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Assessing the Life Cycle Environmental Impacts of Offshore Wind Power Generation and Power Transmission in the North Sea

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Master of Science in Energy and Environment
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MASTER'S THESIS

for

Christine Birkeland

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Environmental implications of power transmission for large-scale deployment of offshore wind power in the North Sea: A life cycle assessment

Livsløpsvurdering av miljøaspekter av kraftoverføring knyttet til omfattende utbygging av havbasert vindkraft i Nordsjøen

Background

Increasing concerns over energy security and harmful climate change are fuelling interest in the development of renewable energy technologies. Electric power generation from wind is generally seen as a key technology in this respect. Already today, wind power is a fast-growing technology, with installed capacities in Europe growing at an average annual rate of more than 20% in the last 15 years. Due to, among other things, lack of suitable space on land, and improved wind conditions when going offshore, in coming decades the wind power sector is expected to increasingly turn towards development in ocean waters. The North Sea is one example of an ocean area with a vast resource potential, and for which ambitious plans for wind power development exists. Offshore power plants require electricity transmission to the grid on shore. In addition, widespread attention has been devoted mitigating the intermittency of wind power by exchanging wind power across different regions and utilizing Norwegian hydropower capacity to compensate for intermittency.

Despite the renewable nature of wind energy conversion, non-renewable resource inputs and emissions occur in the life cycle of wind energy systems. The life cycle of a wind energy system includes extraction of raw materials, manufacturing of components, maintenance and, finally, dismantling and waste handling at the end-of-life. In addition to the actual wind turbines, an offshore wind energy system comprises connection cables and electrical devices facilitating power transmission to the onshore grid, and additional grid capacity required to accommodate this intermittent power. The impacts generated throughout a product's life cycle can be quantified and assessed by the method of life cycle assessment (LCA).

In this work, we are interested in evaluating the environmental implications of electricity transmission associated with large-scale deployment of wind power in the North Sea, in a life cycle perspective.

Objective
The primary objective is to assess the life cycle environmental impacts of electricity transmission for offshore wind power development in the North Sea. It is hoped that the work will result in policy-relevant recommendations for the development of wind power generation and power transmission in the North Sea.

The study should include following elements:

1) Determination of LCA methodology (process-based LCA or hybrid LCA) to be used.
2) Compilation of life cycle inventories for the electricity transmission infrastructure of a typical offshore wind park.
3) Compilation of life cycle inventories for power transmission across the North Sea.
4) Quantification and assessment of environmental impacts associated with offshore wind power generation and power transmission in the North Sea.
5) Discussion on environmental costs and benefits associated with a large-scale expansion of power generation and transmission in the North Sea. What can be concluded with respect to system designs and strategies for maximizing net environmental benefits?
6) Discussion of the role of sea cables on smoothing intermittent wind power and the challenge of power scheduling and standby requirements.

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Within 14 days of receiving the written text on the master thesis, the candidate shall submit a research plan for his project to the department.

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Department of Energy and Process Engineering, 17. January 2011

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Preface

This report is the result of my master thesis work during spring semester 2011, at the Norwegian University of Science and Technology. The thesis completes my final year at the Masters program in Energy and Environmental Engineering, Department of