshore grid only, shown in Figure 23 above. That is a good indication that the processes involved in making the complete system are similar to the ones involved in making the offshore grid. Still, there are some noticeable differences: contribution from electricity production and transport has increased some, and contribution from ‘metal extraction and processing’ and ‘waste management and treatment’ has decreased some.

Climate change impact is quite evenly distributed across the different emission sources, with electricity production being the largest at more than 20%. Freshwater ecotoxicity, human toxicity and marine eutrophication dominant emission source is waste management and treatment. Terrestrial ecotoxicity, terrestrial acidification and particulate matter formation is dominated by metals extraction and processing. Metal depletion is, naturally, entirely due to metals extraction and processing. Photochemical oxidant formation has its largest contribution share from transport, which is in accordance with Figure 27, where the second largest contributor to POF is the foreground transport processes.

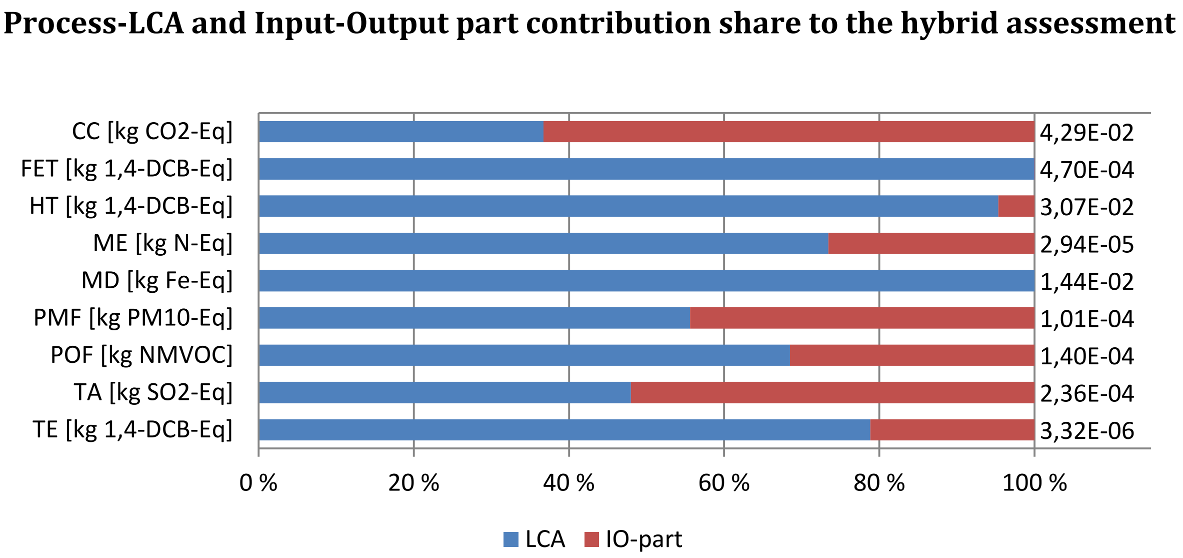

Figure 29: Process-LCA and Input-Output part contribution share to the hybrid LCA results. Deep sea, far from shore offshore wind energy scope, all impact categories.

The contribution share to the impact categories of each of the two parts in the tiered hybrid LCA method, the process-LCA part and the IO part, is shown in Figure 29 above. It is included mainly to illustrate how much the inclusion of an IO part may increase total impacts. It is evident, at least in the case of climate change, that the system boundaries of LCA fail to account for all the emissions caused by the complete system.

The IO part contributes the most to climate change impacts, with its share being 63%. That corresponds to an increase of 172% to a process-based assessment only. There are also significant contributions from the IO part to marine eutrophication, particulate matter formation, photochemical oxidant formation, terrestrial acidification and terrestrial ecotoxicity, ranging from 21% to 52%. There is no contribution to metal depletion, and close to none to freshwater ecotoxicity. The contribution share to human toxicity is less than 5%.

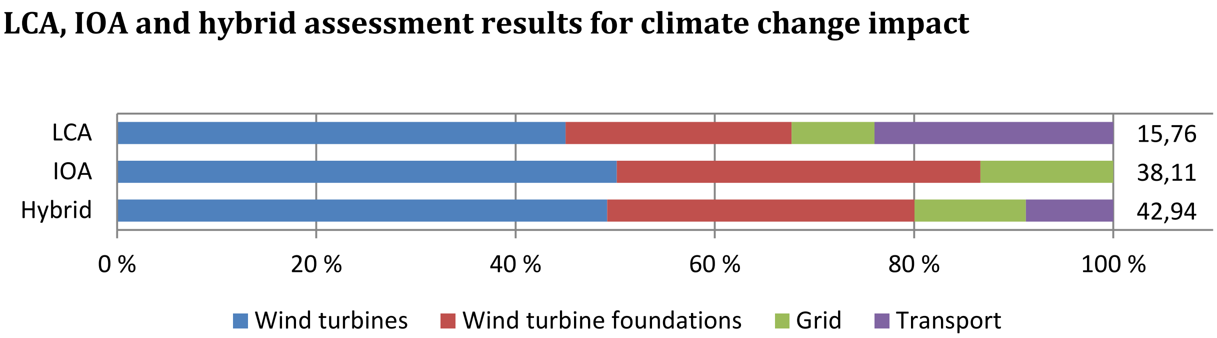

Figure 30: LCA, IOA and hybrid LCA climate change impact results for deep sea, far from shore offshore wind energy. Impact (g CO2-Eq/kWh) allocated to components.

The climate change impact results of the three different methods used to assess the complete system are shown in Figure 30 above, allocated to components. The hybrid LCA gives the highest results: 172% higher than LCA and 13% higher than IOA. The hybrid LCA impact shares sort of become an average between the LCA and IOA, which makes sense since it is a sum of LCA and IOA with double counting avoided. The same results are shown in numbers in Table 16 below.

Table 16: LCA, IOA and hybrid LCA climate change impact results for complete system [g CO2-Eq/kWh].

	Wind turbines	Wind turbine foundations	Grid	Transport	SUM
LCA	7,09	3,58	1,31	3,78	15,76
IOA	19,12	13,91	5,09	0,00	38,11
Hybrid	21,12	13,25	4,79	3,78	42,94

Wind turbines have the largest impact contribution in all three methods, quite evenly distributed. The high cost for constructing and installing a foundation at 40 meter sea depth (8.23M€, year 2000), makes the foundation contribution share in the IOA remarkably high at more than 36%. The foundation contribution share is also high in the LCA, at more than 22%. The grid's contribution share varies from 8% (LCA) to 13% (IOA). It may be noticed that the grid impacts are lower than the total given in the assessment of the grid, which is due to transport demanded by the grid is not included as a part of the grid results. Total foreground transport required by the complete system contributes more than 23% to the LCA, which gives more than 8% contribution to the hybrid LCA. It is obvious from these results that the environmental impacts caused by deep sea, far from shore offshore wind energy are quite different from impacts caused by onshore wind energy. This is discussed more in section 4.4.

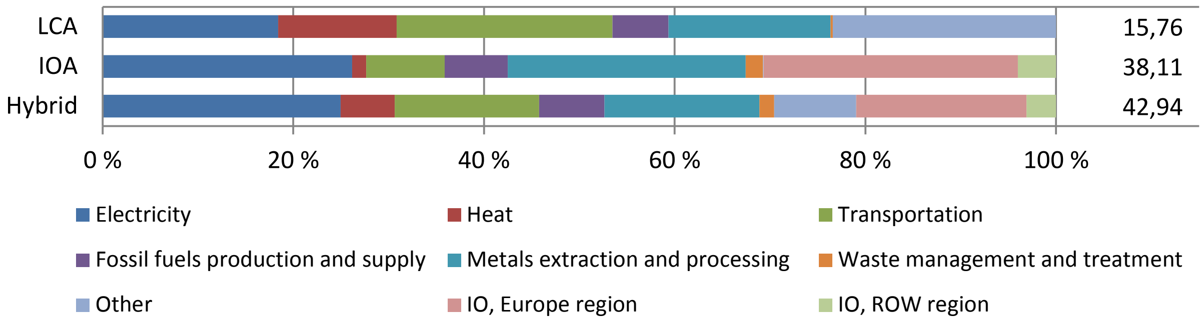

Figure 31: LCA, IOA and hybrid LCA climate change impact results for deep sea, far from shore offshore wind energy. Impact (g CO2-Eq/kWh) allocated to emission sources.

The climate change impact results of the three different methods used to assess the complete system, allocated to emission sources, are shown in Figure 31 above.

Contribution shares are quite similar to those found in the assessment of the grid only. Impacts due to electricity production have about the same contribution share for all three methods, at around 20-25%. Heat contribution share is quite much larger in the LCA than in the IOA, this is mainly due to IOA not having any obvious sector(s) that covers heat production, i.e. it is difficult to allocate it properly. Because of this, double counting for heat production probably has not been avoided properly. Transportation has a quite much larger contribution share in the LCA than in the IOA. Metals extraction and processing has an almost two times larger contribution share in the IOA as in the LCA. This may be due to the more complete system boundaries of IOA, taking into account the entire production chain in the economy related to this activity. The "other-sector" of IOA, namely 'IO, Europe region' plus 'IO, ROW region', make up a quite much larger contribution share than 'Other' does in the LCA. This seems reasonable, as IOA better account for services and other intangible activities than LCA. Again, there are several indications towards that the methods of LCA and IOA tend to complement each other, making the aggregated average of a hybrid LCA possibly the most realistic assessment.

4.3 Analysis and discussion

In this section the results will be analyzed and discussed in a generic way, aimed at pinpointing the most relevant tendencies and information that can be deduced. For a discussion in a broader context, see chapter 5.

The cables are by far the largest contributors to freshwater ecotoxicity and human toxicity in the grid scope. At first glance, it may be reasonable to believe this is due to the large amount of lead demanded by the cables (~22% of total mass for array cables, ~30% of total mass to export cables). With some matrix manipulation it is possible to investigate this claim.

Table 17: Cable insulation and lead contribution to selected impact categories, percentages of grid hybrid LCA results.

	Export cables		**Array cables**	
	MIP insulation	*Lead*	*XLPE insulation*	*Lead*
CC	2,50 %	12,99 %	3,79 %	7,71 %
FET	0,36 %	3,92 %	0,01 %	1,68 %
HT	0,29 %	6,67 %	0,003 %	2,75 %

As shown in Table 17 above it is not the case that lead is the dominating contributor to freshwater ecotoxicity and human toxicity, contributing relatively little to both categories. A quick look at the results obtained for the insulation show that mass-impregnated paper contributes more to FET and HT and a bit less to climate change impact than cross-linked polyethylene. But the contribution to total impacts is so small for both insulation materials that it almost doesn't matter, from an environmental point of view, which insulation type is being used in the cables. The impacts to freshwater ecotoxicity and human toxicity seem to be highly correlated to metal depletion impacts. For both grid and complete system the foreground allocations are almost similar for all three impact categories. This correlation suggests that the high FET and HT impacts are mostly due to activities related to metals extraction and processing.

The contribution of the grid to the complete system is significant for all impact categories, ranging from 46% to human toxicity to 11% to climate change and photochemical oxidant formation. This confirms that the grid connections to deep sea, far from shore offshore wind energy contribute so much to environmental impacts in such a system that it cannot be omitted in an assessment.

The electrical equipment required by the grid (converters, breakers and switchgear) have a significant contribution to the grid results, at 33% to climate change and ranging between 10% and 19% for ME, PMF, POF and TA. It is a very big difference between the results obtained from the LCA and the IOA for these components (almost 10 times larger climate change impact in the IOA), implying much uncertainty related to the results.

Foreground transport necessary for the installation, maintenance and decommissioning have a quite equal contribution in the two scopes. To climate change impacts it contributes more than 13% to the grid and more than 8% to the complete system. This may be reasonable as every kilometer cable has to be carefully laid to sea bottom at installation and removed at end of life. The largest impact contribution by foreground transport is to photochemical oxidant formation, at more than 25% in both scopes. It can be concluded that foreground transport (primarily sea transport) is an important component when assessing the environmental impacts of deep sea, far from shore offshore wind energy.

Operation and maintenance is represented a bit different for the two scopes. For the complete system the environmental impacts caused by operation and maintenance have been allocated to the component that the specific O&M activities are related to. The majority of the activities are related to the wind turbines, and only one is related to the grid. See appendix B for an overview of the O&M activities. For the grid assessment, O&M contributes less than 5% to climate change impact.

The contribution by foundations is different for the two scopes. With only one substructure (foundation plus topside) per 600 MW wind farm for the grid, the contribution is less than 4% to all impact categories. For the complete system the situation is different, each wind farm requiring 120 bottom-mounted concrete foundations at more than 40 meter sea depth average. This is both expensive and material intensive, making a large contribution to most impact categories. Most notably, foundations contribute more than 30% to climate change impact, and more than 20% to particulate matter formation, photochemical oxidant formation, and terrestrial acidification impacts. In other words, the foundations are a very important component of an assessment of the environmental impacts of deep sea, far from shore offshore wind energy.

Focusing on the emission sources, the contribution distribution is almost similar for the two scopes assessed. Heat and electricity generation are quite prevalent in all but a few impact categories. They have the largest contribution to climate change impact (more than 30% to both grid and complete system), mostly due to the use of fossil fuel for the energy generation. Emissions due to waste management and treatment are mostly to freshwater ecotoxicity and human toxicity. The impacts from metals extraction and processing are high for several categories other than metal depletion, most notably particulate matter formation (~40% to grid and ~30% to complete system) and terrestrial ecotoxicity (~70% to grid and ~60% to complete system). The “other sectors” have a significant contribution to CC, ME, PMF, POF and TA, with contribution ranging from 20% to 33%. ‘IO, Europe region’ always has a larger share than ‘IO, ROW region’, which is reasonable since it is assumed that all components are manufactured, installed and decommissioned in the European economy. To refer back to the example of rice cultivation in China used in chapter 2, impacts from this activity is accounted for in ‘IO, ROW region’. Fossil fuels production and supply is present in some impact categories, but generally one of the smaller contributors to all impact categories.

Climate change and photochemical oxidant formation impacts are allocated quite evenly over the different emission sources. The other impact categories generally have one dominating emission source: HT and ME is dominated by waste management and treatment; PMF, TA and TE is dominated by metals extraction and processing; while MD and FET are completely dominated by metals extraction and processing and waste management and treatment, respectively.

More detailed impact data for each of the 71 components/processes included in the foreground and the 4355 processes/sectors in the background are available in the excel-file (results_rn.xlsx) uploaded along with the thesis, or can be acquired by contacting the author.

4.4 Data quality, uncertainty and evaluation of results

In this section the results will be evaluated by assessing the quality of the data used, uncertainty related to methods and a comparison to other studies. The assumptions behind most of the data used in this study have been described previously in this chapter or in chapter 3 Background. Many of the uncertainties related to the data have been discussed previously. Many of the uncertainties related to methods have been discussed in chapter 2 Methods. Thus, in this section it will only be a brief summary of the different uncertainties, followed by a subjective benchmark of the level of uncertainty; uncertainties ranging from little, some to much. Sources of the different data are given in this chapter or in chapter 3 Background.

4.4.1 Inventory data

The term inventory data comprise all processes that are included in the process-LCA part of the assessment.

- **Array cables.** Obtained from the Havsul 1 project, based on data sheets from producers.
  - Uncertainty: little
- **Export cables.** Based on direct measurement of the sample part of the NorNed flat cable at SINTEF Energy Research. Component shares may not be completely accurate.
  - Uncertainty: little/some
- **Offshore substation substructure.** Based on the concrete gravity structures used in the Havsul 1 project. Concrete amount increased to account for the increased sea depth, using relationship given in figure 4.5, WINDSPEED D2.2. There is uncertainty related to the design of foundation choice. Same as the wind turbine foundations, but with a topside.
  - Uncertainty: little/some
- **Substations.** Consisting of an upsized 500 MVA LCC converter from an ABB datasheet. Even though LCC and VSC are different technologies the inventories of the two are probably quite similar.
  - Uncertainty: some
- **Breakers and switchgear.** A 420 kV GIS and a 123-550 kV pantograph disconnector from ABB datasheets. Not entirely correct components, but inventories should be quite similar.
  - Uncertainty: little/some
- **Transport.** Based on the transport sectors used in the Havsul 1 project with some modifications to account for the new functional units, and removing transport sectors related to wind turbines when only the grid is assessed. The distances modeled for many of the sea transport services are likely too small.
  - Uncertainty: some/much
- **Wind turbine foundations.** Based on the concrete gravity structures used in the Havsul 1 project. Concrete amount increased to account for the increased sea depth, using relationship given in figure 4.5, WINDSPEED D2.2. There is uncertainty related to the design of foundation choice.
  - Uncertainty: little/some
- **Wind turbines.** Based on the 5 MW turbines used in the Havsul 1 project, initially obtained from data sheets.
  - Uncertainty: little

- **Ecoinvent database.** The most common LCA database with generic processes, a well established framework. Since the processes are generic and not specific to this study there is some uncertainty.
    - Uncertainty: little/some
- **ReCiPe characterization.** Allocating emissions to impact categories is a process involving uncertainty.
    - Uncertainty: little/some

4.4.2 Monetary data

The term monetary data comprises all costs that are included in the IOA and IO part of the hybrid assessment.

- **WINDSPEED costs.** Costs given by WSP are generic and not based on specific data from manufacturers. It is not stated what prices the costs are given in, but basic prices have been assumed. Modern and expensive technology; costs may be inflated and not accurately reflect the inherent value of the components. Uncertainty related to cost reduction and inflation adjustment. Much uncertainty related to the costs of breakers and switchgear. Decommissioning costs based on a simple assumption of being 50% of installation costs.
    - Uncertainty: some/much
- **Grid operation and maintenance costs.** Based on the crude assumption of being 10% of the total O&M costs in the Havsul 1 project.
    - Uncertainty**:** much
- **Wind turbine foundation costs.** Based on costs from NVE report for a CGS foundation at 40 meters sea depth. Uncertainty related to cost reduction and inflation adjustment.
    - Uncertainty: some
- **Wind turbine costs.** Costs obtained from the Havsul 1 project, used unmodified.
    - Uncertainty: little/some
- **Wind farm operation and maintenance costs.** Costs obtained from the Havsul 1 project. Assumed to be the remaining 90% of the original O&M costs, as 10% is allocated to the grid O&M costs.
    - Uncertainty: some
- **Wind farm capital costs.** Installation, decommissioning, other capital and other variable costs for the wind farm is obtained from the Havsul 1 project. Included in these costs are the Havsul 1 grid connection costs, so the costs have to be adjusted to account for the wind farms only. That is done by the same assumption as described above; grid capital costs constitute 10%, so the remaining 90% are considered to be wind farm capital costs.
    - Uncertainty: some
- **EXIOPOL database.** The recently completed input-output database with main focus on the European economy. Consists of 129 much aggregated generic sectors, resulting in the specific components of this study being allocated to broad economic sectors. E.g. all the electrical equipment in the grid is allocated to the same generic sector for manufacturing of electrical apparatus. It also has much fewer emissions included, compared to Ecoinvent.
    - Uncertainty: some/much (for this study, may be more accurate for assessments of larger systems with less specific components)

By combining all the uncertainties above, it is evident that there is more uncertainty related to monetary data than to inventory data.

4.4.3 Scenario data

- **Capacity factor.** The amount of energy that will be produced by the wind farms is estimated. It may by estimated quite well based on wind data, but as discussed in section 4.1.6 only a small change could change the environmental impacts per unit energy produced considerably.
    - Uncertainty: some
- **Lifetime.** How many years the system will be able to operate is estimated. It may by estimated quite well, but as discussed in section 4.1.6 only a small change could change the environmental impacts per unit energy produced considerably.
    - Uncertainty: some
- **Losses.** Losses are calculated based on generic information about VSC converters and specific NorNed cable losses per km. How far the electricity produced by the wind farms has to travel to reach shore is estimated based on simple assumptions, probably giving a conservative estimate.
    - Uncertainty: some
- **Sea depth.** The average sea depth is calculated based on average sea depths at the coordinates of the wind farm clusters.
    - Uncertainty: some
- **Array cable length.** The array cable length will vary from wind farm to wind farm involving several factors as topography of the ocean floor and how densely the windmills are situated. An average wind farm density is chosen to give a realistic average array cable length, using information given by WINDSPEED.
    - Uncertainty: some

4.4.4 Methods

Since three different methods for environmental assessment have been used in this study, it is possible to have a long and detailed discussion on the pros and cons of the different methods. Assessing methods is not the main goal of this study, so the discussion will be brief. The main focus in this section is to assess whether the issue of double counting has been avoided properly.

The most influential pros and cons of LCA and IOA in *this* study are given in Table 18 below. It does not accurately describe the generic pros and cons of the two methods.

Table 18: LCA vs IOA, the most important pros and cons in this study.

	LCA	IOA
Pros	Ecoinvent is a high resolution framework, giving more accurate assessment More accurate data inputs	Broad system boundaries, does include (ideally) all background production chains
Cons	Narrow system boundaries, does not include all background production chains	EXIOPOL is a low resolution framework, giving less accurate assessment Less accurate data inputs

While LCA has lower uncertainty, the issue of narrow system boundaries is so important that the results may be severely underestimated. Anders Arvesen notes that the cut-off errors of process-based LCA studies of renewable energy systems can be higher than 50% for some impact categories [1]. something that seems to be the case in this study. It also seems reasonable to suggest that each of the two methods better account for the impacts caused by some of the activities in the foreground system in this study: LCA is better suited for modeling transport activities while IOA is better suited for operation and maintenance activities.

Based on the reasoning above, a hybrid assessment combining the two methods is probably a better approach than using one of the two methods seperately. The hybrid assessment becomes a sort of component contribution average between LCA and IOA, and at the same time "dampening" the effect of the inherent weaknesses of the two methods. Another (speculative) generalization is that the process-LCA part probably shows a more correct impact allocation to the components, while the IO part sort of corrects it to better account for total emissions.

The benefits of hybrid LCA are obvious, but if double counting is not avoided properly the accuracy of the assessment may be low, with calculated results being overestimated. So, is the issue of double counting avoided properly in this study? The following paragraphs will try to answer this question.

The method used for avoiding double counting in this study is: for each component's physical process covered by the LCA part, the corresponding economic processes in the IO part are set to zero. The idea is that LCA takes care of the physical processes while IOA takes care of the more "hidden" processes in the economy. The physical inventory of the components are given in Table 11, which sectors that are set to zero are given in appendix B. Assuming that the rationale is correct and that the correct sectors are set to zero, it can be concluded that double counting has been avoided.

There are, however, several ways of avoiding double counting for the tiered hybrid LCA method; perhaps the chosen way is not appropriate for this study. An indication that results may be too high is that, for climate change impacts, they are higher in the hybrid assessment than in the IOA. IOA, having complete system boundaries, should in principle account for *all* emissions. How can results be higher than results from a method that includes all emissions? Does this mean that double counting has not been avoided properly?

Not necessarily, principally because EXIOPOL sectors are merely broad aggregated averages. The broad sectors contain many different types of activities, with some being more and some less, impact intensive than others. Since the sectors are averages, all products assessed using EXIOPOL will be treated as an average product. This will result in inaccuracy when assessing products that are not close to the average product. If the products assessed in this study are more emission intensive than the average product of the corresponding EXIOPOL sector, double counting may be avoided at the same time as the results of the IOA are lower than the results of the hybrid LCA.

Whether this is the case for the offshore grid and complete system components is uncertain, but it may very well be. A detailed investigation of the composition of the relevant EXIOPOL sectors is necessary to confirm or disprove this. If disproved, it can be concluded that the issue of double counting has not been avoided properly. It is beyond the scope of this study to investigate this, but it may be a topic for a future study. On the other hand, the results of the hybrid assessment are not *much* higher than the results of the IOA, and for some components, like for the wind turbine foundation, they are lower.

To wrap it up, from the results obtained it can*not* be concludes that the issue of double counting has *not* been avoided. Disregarding other uncertainty, the results of the hybrid assessment may be quite accurate.

4.4.4 Comparison with other studies

A way to evaluate the results obtained in this study is to compare it with previous similar studies. It may be an indication of quality if the results are in accordance with previous studies. The only impact compared in this section is climate change impact, because it is usually the impact category that is of main interest when assessing renewable energy technologies.

Grid

To the author of this study's knowledge, there are no published articles on the environmental impacts of an interregional meshed grid. But Christine Birkeland's master thesis from 2011 [5], from which much of the data used in this study is obtained from, did an environmental assessment of the same NorNed flat 450 kV cable. Since the cable was assessed with no offshore wind power production connected, the results were given in impacts per MW*km and not per kWh, at 215 kg CO_2-Eq/MW/km. The results for export cables (at 700 MW, the specified capacity of the NorNed cable) of this study converted to the same unit gives 543 kg/MW/km, which is a remarkably high increase when considering the inventory is basically the same. The improved IO part and the added processes of electricity and heat demand in this study are making a big difference. However, after subtracting the impacts of those changes, the difference is still remarkably high. Since both this study and Birkeland's study are only part of master thesis work, this comparison should not be given too much emphasis.

Complete system

For the complete system a hybrid LCA study of onshore wind power in the UK is considered a relevant comparison. The article is called "Application of Hybrid Life Cycle Approaches to Emerging Energy Technologies - The Case of Wind Power in the UK", by Sangwon Suh et al, published in 2011 [4]. Three methods were used in the study: process-based LCA, integrated hybrid LCA and IO-based hybrid LCA. The results of the integrated hybrid LCA will be used for comparison.

The scope of the study is, as stated in the article: "The Ecoinvent life cycle inventory (LCI) data include the construction, operation, and decommissioning of the concrete foundation of the wind turbine, the tower, the transformer, the assemblage, the rotor blades, and the mechanical and electronic components within the nacelle. A lifetime of 20 years and a capacity factor of 30% have been assumed in the Ecoinvent data set." The results are presented as allocated to foreground processes: cement, iron, steel etc.

To be able to compare the studies the scopes must be modified. Offshore and onshore foundations are very different and must be subtracted in both studies. Sea transport and grid connection is not present in the onshore assessment, so contribution from these components must be subtracted from the results of this study. Thus, the comparison is of what is called 'wind turbines' in study with t wind turbines less cement in Suh et al. Since different lifetimes and capacity factors are used, the results have to be altered too to make a relevant comparison. The results are shown in Table 19 below.

Table 19: Results of this study compared to Suh et al hybrid LCA of onshore wind power

	Original lifetime and capacity factor	20 y lifetime 30% capacity factor	25 y lifetime 37,24% capacity factor
This study	21,1	32,7	21,1
Suh et al	26,2	26,2	16,9

As the table shows, adjusted for lifetime and capacity factor, the results of this study are 25% higher. Compared to the results of IO-based hybrid LCA the difference is even larger, at 54%.

The value of such a comparison is certainly limited, primarily because the inventories and assumptions made in each study are very different. The wind turbines assessed in Suh et al is only at 2 MW and the wind turbines may be composed very differently. Nevertheless, the comparison may be an indication of the results being a bit high, perhaps because double counting has not been properly avoided.

It has to be mentioned that what is compared (wind turbines) is actually not the work of this study; but data obtained from the Havsul 1 project and used unmodified. The comparison is still considered relevant because it is first and foremost a comparison of methods. Since the IO part contribution share is almost equal for wind turbines and the grid (66% vs. 63%) and considering their quite similar material requirements, it is fair to say that if double counting is not properly avoided for the wind turbines it is probably not for the grid either.

To conclude the evaluation based on all aspects mentioned in this section, there is quite much uncertainty in the IO part of the assessment, both related to the data and the issue of double counting. Nevertheless, the results should be considered to be quite accurate, but, if anything, tending towards being in the higher range.

5 Offshore grid and wind energy in the North Sea – a good solution?

In this chapter different aspects of interregional meshed offshore grid and deep sea, far from shore offshore wind energy are discussed. The main focus is on the environmental costs and benefits, but the economics and the implications of installing an interregional grid for energy balance and grid storage are also considered.

5.1 Environmental costs and benefits

There are few things that it would be of relevance to compare the environmental impacts of the interregional meshed offshore grid with. Onshore grids are very different, and since it is only there for the purpose of transporting energy, it is not relevant to compare it to energy sources. In this section the scope of deep sea, far from shore wind energy will be compared with other energy technologies, but the corresponding contribution share of the grid to each impact category (Figure 27, section 4.2.2) is also considered on its own in order to try to analyze the influence of the grid to total impacts.

The energy sources used for comparison are natural gas combined cycle best available technology plant (NGCC BAT), natural gas plant with CCS (Carbon Capture and Storage) and coal plant with CCS. NGCC BAT numbers are obtained from Ecoinvent, both plants with CCS are obtained from a study of Singh et al [53]. The selection of energy sources used for comparison is primarily based on the notion that these technologies are the most realistic alternatives. With nuclear power phasing out, coal without CCS not an option if ambitious targets for CO_2-cuts are to be met and little unused hydropower potential left, there are not many other available competitive technologies to wind power left. Of course, there are the other intermittent renewable energy sources like solar, wave, tidal etc., but they are not considered to be in competition with wind power because *all* renewable energy technologies need to be developed to reach ambitious environmental targets. And, as discussed more in detail in chapter 3 Background, one kind of intermittent energy source can not serve grid demands entirely. For that, grid storage capability needs to be improved greatly. The question asked in the comparison made is: how much better is deep sea, far from shore offshore wind energy than the least emission intensive fossil fueled power plants? It should be noted that CCS is not yet commercialized and should be seen as a potential future technology. By the start of the WINDSPEED period (2020) it may be commercialized. The comparison is presented in two different ways, in Table 20 and Figure 32 below.

Table 20: Deep sea, far from shore offshore wind energy better with so many times. Green: offshore wind better, Orange: about equal impact, Red: other technology better.

	Natural gas, NGCC BAT	Natural gas, with CCS	Coal, with CCS
Climate Change	🟩 5,820	🟩 1,918	🟩 2,740
Freshwater Ecotoxicity	🟥 0,089	🟥 0,079	🟥 0,300
Human Toxicity	🟥 0,065	🟥 0,061	🟥 0,249
Marine Eutrophication	🟧 0,829	🟩 1,421	🟩 3,403
Metal Depletion	🟥 0,070		
Particulate Matter Formation	🟥 0,635	🟧 0,992	🟩 2,450
Photochemical Oxidant Formation	🟩 1,460	🟩 2,243	🟩 3,791
Terrestrial Acidification	🟧 0,797	🟧 1,249	🟩 2,747
Terrestrial Ecotoxicity	🟧 1,262	🟩 4,070	🟩 5,840

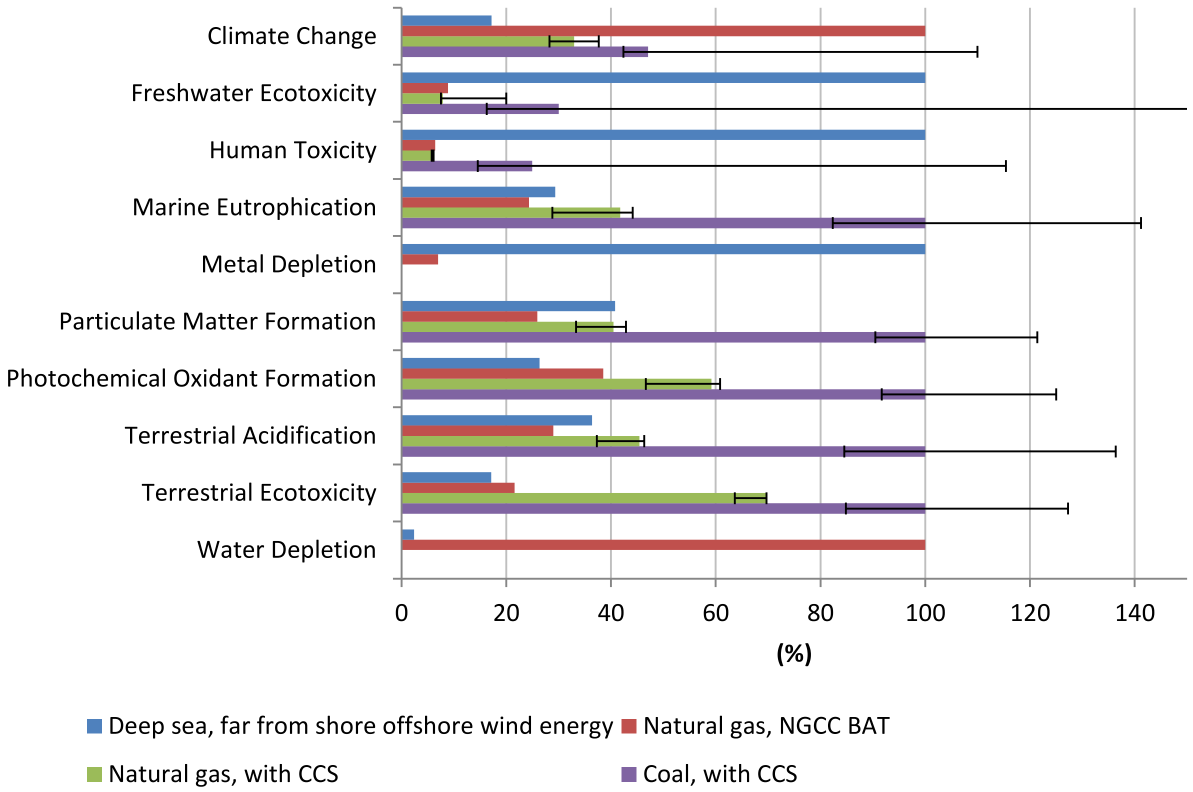

Figure 32: Deep sea, far from shore offshore wind energy compared with relevant fossil fueled energy technologies. The error bars represent variation between different possible CCS technologies.

In most environmental impact categories deep sea, far from shore offshore wind energy is the least impact intensive. But there are three sectors where it is the most impact intensive by a good margin: freshwater ecotoxicity, human toxicity and metal depletion. The difference in impacts is large, up to more than 16 times higher for offshore wind. As mentioned, there seems to be a high correlation between these three impact categories, which also agrees with the results of this comparison. The correlation indicates that high demand for metals lead to high freshwater ecotoxicity and human toxicity impacts. Of the total, the grid is responsible for 30 % freshwater ecotoxicity impacts, 46% of human toxicity impacts and 30% of metal depletion impacts, i.e. a significantly high contribution share to all three impact categories. There is also a noticeable higher particulate matter formation impact from offshore wind than from natural gas without CCS.

When focusing on climate change impacts, offshore wind is the best alternative. Natural gas with CCS is not that far behind, with almost twice as high impact, but it is important to note that this would depend on the so far unresolved problem of long term storage of CO_2. This problem is not present for offshore wind, as the emissions are avoided rather than captured. On the other hand, it may be surprising to find that a technology that is often referred to as carbon neutral by policy-makers is less than six times as climate change intensive as the most efficient natural gas power plants without CCS. Considering the benefits of lower investment costs and predictable energy supply of a natural gas power plant, how much one should be willing to pay for the reduced climate change impacts is a topic worthy of a discussion. What is a likely scenario in Europe is a large scale deployment of both natural gas and wind energy, as wind energy cannot adequately cover grid demands at all times.

In the end, what technology that is regarded as the most environmentally friendly depends on how the different impact categories are valued in relation to each other. If freshwater ecotoxicity and human toxicity is regarded as big problems and metals are considered an increasingly scarce resource, some fossil fuel energy sources may be regarded as more environmentally friendly than deep sea, far from shore offshore wind energy. But this valuation of impacts is not the most likely, primarily because there is so much focus on climate change today. In the context of valuating climate change impacts the most; deep sea, far from shore offshore wind energy is the most environmentally friendly technology of the ones compared.

There are other important environmental impacts caused by offshore wind energy that this study has not assessed, primarily influence on wildlife habitat (especially birds and marine wildlife), noise pollution and visual pollution. The last two should be considered as minor problems, because the wind farms are far from shore and will not be seen or heard from shore. How much these environmental impacts account for is dependent on the relative valuation of them in relation to the total environmental impacts.

Deep sea, far from shore offshore wind energy is, not surprisingly, quite much more impact intensive than onshore wind energy. It is almost exactly twice as high, according to the results of this study. Still, it is quite much better than fossil alternatives, at least in the context of emissions contributing to climate change. The most pronounced disadvantage of deep sea, far from shore offshore wind energy is the high demand for metal required to build it. Due to this demand, emissions causing freshwater ecotoxicity and human toxicity impacts are substantially higher than for other energy technologies.

5.2 The economics of offshore grid and wind energy

In this section the economic aspects of deep sea, far from shore wind energy will be calculated, compared and discussed. The main reason for this is that for all environmental considerations the cost aspect can not be ignored. In basic macroeconomics it is stated that the optimal balance between mitigation of emissions and the costs spent on mitigation is when the gain to society is maximized. In other words, optimal emission level is not necessarily zero emission and the environmental gains of a technology may be regarded as too expensive to achieve. Thus, it is relevant to see how much the environmental gain from deep sea, far from shore offshore energy actually costs to achieve. Since all investment costs for the system components[5] and operation and maintenance costs were obtained for the environmental assessment, a common method for calculating total costs of electricity production sources can be used. It is called Levelized Energy Costs (LEC) and is calculated by

$$LEC = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}} \qquad 5.1$$

where

- LEC = Average lifetime levelized electricity generation cost
- I_t = Investment costs in the year t
- M_t = Operations and maintenance costs in the year t
- F_t = Fuel costs in the year t
- E_t = Electricity generation in the year t
- r = Discount rate
- n = Life of the system

To use this formula investment costs is distributed over the 25 year lifetime and a discount rate of 10% is used. Fuel costs are obviously zero. The results are shown in Table 21 below, in 2010 €.

Table 21: Levelized Energy Costs of WINDSPEED Grand Design v05 scenario.

	LEC (€/MWh)	Share
Complete system	175,5	100 %
Wind farms only	152,3	87 %
Grid only	23,2	13 %

The grid only cost does not make sense on its own since it does not produce any energy, but the share it contributes total LEC is still relevant. To put the results in context the LEC of different energy sources in the UK as calculated in a Parsons Brinkerhof report are used for comparison [54] [55]. The results are shown in Table 22 below, in 2010 € using exchange rate 1.13 €/£.

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[5] The installation costs for the wind turbines are probably a bit low, since they are for the close to shore Havsul 1 wind farm. The increased cost of foundation installation at deep water is accounted for, but the increased transport necessary to reach far from shore is not. Other uncertainties related to costs are discussed in section 4.4.2.

Table 22: UK Levelized Energy Costs. [54]

	Cost range (€/MWh)	
	Low end	High end
Onshore wind	90	124
Offshore wind	170	237
Natural gas turbine, no CCS	62	124
Natural gas turbines with CCS	68	147
Coal with CCS	113	175
New nuclear	90	119

The UK levelized energy costs have been calculated using a 10% discount rate. The cost range is due to investment cost sensitivities, more precisely by a min/max range as expected by the marked. Scope is until grid connection. Generally, the results calculated in the report are quite high as compared to many other sources, for example the IEA. The reason for using these results is that comparing the costs of offshore wind energy in the UK is considered appropriate, as the WINDSPEED scenario is in the North Sea and has several wind farms in UK waters. For the comparison the focus will be on the low end of the cost range.

The wind farms only result has to be used for comparing the WINDSPEED results with the UK offshore wind results, making the scopes similar. WINDSPEED results of 152.3 €/MWh are a bit lower than the lower range of the UK results at 170 €/MWh. As mentioned, the UK results tend be high and are for deployment of the technology in 2006. The wind farm costs are for the future Havsul 1 project; some cost reduction is probable. Regardless of this, the results are a good indication that the costs used in this study for the environmental assessment are not too high, which could potentially have been a reason for the environmental impacts to tend towards being high.

For comparison with other technologies it is reasonable to include grid costs, as they can be expected to be much lower for all of the other energy sources. It is the most expensive technology, being more than almost three times more expensive than natural gas, with or without CCS, about 50% higher than coal with CCS, and almost twice as expensive as new nuclear and onshore wind. As a coincidence, deep sea, far from shore offshore wind energy is quite accurately both twice as expensive and climate change impact intensive as onshore wind.

When calculating the LEC it is easy to find out which energy technologies that are profitable and which aren't, it is simply to compare it to the present electricity price. The average electricity price in the UK in 2012 is less than 55 €/MWh [56] implying that none of the technologies above are considered a profitable investment today. Another UK report, by Mott MacDonald calculating as high LEC [57] explains it like this: "In the first few years of the new millennium, the spike in commodities prices, combined with insufficient investment in supply chains has meant that equipment prices for most power generation equipment and construction services are at historically high levels. This means that a plant ordered today would be expensive." Still, natural gas power plants are quite close to break-even; the gap between costs and electricity price is so small that it could easily be covered by subsidies or a small increase in electricity price. For deep sea, far from shore offshore wind energy that is not the case, leaving a big gap of 175.5-55 = 120.5 €/MWh, which makes the investment far from profitable. Much subsidies are required for a large scale deployment of deep sea, far from shore offshore wind energy.

There are some uncertainties related to calculating the LEC of a power plant over a 20-40 years lifetime, especially related to fuel prices. Another risk is carbon risk; the chance that carbon emissions might get heavily taxed or requires expensive quotas in the future. EWEA claims in their report "Economics of Wind Energy" [52] that it might be wrong to calculate the LEC with the same interest rate for fuel costs as for investment costs, claiming that historically the variation of fuel prices has been higher than what the standard LEC calculation accounts for. The results, using IEA LEC as a base level, are shown below in Figure 33.

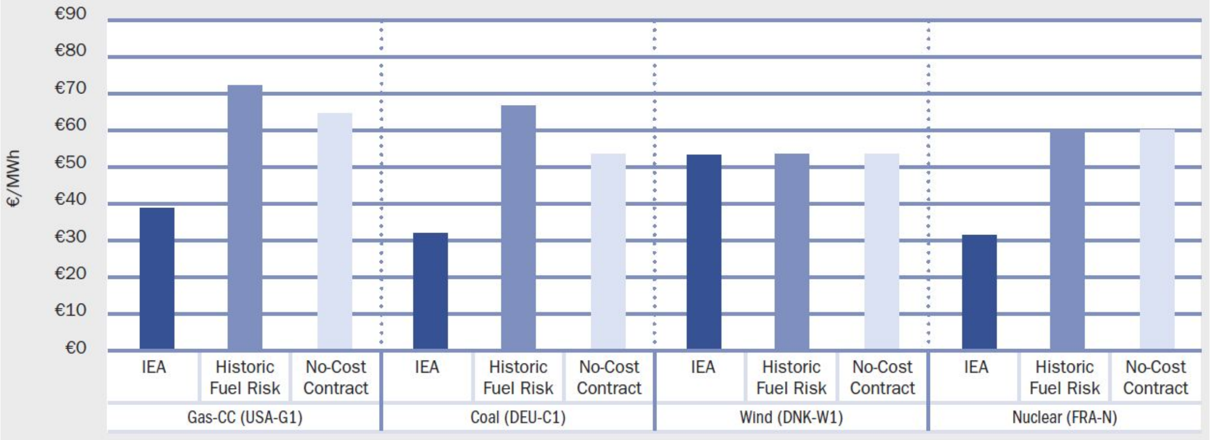

Figure 33: EWEA risk-adjusted power generating cost of gas, coal and wind power. [52]

The No-Cost Contract column shows the LEC when using a no-cost 40 year fuel purchase contract. The results show that the LEC of energy technologies using fuels more than doubles. By including the aspect of fuel price risk makes wind energy more competitive because other energy technologies become more expensive, but it does not make wind energy cheaper. Thus, 175.5 €/MWh is still very expensive regardless of whether fuel risks are taken into account or not. Deep sea, far from shore offshore wind energy is an energy technology that would require much subsidies for being deployed at a large scale, unless costs were to decrease dramatically.

In the end the question of whether or not to deploy deep sea, far from shore offshore wind energy at a large scale in the North Sea depends on how much the surrounding countries are willing to pay for the increased benefits of less environmental impacts and increased electricity transfer capacities between regions.

5.3 Implications for balancing and storage options

This last section is included in order to try to answer: how does the cost of an offshore grid compare to the benefit in terms of making renewable energy sources accessible and reducing the need for other balancing/storage options?

In pure economic cost-benefit terms, prior experiences tend to show that interregional HVDC cables are a net profit investment. The NorNed cable has turned out be highly profitable for the Norwegian and Dutch transmission firms Statnett and Tennet. In first six months of the cable's operation, the earnings were twice as high as forecasts predicted [58]. This might be the case with other interregional HVDC connections.

Generally, an interregional grid between countries in the North Sea is solely positive, with the main exception being the environmental impacts. Interregional cables result in

- Improving competition and market conditions in each region connected, increasing socioeconomic benefits.
- Improved balance management, increasing opportunities for integration of intermittent renewable energy.
- Increased security of supply. The risk of not meeting grid demands in each region connected decreases.

The environmental impacts caused by the Grand Design v05 grid are not easy to present in useful units when only looking at the grid. This is because the grid is primarily designed for the connection of offshore wind, and not interregional connections. Still, it gives a meaningful perspective to see how much the impacts of the grid contribute to total impacts for the complete system. The contribution share to climate change impacts of the complete system is 11.2%, a value that confirms that most of the impacts are due to other parts of the complete system and that the impacts caused by the grid itself is relatively low.

Implications for other balancing/storage options are generally only positive. An interregional grid decreases the need for other balancing/storage options, and would at the same time only be beneficial to the potential grid storage solutions. If large scale energy storage in the grid will someday become a part of the grid, it would only benefit from increased transfer capacity; by enabling both storage of energy produced far away from the location of the storage device and deliverance of energy to locations far away from the location of the storage device. The most common balancing power today is to run thermal power plants operating on part-load, which is neither efficient nor environmentally friendly. Including the aspect of a decreased need for thermal power part-load into the overall environmental impacts, it may actually be that the net environmental impacts of an interregional grid is positive.

6 Conclusion and further studies

The interest in offshore wind and interregional offshore grid connections has been continuously increasing in recent years. In response to that the potential environmental impacts they cause should be assessed. In this study it has been conducted a life cycle impact assessment of the impacts caused by an interregional meshed offshore grid and a deep sea, far from shore offshore wind energy in the North Sea. The primary results were obtained by using the tiered hybrid life cycle assessment method, but the two methods of process-based life cycle assessment and input-output analysis have also been used for complementary reasons. This study has used much generic data, not only numbers from the industry, and the tiered hybrid life cycle assessment method has some inherent disadvantages that it is uncertain whether have been overcome. As such, the results from this study should be considered only to be indicative rather than definite.

The environmental assessment of the interregional meshed offshore grid found that the largest contribution to environmental impacts is from manufacturing and installation of export cables. Sea transport required for installation of components and operation and maintenance contributes between 5 and 25 percent to most impact categories. The electrical equipment (converters, breakers and switchgear) required by the grid has a quite varying contribution, from almost none to some impact categories to about 35 percent to climate change impact. In the environmental assessment of the deep sea, far from shore offshore wind energy, the largest contributor to environmental impacts were found to be the wind turbines. But the other components required – deep sea foundations, grid and sea transport for installation, operation and maintenance – makes the environmental impacts caused by it around twice as high as for onshore wind energy installations. Total climate change impacts were found to be 42.9 g CO_2-Eq/kWh; the grid is responsible for 11, foundations 31 and sea transport 9 percent of that. The distribution of impacts to emission sources was almost identical for the two scopes; with electricity production, background transport and metals extraction and processing the largest contributors to climate change impact.

The largest impacts of deep sea, far from shore offshore wind energy as compared to other relevant energy sources are to the impact categories freshwater ecotoxicity, human toxicity and metal depletion. The impacts to these categories are many times larger, up to almost 20 times, compared to other relevant fossil fueled energy sources. The impacts to all the other impact categories are substantially lower.

To judge how the *total* environmental impacts are in comparison to other energy sources are thus not straight forward, it depends on how the impact categories are valued in relation to each other. But, as climate change impact often is considered the most important impact category today; deep sea, far from shore offshore wind energy comes out considerably better than relevant fossil alternatives.

Taking all aspects into account, the overall recommendation to policy makers is a clear go-ahead for large scale deployment of an interregional offshore grid. The overall benefits outweigh the environmental impact by a good margin. In fact there may be net environmental benefits because of a possible decrease in fossil energy production onshore. As for large scale deployment of deep sea, far from shore offshore wind energy, a general recommendation is harder to make. There is low climate change impact, but high freshwater ecotoxicity, human toxicity and metal depletion impacts and the monetary costs are quite much higher than for alternatives. In the end, it depends on how much "society" is willing to pay for cuts in climate change emissions.

Further studies

There are many ways to improve the assessment conducted in this study; primarily by obtaining more accurate data, expanding the scope and refining the methods used. Specifically:

- Obtain more accurate inventory and cost data, best source is probably from the industry.
- Improved mapping of sea transport.
- Expand the scope to include the required expansion of, and other implications, for the onshore AC transmission grid.
- Assess other grid scenarios than the ones proposed by the WINDSPEED project, for example of scenarios in the OffshoreGrid project.
- Include estimations of the decreased need for fossil fueled thermal balancing power.
- Include estimations of how the energy production mix in each country is affected by an interregional grid and large scale deployment of offshore wind.
- Investigate the composition of the relevant EXIOPOL sectors to assess if double counting has been avoided properly.
- Use other methods for avoiding double counting, for comparison.
- Use other hybrid assessment methods, for comparison.

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Appendices

Appendix A – Matlab script

Following are the entire Matlab script used to calculate the results obtained in this study. The equations used are explained in chapter 2 Methods, and how the numbers in the foreground system of the A-matrix were obtained is described in chapter 3 Background. All the foreground data is imported from excel-files with the command xlsread. The actual excel-files are uploaded as digital attachments to this thesis, but all data are also given in this thesis, either in chapter 4 Results or in Appendix B. The matrices for EXIOPOL, Ecoinvent and Recipe are all stored in the Databases.mat, which is imported. The resulting matrices have been copied to excel (results_rn.xlsx) and worked on there to produce the results presented in chapter 4.

The script is actually divided into three separate files for practical reasons, but is here given as one file:

```
% Matlab script start
load ('Databases.mat'); % Import of all necessary already established
databases:
% EXIOPOL (A_exiopol), Ecoinvent process matrix (A_Ecoinvent), Ecoinvent
% stressor matrix (F), (modified to take into account EXIPOL stressors too)
% and the ReCiPe charachterization matrix (F).

%% Choose method: 1=tiered hybrid LCA, 2=LCA, 3=IOA, 4=IO-part
method=1;

%% Imports of foreground data
A_f=xlsread('MatLab Import.xlsx', 'A_f', 'D6:BV4431'); % A_f contains
% A_ff (foreground inter-process requirements matrix) and
% A_nf (matrix of requirements from the foreground to Ecoinvent)
y_functional_unit=xlsread('MatLab Import.xlsx', 'y', 'E7:L77');
y_demand=xlsread('MatLab Import.xlsx', 'y_factors', 'D7:K77');
D_em_class=xlsread('MatLab Import.xlsx', 'P_class', 'C2:K4427');

A_f(isnan(A_f))=0; % Making sure all empty fields are 0
D_em_class(isnan(D_em_class))=0; % Making sure all empty fields are 0

% Create the A_pf (matrix of requirements from the foregtround
% to EXIOPOL) matrices required for the different methods
A_pf_zero=xlsread('MatLab Import.xlsx', 'Abf_zero', 'D3:BV260');
A_pf_org=xlsread('MatLab Import.xlsx', 'Abf_org', 'D4:BV261');
A_pf_no0=A_exiopol*A_pf_org;
A_pf_with0=A_pf_no0.*A_pf_zero;

%% Construct A-matrix
[m n]=size(A_f);
A=zeros(m,m);
A(1:m,1:71)=A_f;
A(72:329,72:329)=A_exiopol;
A(330:m,330:m)=A_ecoinvent;

% Depending on method chosen, the A-matrix is adjusted accordingly:
if method==1
    A(72:329,1:71)=A_pf_with0;
elseif method==2
```

```
    A(72:329,1:71)=0; % To calculate a "pure" LCA
elseif method==3
    A(72:329,1:71)=A_pf_no0; % To calculate a "pure" IOA
    A(330:4426,1:71)=0;
elseif method==4
    A(330:4426,1:71)=0; % To calculate IO-part only
end

%% Finding total output
I=eye(size(A));
L=inv(I-A);

y=zeros(4426,8);
y(1:71,1:8)=y_functional_unit.*y_demand;

x=L*y;

%% Emissions and impacts
e=F*x; % Calculates the vector of total emissions generated for a given
external demand
d=C*e; % Vector of total impacts for each scenario

%% Emissions allocated to foreground processes
temp=C*F*L;
D_pro_ff_w_ITD20=temp*diag(y(:,1));
D_pro_ff_w_ITDx0=temp*diag(y(:,2));
D_pro_ff_w_v05=temp*diag(y(:,3));
D_pro_ff_w_v06=temp*diag(y(:,4));
D_pro_ff_g_ITD20=temp*diag(y(:,5));
D_pro_ff_g_ITDx0=temp*diag(y(:,6));
D_pro_ff_g_v05=temp*diag(y(:,7));
D_pro_ff_g_v06=temp*diag(y(:,8));

% Emissions allocated to emssision sources
temp2=C*F;
D_pro_w_ITD20=temp2*diag(x(:,1))*D_em_class;
D_pro_w_ITDx0=temp2*diag(x(:,2))*D_em_class;
D_pro_w_v05=temp2*diag(x(:,3))*D_em_class;
D_pro_w_v06=temp2*diag(x(:,4))*D_em_class;
D_pro_g_ITD20=temp2*diag(x(:,5))*D_em_class;
D_pro_g_ITDx0=temp2*diag(x(:,6))*D_em_class;
D_pro_g_v05=temp2*diag(x(:,7))*D_em_class;
D_pro_g_v06=temp2*diag(x(:,8))*D_em_class;


%% SF6 leakage CO2-eq contribution. Not added to IOA or IO-part.
%% Is added to the contribution of offshore and onshore switchgear
if method==1||2
    char=22800; % ReCiPe's characterization factor of SF6 to CO2-eq
    leak=29.6; % leakage of CO2 for a GIS switchgear over entire lifetime,
in kg
    offshore_add=char*leak*y(16,1:8);
    onshore_add=char*leak*y(18,1:8);
    for j=1:8
        d(2,j)=d(2,j)+offshore_add(1,j)+onshore_add(1,j);
    end

    % To D_pro_ff
    D_pro_ff_w_ITD20(2,16)=D_pro_ff_w_ITD20(2,16)+offshore_add(1,1);
```

```
    D_pro_ff_w_ITD20(2,18)=D_pro_ff_w_ITD20(2,18)+onshore_add(1,1);
    D_pro_ff_w_ITDx0(2,16)=D_pro_ff_w_ITDx0(2,16)+offshore_add(1,2);
    D_pro_ff_w_ITDx0(2,18)=D_pro_ff_w_ITDx0(2,18)+onshore_add(1,2);
    D_pro_ff_w_v05(2,16)=D_pro_ff_w_v05(2,16)+offshore_add(1,3);
    D_pro_ff_w_v05(2,18)=D_pro_ff_w_v05(2,18)+onshore_add(1,3);
    D_pro_ff_w_v06(2,16)=D_pro_ff_w_v06(2,16)+offshore_add(1,4);
    D_pro_ff_w_v06(2,18)=D_pro_ff_w_v06(2,18)+onshore_add(1,4);
    D_pro_ff_g_ITD20(2,16)=D_pro_ff_g_ITD20(2,16)+offshore_add(1,5);
    D_pro_ff_g_ITD20(2,18)=D_pro_ff_g_ITD20(2,18)+onshore_add(1,5);
    D_pro_ff_g_ITDx0(2,16)=D_pro_ff_g_ITDx0(2,16)+offshore_add(1,6);
    D_pro_ff_g_ITDx0(2,18)=D_pro_ff_g_ITDx0(2,18)+onshore_add(1,6);
    D_pro_ff_g_v05(2,16)=D_pro_ff_g_v05(2,16)+offshore_add(1,7);
    D_pro_ff_g_v05(2,18)=D_pro_ff_g_v05(2,18)+onshore_add(1,7);
    D_pro_ff_g_v06(2,16)=D_pro_ff_g_v06(2,16)+offshore_add(1,8);
    D_pro_ff_g_v06(2,18)=D_pro_ff_g_v06(2,18)+onshore_add(1,8);

    % To D_pro

D_pro_w_ITD20(2,7)=D_pro_w_ITD20(2,7)+onshore_add(1,1)+offshore_add(1,1);
D_pro_w_ITDx0(2,7)=D_pro_w_ITDx0(2,7)+onshore_add(1,2)+offshore_add(1,2);
D_pro_w_v05(2,7)=D_pro_w_v05(2,7)+onshore_add(1,3)+offshore_add(1,3);
D_pro_w_v06(2,7)=D_pro_w_v06(2,7)+onshore_add(1,4)+offshore_add(1,4);
D_pro_g_ITD20(2,7)=D_pro_g_ITD20(2,7)+onshore_add(1,5)+offshore_add(1,5);
D_pro_g_ITDx0(2,7)=D_pro_g_ITDx0(2,7)+onshore_add(1,6)+offshore_add(1,6);
D_pro_g_v05(2,7)=D_pro_g_v05(2,7)+onshore_add(1,7)+offshore_add(1,7);
D_pro_g_v06(2,7)=D_pro_g_v06(2,7)+onshore_add(1,8)+offshore_add(1,8);
end

%% Calculates total impact divided by total energy produced for each
%% scenario
TWh=[4228 4732 7188 6951 4228 4732 7188 6951];
for i=1:18
    d_g(i,:)=d(i,:)./(TWh*1000*1000); %returns g CO2-eq/kWh
end

disp('analysis done');
% Matlab script end
```

Appendix B – Additional tables used in calculations

Table 23: IO-part cost allocation. Allocated the same way for hybrid LCA and IOA.

EXIOPOL sector	Wind turbine foundation	Array cables	Export cables	Offshore substation substructure	Offshore substation	Offshore substation DC breakers and switchgear	Onshore substation equipment	Onshore substation DC breakers and switchgear	Operation and maintenance
Manufacture of cement, lime and plaster	0,2			0,2					
Manufacture of fabricated metal products, except machinery and equipment (28)	0,1			0,1	0,1		0,1		
Manufacture of electrical machinery and apparatus n.e.c. (31)		0,7	0,4		0,85	1	0,85	1	0,2
Construction (45)	0,4	0,2	0,3	0,4	0,05		0,05		0,5
Sale, maintenance, repair of motor vehicles, motor vehicles parts, motorcycles, motor cycles parts and accessoires									
Sea and coastal water transport	0,2	0,1	0,2	0,2					0,1
Other business activities (74)	0,1		0,1	0,1					0,2

Table 24: IO-sectors set to 0 to avoid double counting. Done to both EU and ROW region.

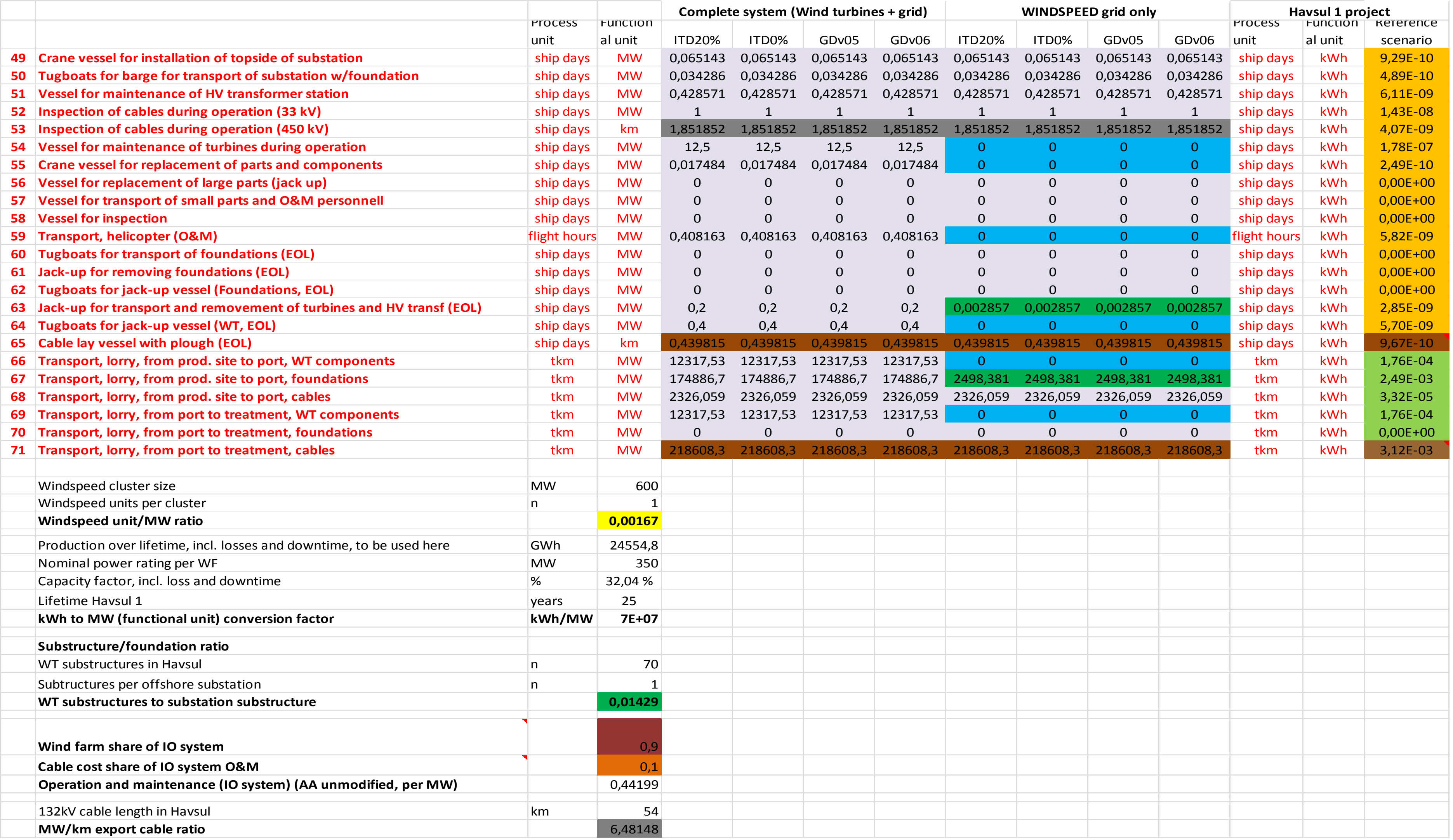
EXIOPOL sector	Wind turbine foundation	Array cables	Export cables	Offshore substation substructure	Offshore substation	Offshore substation DC breakers and switchgear	Onshore substation equipment	Onshore substation DC breakers and switchgear	Operation and maintenance
Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials (20)	1	1	1	1	0	0	0	0	1
Manufacture of pulp, paper and paper products (21)	1	1	0	1	0	1	0	1	1
Manufacture of kerosene, including kerosene type jet fuel	1	1	1	1	1	1	1	1	0
Manufacture of gas oils	1	1	1	1	1	1	1	1	0
Manufacture of fuel oils n.e.c.	1	1	1	1	1	1	1	1	0
Manufacture of other petroleum products	1	1	1	1	0	1	0	1	1
Manufacture of chemicals and chemical products (24)	1	0	0	1	1	0	1	0	1
Manufacture of rubber and plastic products (25)	1	1	1	1	0	0	0	0	1
Manufacture of glass and glass products	1	1	1	1	1	1	1	1	0
Manufacture of cement, lime and plaster	0	1	1	0	1	1	1	1	1
Manufacture of basic iron and steel and of ferro-alloys and first products thereof	0	0	0	0	0	1	0	1	0
Aluminium production	1	1	1	1	0	0	0	0	1
Lead, zinc and tin production	1	0	0	1	1	1	1	1	1
Copper production	1	0	0	1	0	0	0	0	0
Casting of metals	1	1	1	1	0	1	0	1	1
Production of electricity by coal	1	0	0	1	0	0	0	0	1
Production of electricity by gas	1	0	0	1	0	0	0	0	1
Production of electricity by nuclear	1	0	0	1	0	0	0	0	1
Production of electricity by hydro	1	0	0	1	0	0	0	0	1
Production of electricity by wind	1	0	0	1	0	0	0	0	1
Production of electricity nec, including biomass and waste	1	0	0	1	0	0	0	0	1
Manufacture of gas; distribution of gaseous fuels through mains	1	0	0	1	0	0	0	0	1

Table 25: Transport sectors included in the foreground and their corresponding Ecoinvent process, as obtained unmodified by the Havsul 1 project.

		Excavator	Barge for excavator	Barge for disposal of seabed material	Vessel for transport of rock for stone bed	Vessel for dumping of rock for stone bed	Tugboats for transport of foundations	Jack-up vessel for installation of foundations	Tugboats for jack-up for installation of foundation	Vessel for transport of rock for scour protection	Vessel for dumping of rock for scour protection
		ship days	ship days	ship days	ship days	ship days	ship days	ship days	ship days	ship days	ship days
transport, helicopter/ GLO/ h	h										
transport, lorry >32t, EURO5/ RER/ tkm	tkm										
operation, barge/ RER/ tkm	tkm	218019,7665					707466,7541		707466,7541		
operation, transoceanic freight ship/ OCE/ tkm	tkm		526134,0845	526134,0845	3288338,028	1946696,113		789201,1268		3288338,028	1946696,113
		Jack-up vessel for transport and installation of WTs	Tugboats for jack-up for installation of WTs	Cable lay vessel with plough for installation of 33 kV cables	Cable lay vessel with plough for installation of 132 kV cables	Vessel for tie-in of 33 kV cables for installation	Jack-up vessel for installation of substation foundation	Tugboats for jack-up vessel (installation HVtransf)	Crane vessel for installation of topside of substation	Tugboats for barge for transport of substation w/foundation	Vessel for maintenance of HV transformer station
		ship days	ship days	ship days	ship days	ship days	ship days	ship days	ship days	ship days	ship days
transport, helicopter/ GLO/ h	h										
transport, lorry >32t, EURO5/ RER/ tkm	tkm										
operation, barge/ RER/ tkm	tkm		707466,7541	982788,9085	982788,9085	796855,8717		707466,7541		707466,7541	218019,7665
operation, transoceanic freight ship/ OCE/ tkm	tkm	789201,1268					789201,1268		1446868,732		
		Inspection of cables during operation (33 kV)	Inspection of cables during operation (132 kV)	Vessel for maintenance of turbines during operation	Crane vessel for replacement of parts and components	Vessel for replacement of large parts (jack up)	Vessel for transport of small parts and O&M personnell	Vessel for inspection	Transport, helicopter (O&M)	Tugboats for transport of foundations (EOL)	Jack-up for removing foundations (EOL)
		ship days	ship days	ship days	ship days	ship days	ship days	ship days	flight hours	ship days	ship days
transport, helicopter/ GLO/ h	h								1		
transport, lorry >32t, EURO5/ RER/ tkm	tkm										
operation, barge/ RER/ tkm	tkm	218019,7665	218019,7665	218019,7665		218019,7665	290693,022	290693,022		707466,7541	
operation, transoceanic freight ship/ OCE/ tkm	tkm				1446868,732						789201,1268
		Tugboats for jack-up vessel (Foundations, EOL)	Jack-up for transport and removement of turbines and HV transf (EOL)	Tugboats for jack-up vessel (WT, EOL)	Cable lay vessel with plough (EOL)	Transport, lorry, from prod. site to port, WT components	Transport, lorry, from prod. site to port, foundations	Transport, lorry, from prod. site to port, cables	Transport, lorry, from port to treatment, WT components	Transport, lorry, from port to treatment, foundations	Transport, lorry, from port to treatment, cables
		ship days	ship days	ship days	ship days	tkm	tkm	tkm	tkm	tkm	tkm
transport, helicopter/ GLO/ h	h										
transport, lorry >32t, EURO5/ RER/ tkm	tkm					1	1	1	1	1	1
operation, barge/ RER/ tkm	tkm	707466,7541		707466,7541	982788,9085						
operation, transoceanic freight ship/ OCE/ tkm	tkm		789201,1268								

Table 26: The y-vectors used for all scenarios. The y-vector used in the Havsul 1 project to the right.

				Complete system (Wind turbines + grid)				WINDSPEED grid only				Havsul 1 project		
		Process unit	Functional unit	ITD20%	ITD0%	GDv05	GDv06	ITD20%	ITD0%	GDv05	GDv06	Process unit	Functional unit	Reference scenario
1	**Wind turbine, assembly, misc.**	unit	MW	0,2	0,2	0,2	0,2	0	0	0	0	unit	kWh	2,85E-09
2	**Rotor blades**	unit	MW	0,2	0,2	0,2	0,2	0	0	0	0	unit	kWh	2,85E-09
3	**Hub, incl. nose cone**	unit	MW	0,2	0,2	0,2	0,2	0	0	0	0	unit	kWh	2,85E-09
4	**Bed frame/plate**	unit	MW	0,2	0,2	0,2	0,2	0	0	0	0	unit	kWh	2,85E-09
5	**Generator**	unit	MW	0,2	0,2	0,2	0,2	0	0	0	0	unit	kWh	2,85E-09
6	**Gearbox**	unit	MW	0,2	0,2	0,2	0,2	0	0	0	0	unit	kWh	2,85E-09
7	**LV transformer**	unit	MW	0,2	0,2	0,2	0,2	0	0	0	0	unit	kWh	2,85E-09
8	**Main shaft**	unit	MW	0,2	0,2	0,2	0,2	0	0	0	0	unit	kWh	2,85E-09
9	**Cover**	unit	MW	0,2	0,2	0,2	0,2	0	0	0	0	unit	kWh	2,85E-09
10	**Tower**	unit	MW	0,2	0,2	0,2	0,2	0	0	0	0	unit	kWh	2,85E-09
11	**Foundation wind turbine**	unit	MW	0,2	0,2	0,2	0,2	0	0	0	0			
12	**Array cables**	unit	MW	0,001667	0,001667	0,001667	0,001667	0,001667	0,001667	0,001667	0,001667			
13	**Export cables**	km	km	1	1	1	1	1	1	1	1			
14	**Offshore substation substructure**	unit	MW	0,001667	0,001667	0,001667	0,001667	0,001667	0,001667	0,001667	0,001667			
15	**Offshore substation equipment**	unit	MW	0,001667	0,001667	0,001667	0,001667	0,001667	0,001667	0,001667	0,001667			
16	**Offshore substation DC breakers and switchgear**	unit	MW	0,001667	0,001667	0,001667	0,001667	0,001667	0,001667	0,001667	0,001667			
17	**Onshore substation equipment**	unit	unit	1	1	1	1	1	1	1	1			
18	**Onshore substation DC breakers and switchgear**	unit	unit	1	1	1	1	1	1	1	1			
19	**Operation and maintenance (Grid Only)**	10^6 Euro	MW	0,044199	0,044199	0,044199	0,044199	0,044199	0,044199	0,044199	0,044199			
20	**Installation (IO system)**	106 Euro	MW	0,366248	0,366248	0,366248	0,366248	0	0	0	0	106 Euro	kWh	5,80E-09
21	**Operation and maintenance (IO system)**	106 Euro	MW	0,397788	0,397788	0,397788	0,397788	0	0	0	0	106 Euro	kWh	7,00E-09
22	**Decommissioning (IO system)**	106 Euro	MW	0,183124	0,183124	0,183124	0,183124	0	0	0	0	106 Euro	kWh	2,90E-09
23	**External cabling (IO system)**	106 Euro	MW	0	0	0	0	0	0	0	0	106 Euro	kWh	2,69E-09
24	**Other capital costs**	106 Euro	MW	0,289143	0,289143	0,289143	0,289143	0	0	0	0	106 Euro	kWh	4,58E-09
25	**Other variable costs**	106 Euro	MW	0,441987	0,441987	0,441987	0,441987	0	0	0	0	106 Euro	kWh	7,00E-09
26	**Replacement, total, min**	unit	MW	0	0	0	0	0	0	0	0	unit	kWh	0,00E+00
27	**Replacement, total, reference**	unit	MW	2,425	2,425	2,425	2,425	0	0	0	0	unit	kWh	3,46E-08
28	**Replacement, total, max**	unit	MW	0	0	0	0	0	0	0	0	unit	kWh	0,00E+00
29	**Replacement, heavy component**	unit	MW	0	0	0	0	0	0	0	0	unit	kWh	0,00E+00
30	**Replacement, large part**	unit	MW	0	0	0	0	0	0	0	0	unit	kWh	0,00E+00
31	**Replacement, small part**	unit	MW	0	0	0	0	0	0	0	0	unit	kWh	0,00E+00
32	**Excavator**	ship days	MW	0,6	0,6	0,6	0,6	0,008571	0,008571	0,008571	0,008571	ship days	kWh	8,55E-09
33	**Barge for excavator**	ship days	MW	0,6	0,6	0,6	0,6	0,008571	0,008571	0,008571	0,008571	ship days	kWh	8,55E-09
34	**Barge for disposal of seabed material**	ship days	MW	0,45	0,45	0,45	0,45	0,006429	0,006429	0,006429	0,006429	ship days	kWh	6,41E-09
35	**Vessel for transport of rock for stone bed**	ship days	MW	0,91125	0,91125	0,91125	0,91125	0,013018	0,013018	0,013018	0,013018	ship days	kWh	1,30E-08
36	**Vessel for dumping of rock for stone bed**	ship days	MW	0,6	0,6	0,6	0,6	0,008571	0,008571	0,008571	0,008571	ship days	kWh	8,55E-09
37	**Tugboats for transport of foundations**	ship days	MW	0,4	0,4	0,4	0,4	0,005714	0,005714	0,005714	0,005714	ship days	kWh	5,70E-09
38	**Jack-up vessel for installation of foundations**	ship days	MW	0,2	0,2	0,2	0,2	0,002857	0,002857	0,002857	0,002857	ship days	kWh	2,85E-09
39	**Tugboats for jack-up for installation of foundation**	ship days	MW	0,4	0,4	0,4	0,4	0,005714	0,005714	0,005714	0,005714	ship days	kWh	5,70E-09
40	**Vessel for transport of rock for scour protection**	ship days	MW	0,91125	0,91125	0,91125	0,91125	0	0	0	0	ship days	kWh	1,30E-08
41	**Vessel for dumping of rock for scour protection**	ship days	MW	0,6	0,6	0,6	0,6	0	0	0	0	ship days	kWh	8,55E-09
42	**Jack-up vessel for transport and installation of WTs**	ship days	MW	0,2	0,2	0,2	0,2	0	0	0	0	ship days	kWh	2,85E-09
43	**Tugboats for jack-up for installation of WTs**	ship days	MW	0,4	0,4	0,4	0,4	0	0	0	0	ship days	kWh	5,70E-09
44	**Cable lay vessel with plough for installation of 33 kV cables**	ship days	MW	0,04	0,04	0,04	0,04	0,04	0,04	0,04	0,04	ship days	kWh	5,70E-10
45	**Cable lay vessel with plough for installation of 450 kV cables**	ship days	km	0,092593	0,092593	0,092593	0,092593	0,092593	0,092593	0,092593	0,092593	ship days	kWh	2,04E-10
46	**Vessel for tie-in of 33 kV cables for installation**	ship days	MW	0,248571	0,248571	0,248571	0,248571	0,248571	0,248571	0,248571	0,248571	ship days	kWh	3,54E-09
47	**Jack-up vessel for installation of substation foundation**	ship days	MW	0,065143	0,065143	0,065143	0,065143	0,065143	0,065143	0,065143	0,065143	ship days	kWh	9,29E-10
48	**Tugboats for jack-up vessel (installation HVtransf)**	ship days	MW	0,034286	0,034286	0,034286	0,034286	0,034286	0,034286	0,034286	0,034286	ship days	kWh	4,89E-10

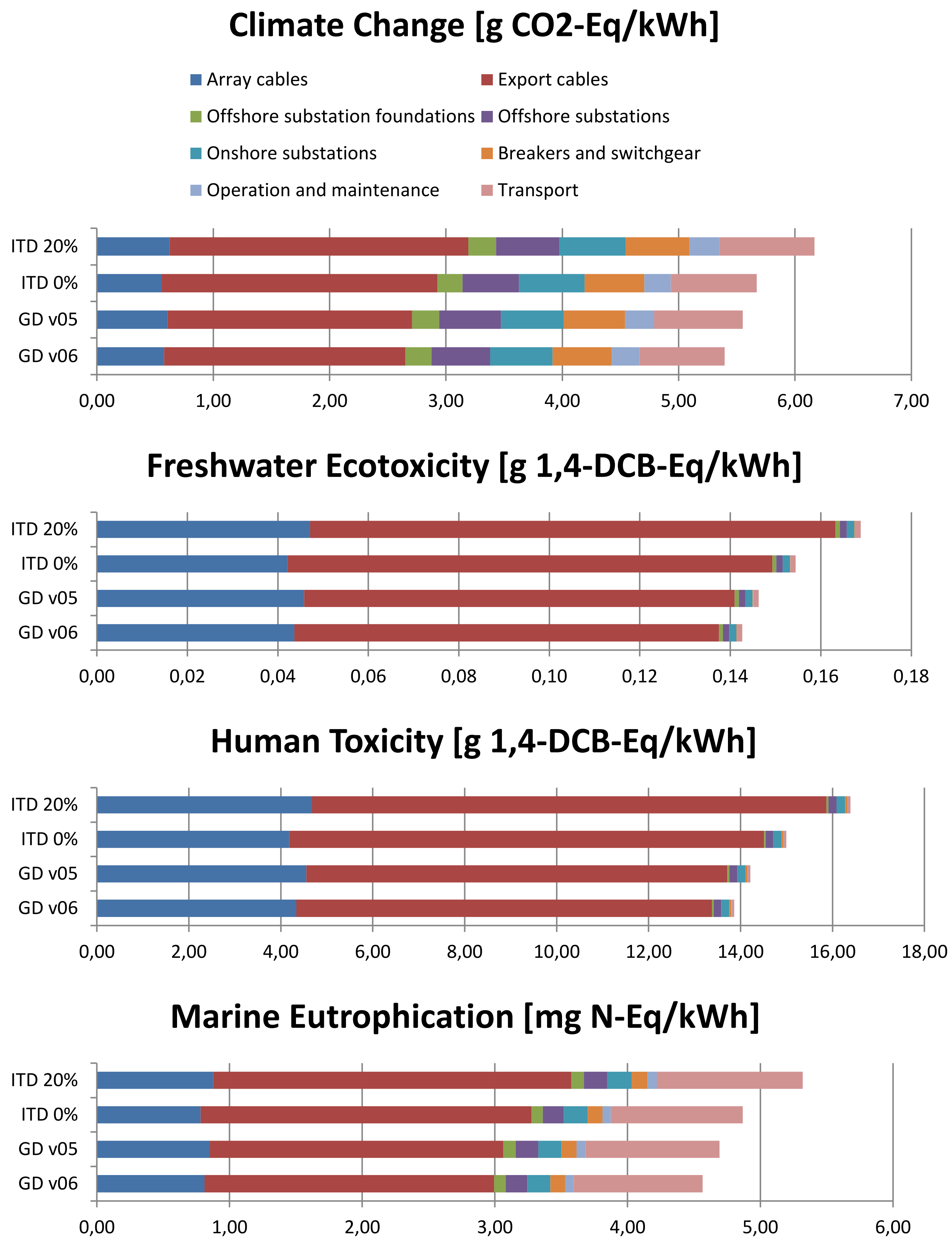


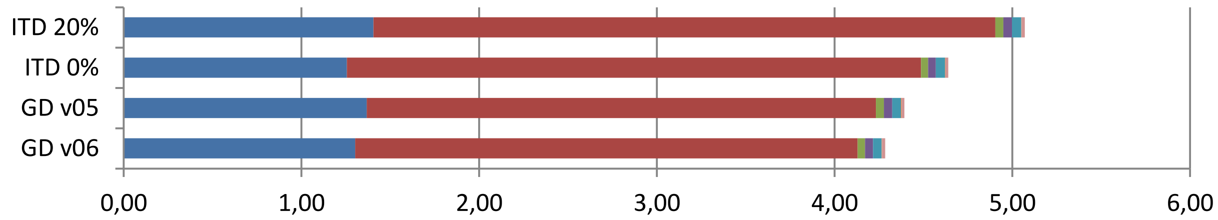
				Complete system (Wind turbines + grid)				WINDSPEED grid only				Havsul 1 project		
		Process unit	Functional unit	ITD20%	ITD0%	GDv05	GDv06	ITD20%	ITD0%	GDv05	GDv06	Process unit	Functional unit	Reference scenario
49	**Crane vessel for installation of topside of substation**	ship days	MW	0,065143	0,065143	0,065143	0,065143	0,065143	0,065143	0,065143	0,065143	ship days	kWh	9,29E-10
50	**Tugboats for barge for transport of substation w/foundation**	ship days	MW	0,034286	0,034286	0,034286	0,034286	0,034286	0,034286	0,034286	0,034286	ship days	kWh	4,89E-10
51	**Vessel for maintenance of HV transformer station**	ship days	MW	0,428571	0,428571	0,428571	0,428571	0,428571	0,428571	0,428571	0,428571	ship days	kWh	6,11E-09
52	**Inspection of cables during operation (33 kV)**	ship days	MW	1	1	1	1	1	1	1	1	ship days	kWh	1,43E-08
53	**Inspection of cables during operation (450 kV)**	ship days	km	1,851852	1,851852	1,851852	1,851852	1,851852	1,851852	1,851852	1,851852	ship days	kWh	4,07E-09
54	**Vessel for maintenance of turbines during operation**	ship days	MW	12,5	12,5	12,5	12,5	0	0	0	0	ship days	kWh	1,78E-07
55	**Crane vessel for replacement of parts and components**	ship days	MW	0,017484	0,017484	0,017484	0,017484	0	0	0	0	ship days	kWh	2,49E-10
56	**Vessel for replacement of large parts (jack up)**	ship days	MW	0	0	0	0	0	0	0	0	ship days	kWh	0,00E+00
57	**Vessel for transport of small parts and O&M personnell**	ship days	MW	0	0	0	0	0	0	0	0	ship days	kWh	0,00E+00
58	**Vessel for inspection**	ship days	MW	0	0	0	0	0	0	0	0	ship days	kWh	0,00E+00
59	**Transport, helicopter (O&M)**	flight hours	MW	0,408163	0,408163	0,408163	0,408163	0	0	0	0	flight hours	kWh	5,82E-09
60	**Tugboats for transport of foundations (EOL)**	ship days	MW	0	0	0	0	0	0	0	0	ship days	kWh	0,00E+00
61	**Jack-up for removing foundations (EOL)**	ship days	MW	0	0	0	0	0	0	0	0	ship days	kWh	0,00E+00
62	**Tugboats for jack-up vessel (Foundations, EOL)**	ship days	MW	0	0	0	0	0	0	0	0	ship days	kWh	0,00E+00
63	**Jack-up for transport and removement of turbines and HV transf (EOL)**	ship days	MW	0,2	0,2	0,2	0,2	0,002857	0,002857	0,002857	0,002857	ship days	kWh	2,85E-09
64	**Tugboats for jack-up vessel (WT, EOL)**	ship days	MW	0,4	0,4	0,4	0,4	0	0	0	0	ship days	kWh	5,70E-09
65	**Cable lay vessel with plough (EOL)**	ship days	km	0,439815	0,439815	0,439815	0,439815	0,439815	0,439815	0,439815	0,439815	ship days	kWh	9,67E-10
66	**Transport, lorry, from prod. site to port, WT components**	tkm	MW	12317,53	12317,53	12317,53	12317,53	0	0	0	0	tkm	kWh	1,76E-04
67	**Transport, lorry, from prod. site to port, foundations**	tkm	MW	174886,7	174886,7	174886,7	174886,7	2498,381	2498,381	2498,381	2498,381	tkm	kWh	2,49E-03
68	**Transport, lorry, from prod. site to port, cables**	tkm	MW	2326,059	2326,059	2326,059	2326,059	2326,059	2326,059	2326,059	2326,059	tkm	kWh	3,32E-05
69	**Transport, lorry, from port to treatment, WT components**	tkm	MW	12317,53	12317,53	12317,53	12317,53	0	0	0	0	tkm	kWh	1,76E-04
70	**Transport, lorry, from port to treatment, foundations**	tkm	MW	0	0	0	0	0	0	0	0	tkm	kWh	0,00E+00
71	**Transport, lorry, from port to treatment, cables**	tkm	MW	218608,3	218608,3	218608,3	218608,3	218608,3	218608,3	218608,3	218608,3	tkm	kWh	3,12E-03
	Windspeed cluster size	MW	600											
	Windspeed units per cluster	n	1											
	Windspeed unit/MW ratio		**0,00167**											
	Production over lifetime, incl. losses and downtime, to be used here	GWh	24554,8											
	Nominal power rating per WF	MW	350											
	Capacity factor, incl. loss and downtime	%	32,04 %											
	Lifetime Havsul 1	years	25											
	kWh to MW (functional unit) conversion factor	**kWh/MW**	**7E+07**											
	Substructure/foundation ratio													
	WT substructures in Havsul	n	70											
	Subtructures per offshore substation	n	1											
	WT substructures to substation substructure		**0,01429**											
	Wind farm share of IO system		0,9											
	Cable cost share of IO system O&M		0,1											
	Operation and maintenance (IO system) (AA unmodified, per MW)		0,44199											
	132kV cable length in Havsul	km	54											
	MW/km export cable ratio		6,48148											

The y-vectors are given per functional unit, so they have to be multiplied with the final demand in each scenario (see section 4.1). The Havsul 1 project y-vector is also given since it is the basis for the y-vector used in this study. At the bottom are some numbers used to alter the Havsul 1 project basis, so that it could be used in this study. The rows in yellow are the processes obtained in this study

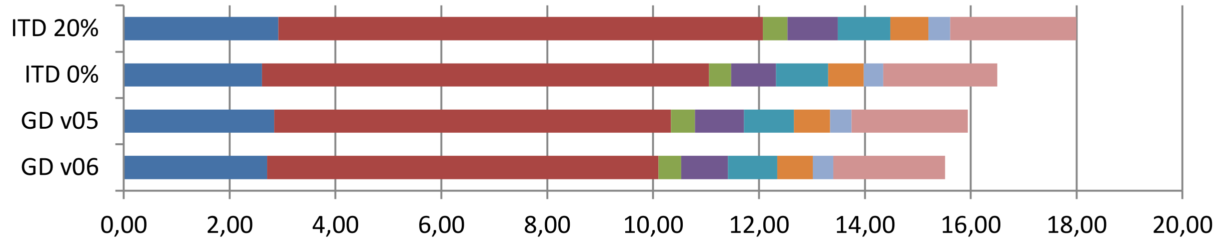
Appendix C – Results for all grid scenarios, all impact categories

Figure 34: Environmental impacts for all grid scenarios, per unit energy produced.

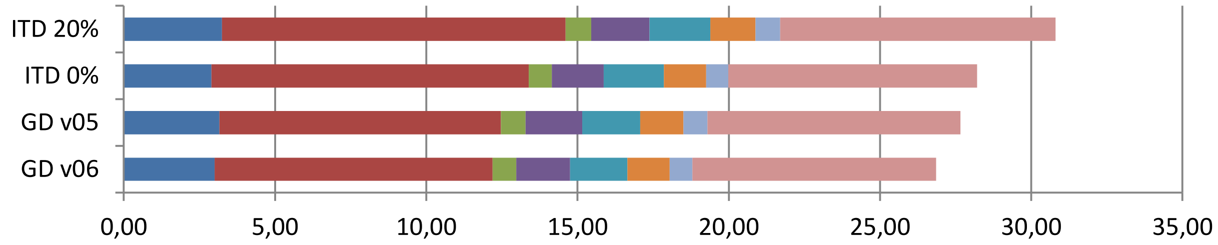




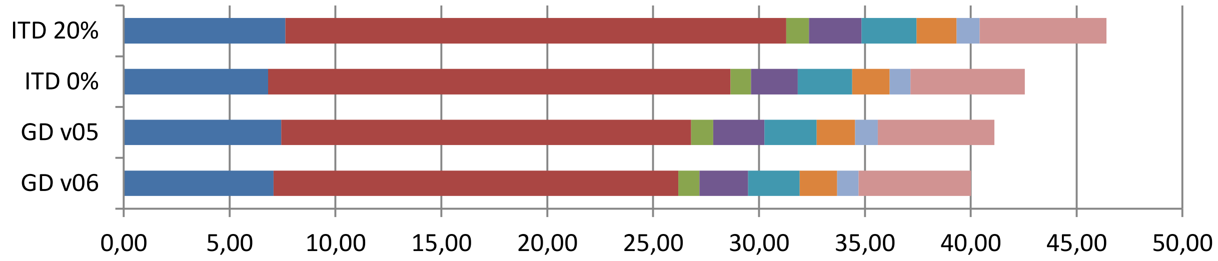
Metal Depletion [g Fe-Eq/kWh]



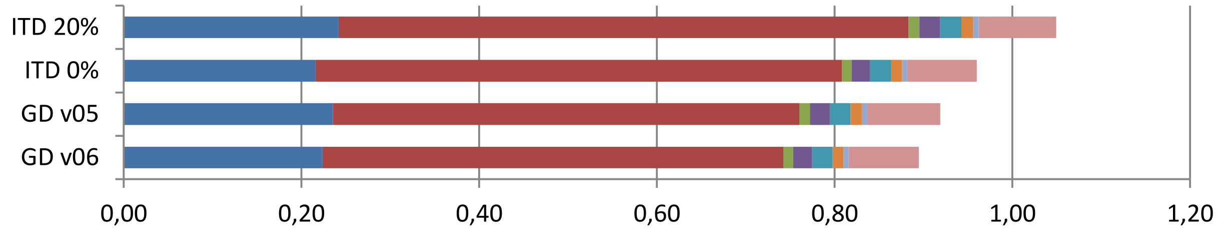
Particulate Matter Formation [mg PM10-Eq/kWh]



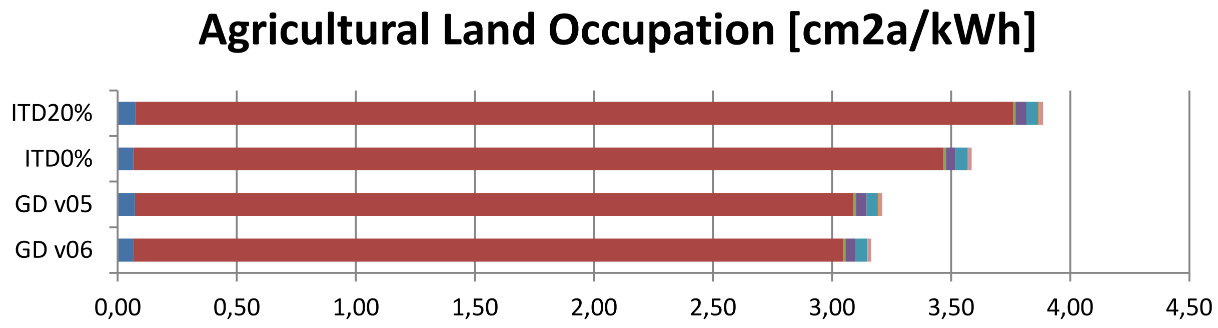
Photochemical Oxidant Formation [mg NMVOC/kWh]

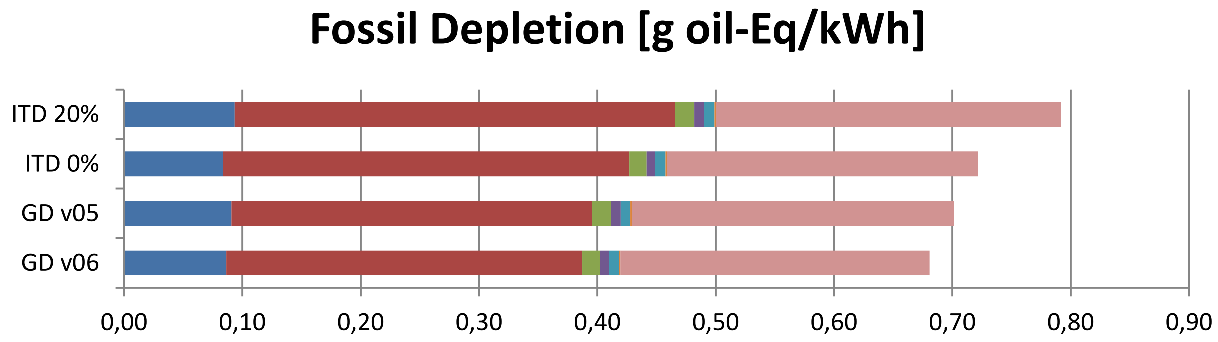


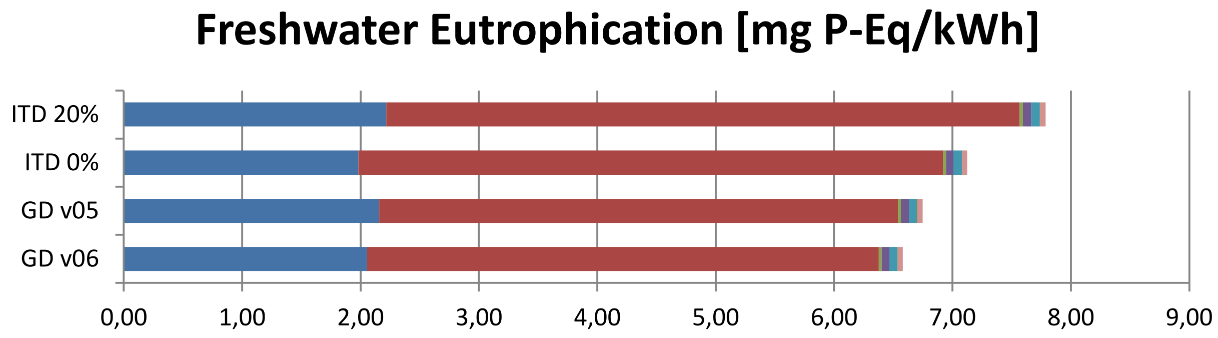
Terrestrial Acidification [mg SO2-Eq/kWh]

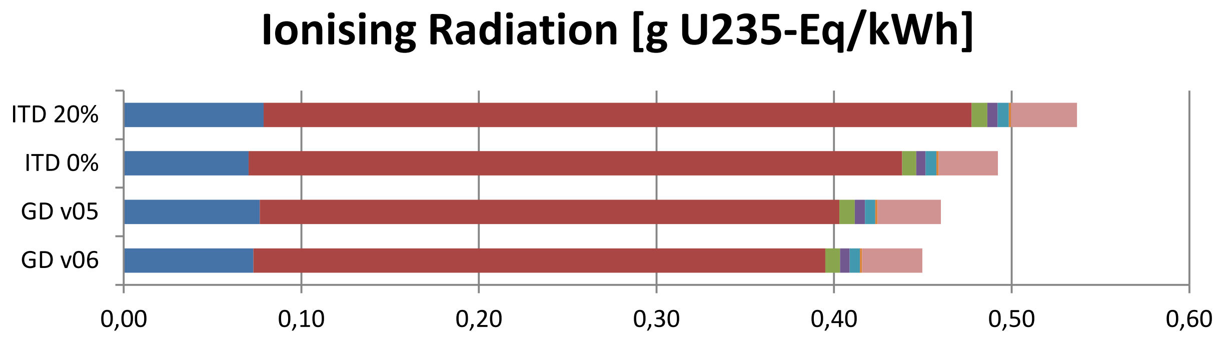


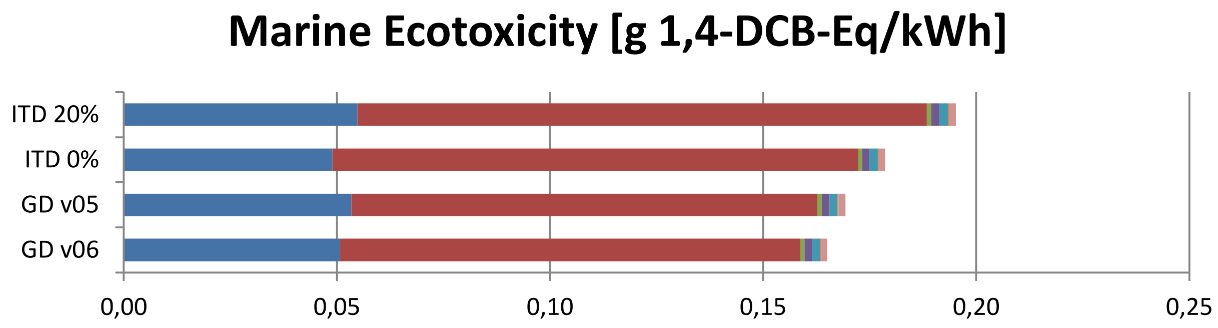
Terrestrial Ecotoxicity [mg 1,4-DCB-Eq/kWh]

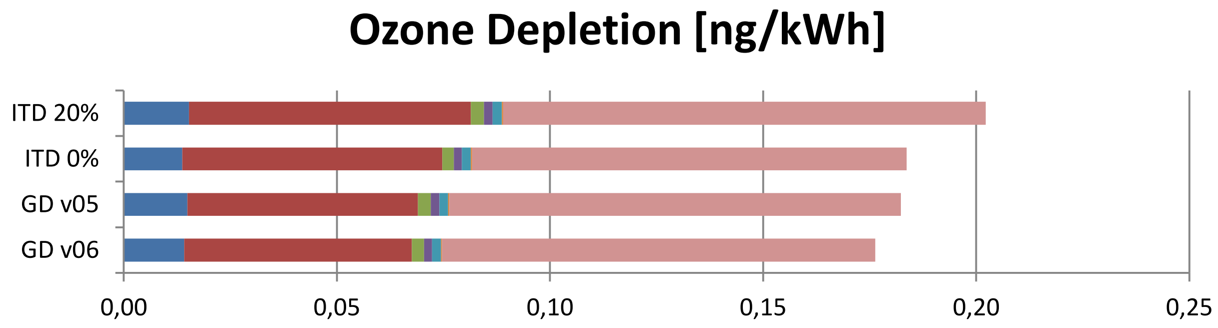

Agricultural Land Occupation [cm2a/kWh]
ITD20%
ITD0%
GD v05
GD v06
0,00
0,50
1,00
1,50
2,00
2,50
3,00
3,50
4,00
4,50

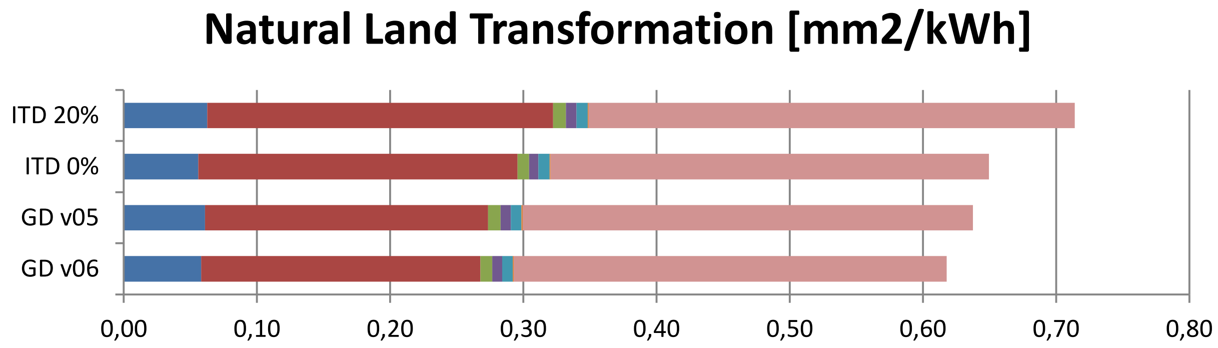

Fossil Depletion [g oil-Eq/kWh]
ITD 20%
ITD 0%
GD v05
GD v06
0,00
0,10
0,20
0,30
0,40
0,50
0,60
0,70
0,80
0,90

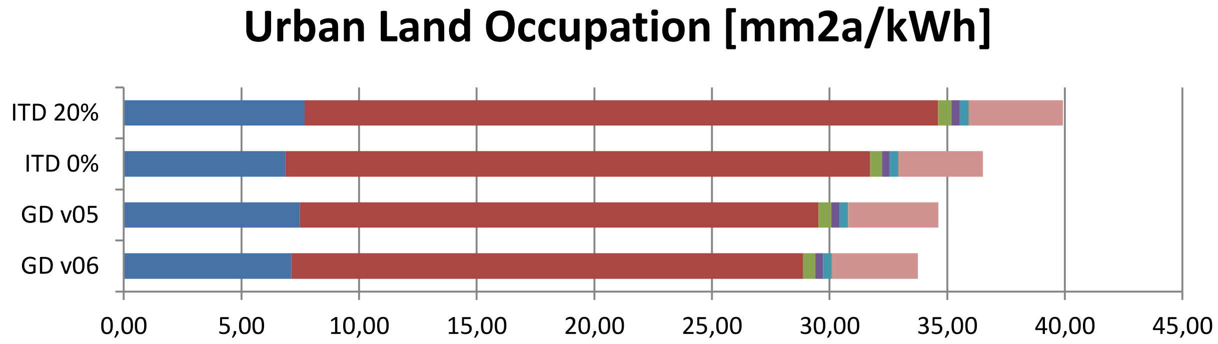

Freshwater Eutrophication [mg P-Eq/kWh]
ITD 20%
ITD 0%
GD v05
GD v06
0,00
1,00
2,00
3,00
4,00
5,00
6,00
7,00
8,00
9,00

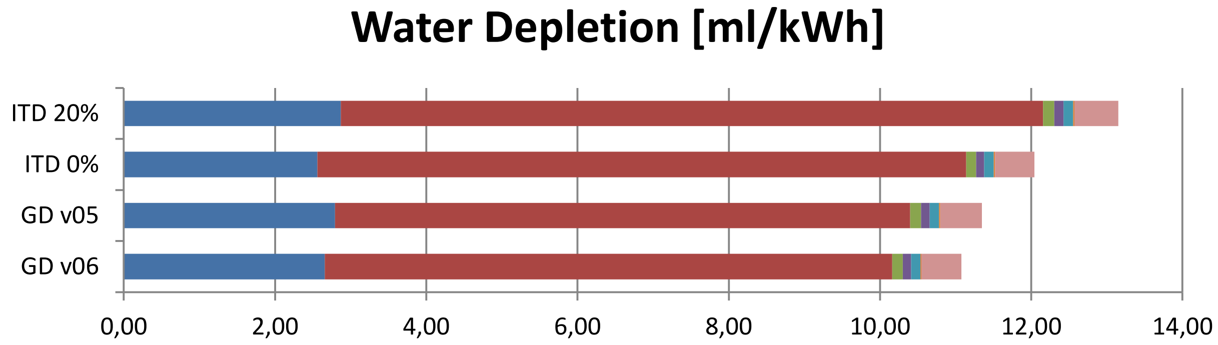

Ionising Radiation [g U235-Eq/kWh]
ITD 20%
ITD 0%
GD v05
GD v06
0,00
0,10
0,20
0,30
0,40
0,50
0,60


Marine Ecotoxicity [g 1,4-DCB-Eq/kWh]
ITD 20%
ITD 0%
GD v05
GD v06
0,00
0,05
0,10
0,15
0,20
0,25









As seen, it is very little difference in impacts per unit energy produced. The same is valid for the results for the complete system scenarios as well, and is thus not included. Generally, the second most ambitious scenario (GD v06) is the least impact intensive scenario, followed closely by the GD v05.

Appendix D – Additional technology figures

Foundation types

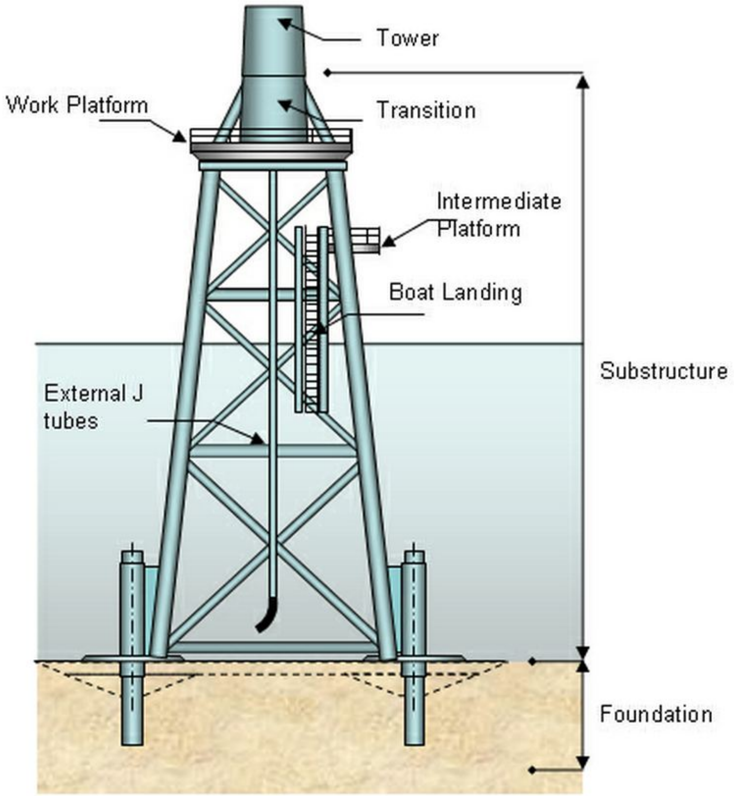


Figure 35: Jacket structure [42]

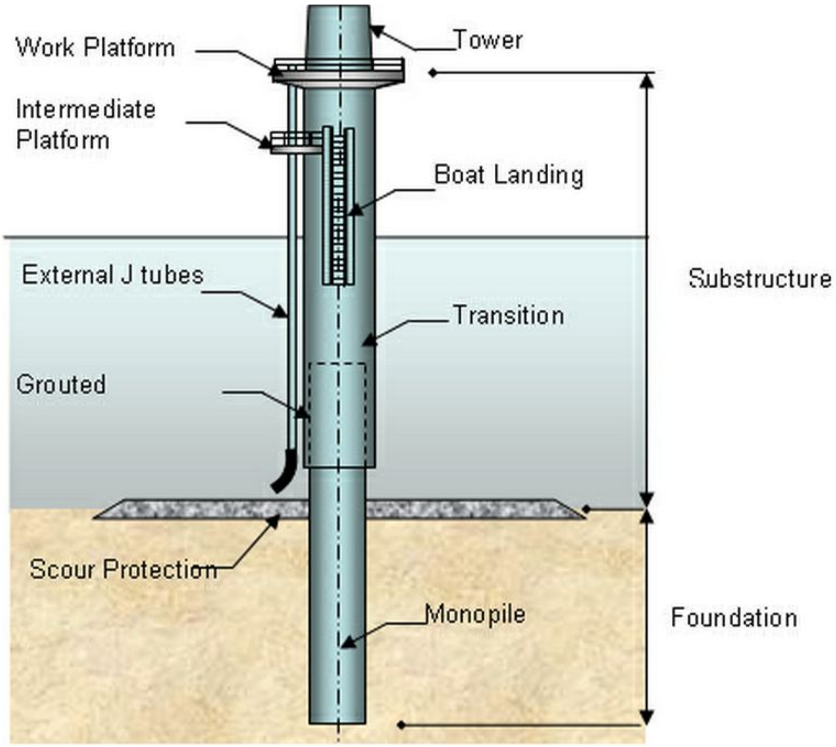


Figure 36: Monopile [42]

Appendix E – Additional WINDSPEED figures

WINDSPEED costs as given in D2.2

Table 27: Original WINDSPEED costs as given in D2.2

Summary of HVDC export system costs for a 600MW cluster (2010 M€)	**Mobilization** (per 600 MW cable)	Supply	Installation	Totals	Unit
Array cables		65,5	15,4	80,9	per 600 MW wind farm
Offshore substation equipment		133	6,6	139,6	per 600 MW wind farm
Offshore substation structure		10,4	17,2	27,6	per 600 MW wind farm
DC breakers and switchgear offshore		55,7		55,7	per 600 MW wind farm
Subsea export cables 600 MW	5	0,2	0,18	0,76	per km cable laid
Onshore substation		129,6	6,5	136,1	per 600 MW connection point
DC breakers and switchgear onshore		45,4		45,4	per 600 MW connection point

Array cables were calculated using formula on page 32 in D2.2 assuming a 2 MW/km2 density.

Tech learning graph, cost reduction

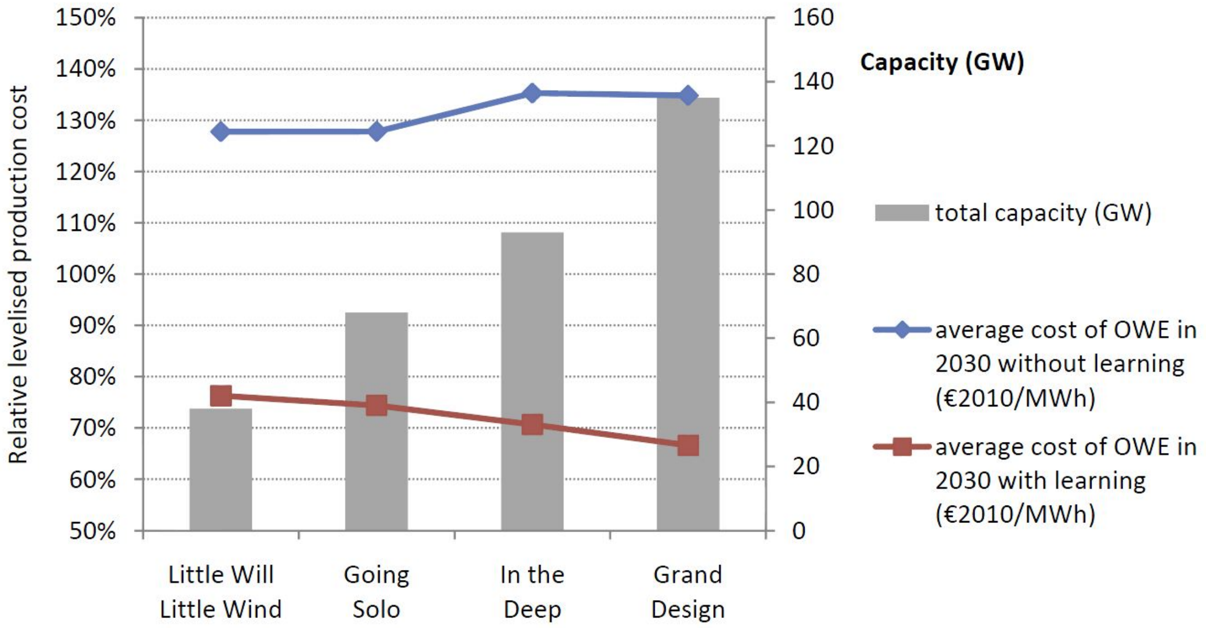


Figure 37: WINDSPEED cost reduction as a consequence of technology learning scenarios. The most optimistic are assumed in this study. [source: D6.1]

Spatial and economic potential found by the DSS tool

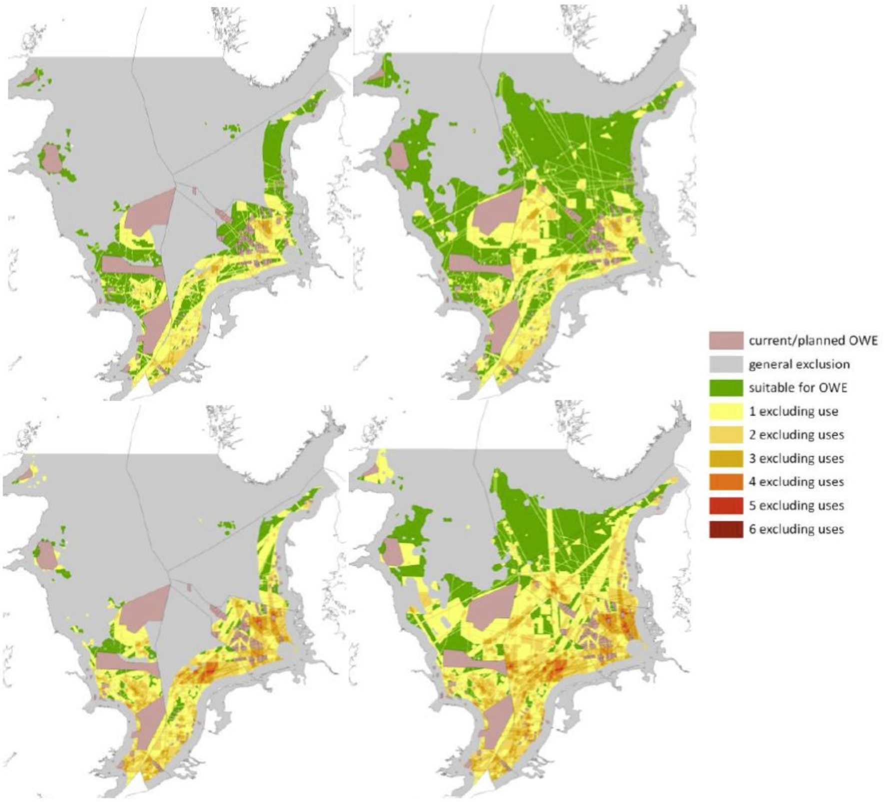


Figure 38: Map of spatial potential in the North Sea for each scenario as found by the DSS tool: Little Will Little Wind [bottom left], Going Solo [top left], In The Deep [bottom right] and Grand Design [top right].

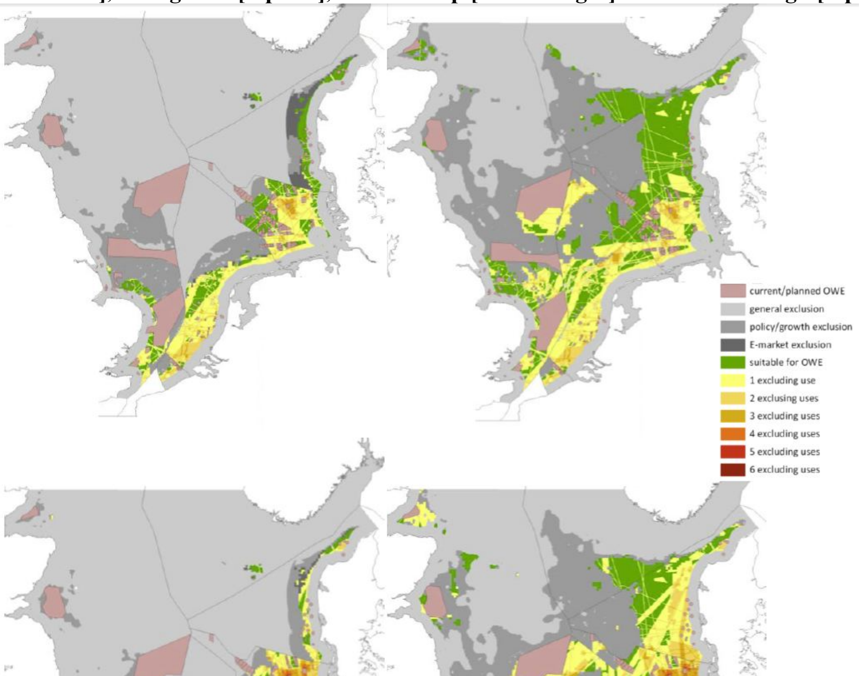


Figure 39: Map of economic potential in the North Sea for each scenario as found by the DSS tool: Little Will Little Wind [bottom left], Going Solo [top left], In The Deep [bottom right] and Grand Design [top right].

In The Deep 20% maps

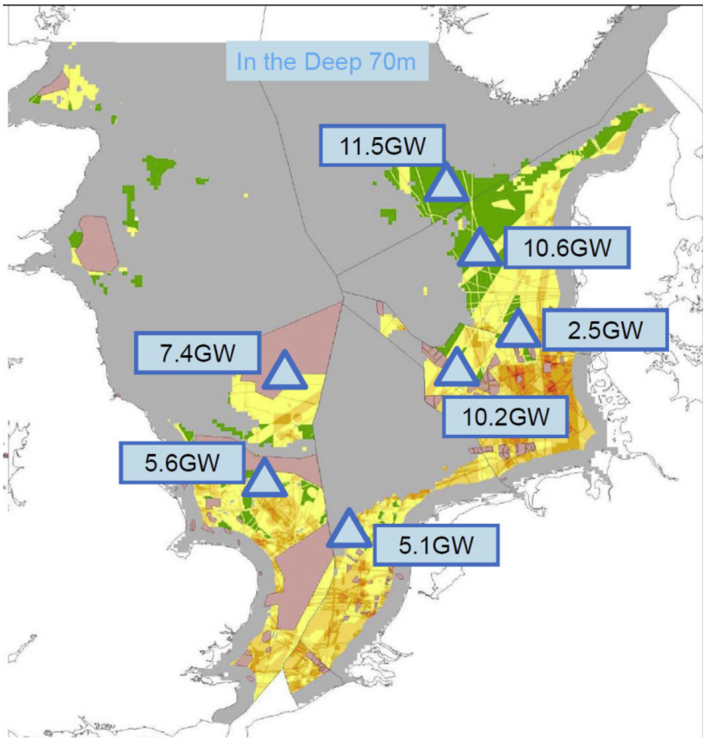


Figure 40: In The Deep 20% scenario total effect from wind farm clusters

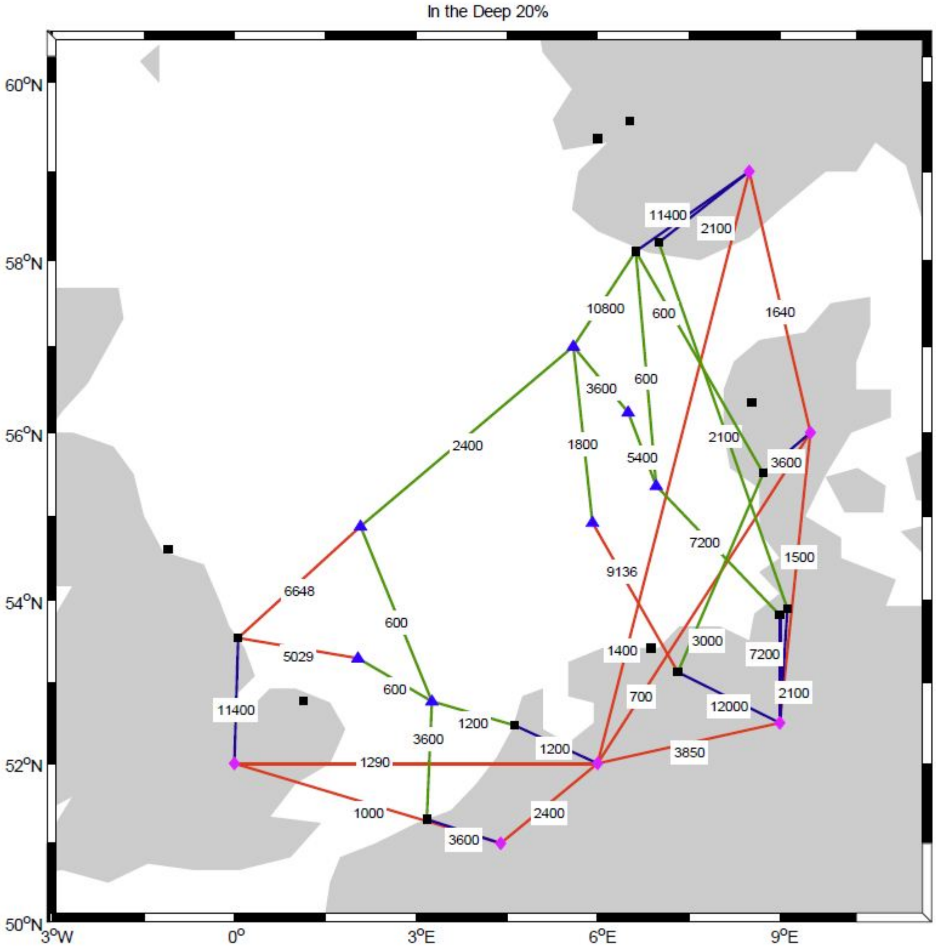


Figure 41: In The Deep 20% scenario cable capacities. Triangles represent wind farm clusters and squares represent onshore connection points

In The Deep 0% maps

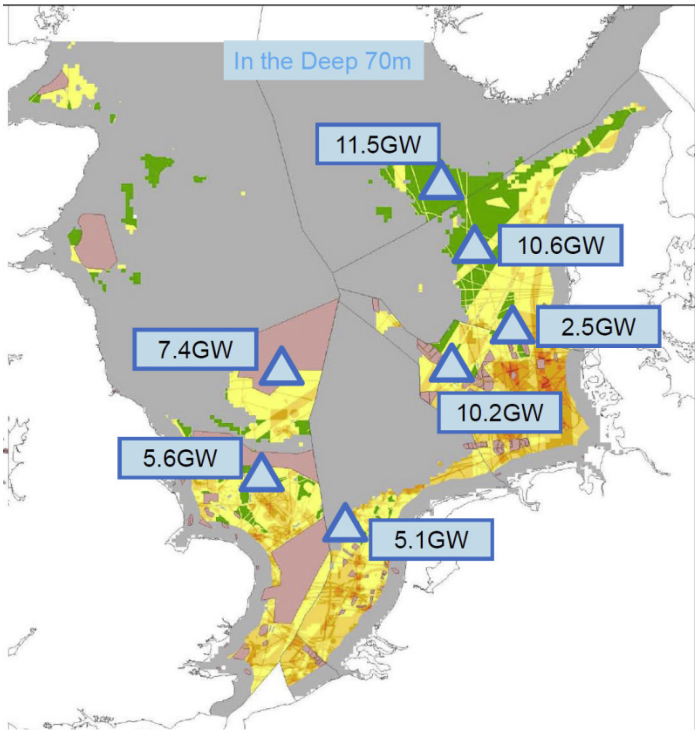


Figure 42: In The Deep 0% scenario total effect from wind farm clusters

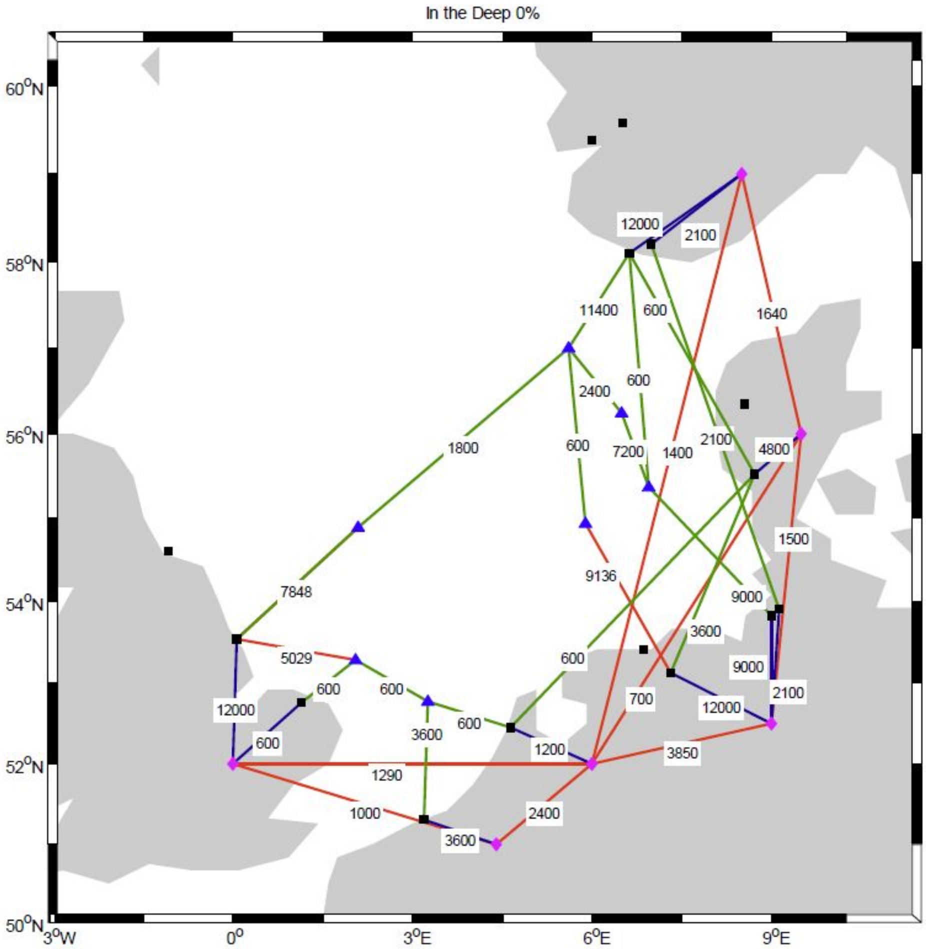


Figure 43: In The Deep 0% scenario cable capacities. Triangles represent wind farm clusters and squares represent onshore connection points

Grand Design v06 maps

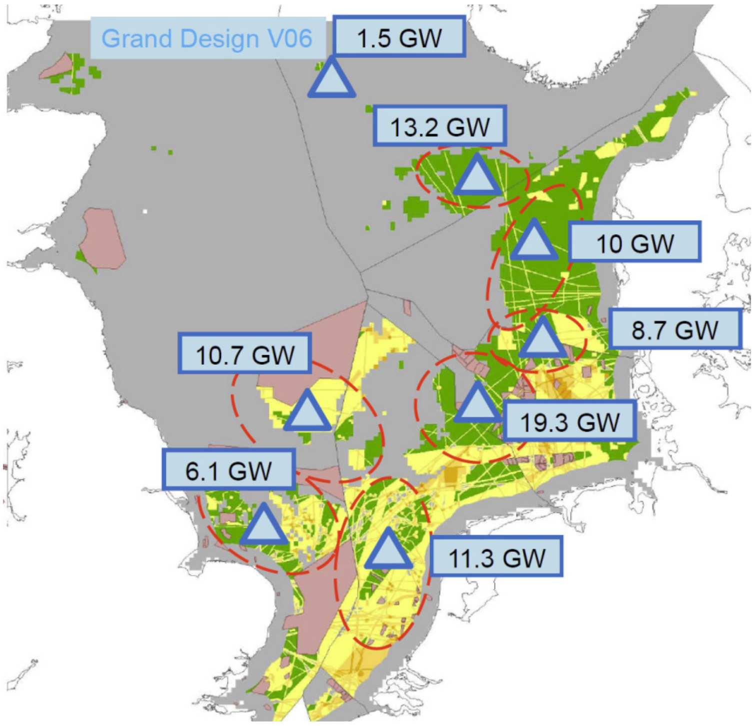


Figure 44: Grand Design v06 scenario total effect from wind farm clusters

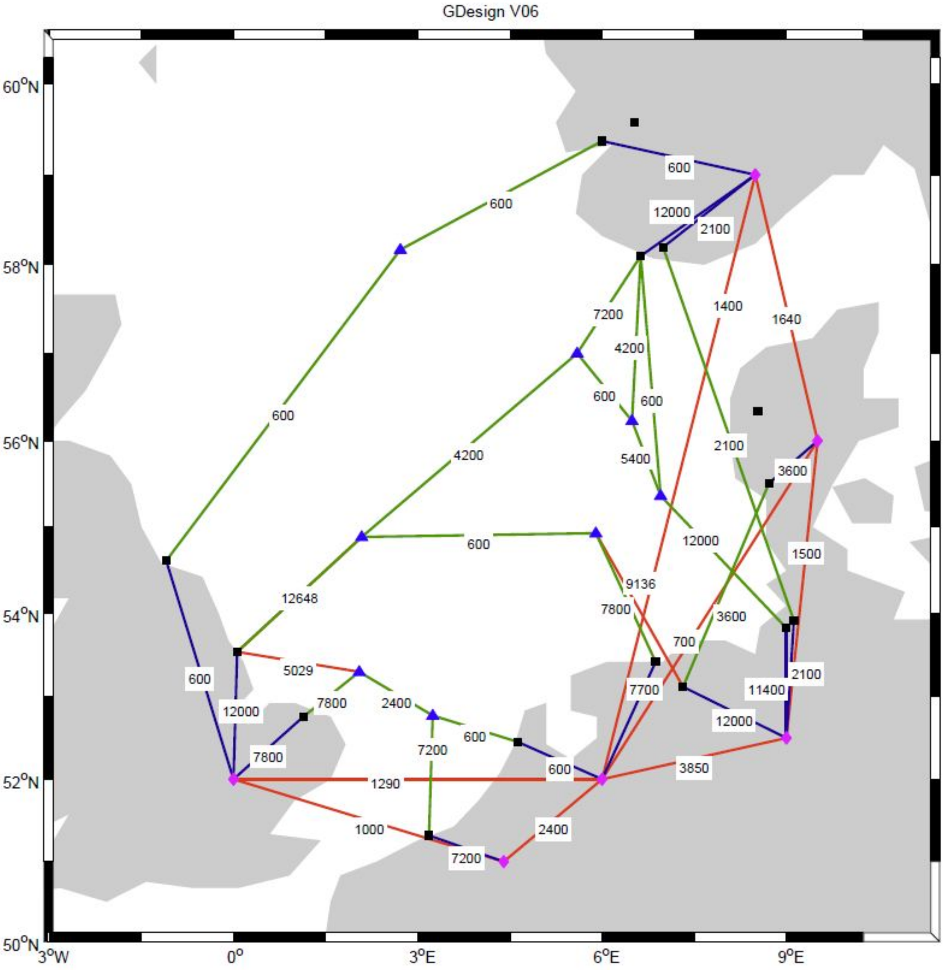
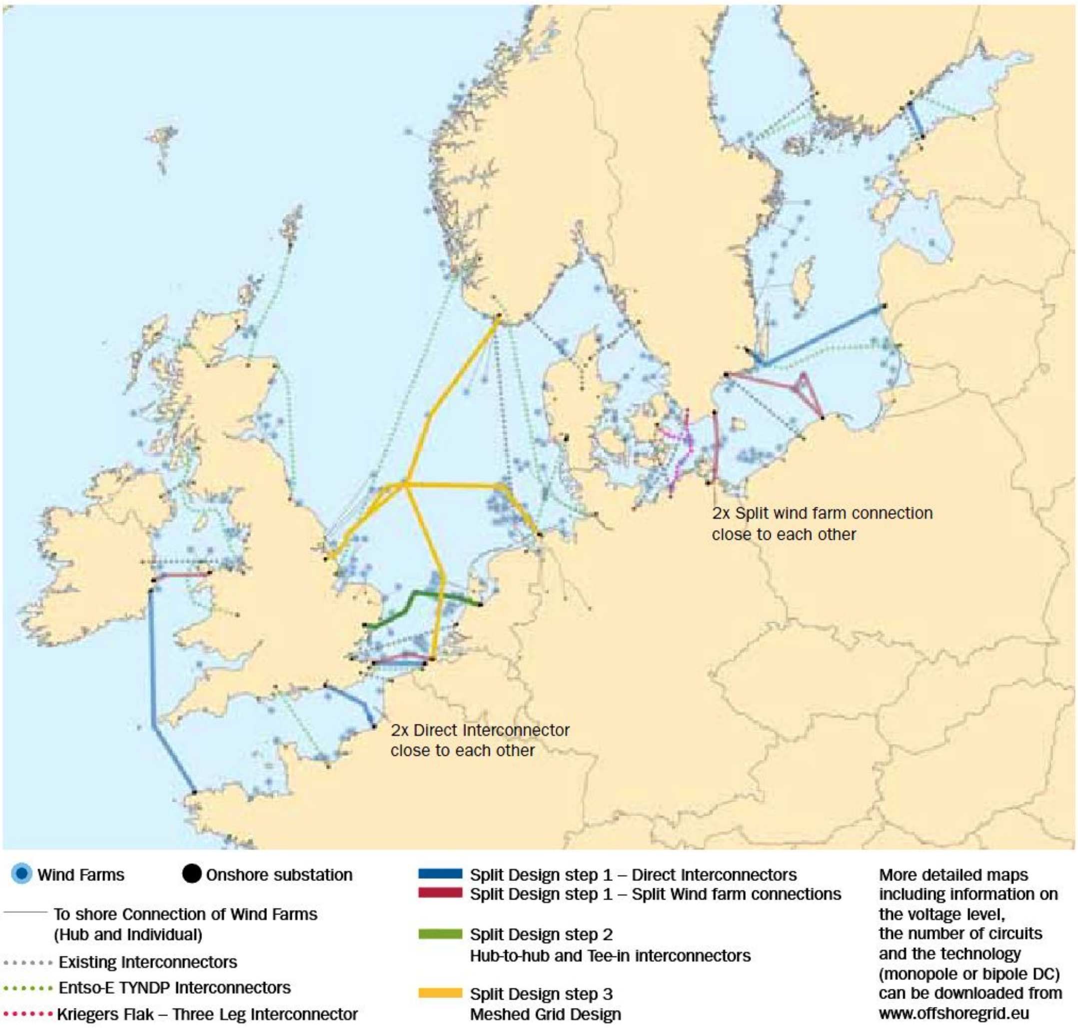


Figure 45: Grand Design v06 scenario cable capacities. Triangles represent wind farm clusters and squares represent onshore connection points

Appendix F – Additional OffshoreGrid figures

Split Design overview map



2x Split wind farm connection close to each other

2x Direct Interconnector close to each other

More detailed maps including information on the voltage level, the number of circuits and the technology (monopole or bipole DC) can be downloaded from www.offshoregrid.eu

Figure 46: OffshoreGrid Split Design overview map. [24]

Radial vs meshed grid threshold graph

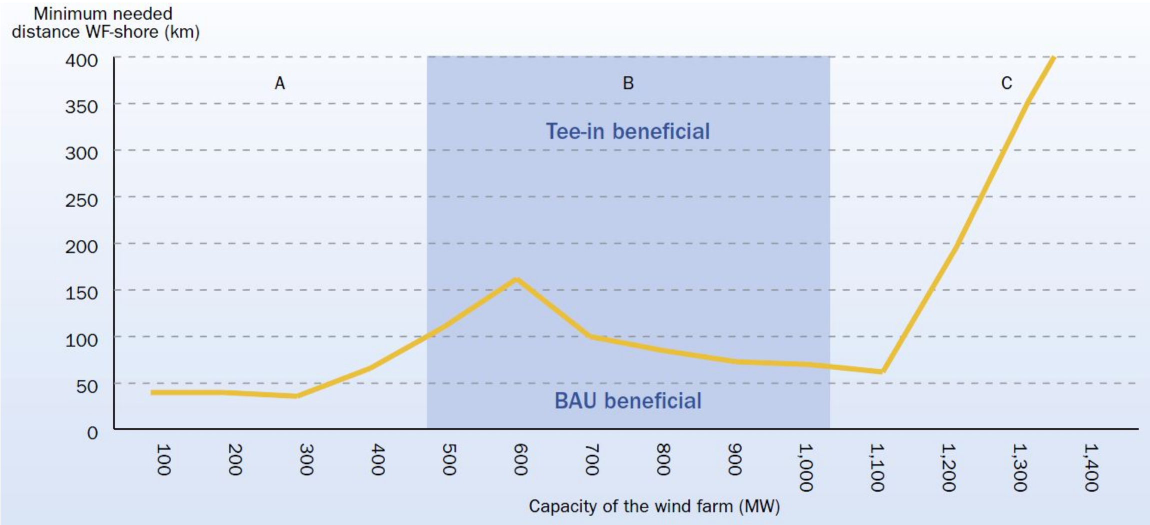


Figure 47: Offshoregrid radial vs meshed grid threshold graph [24]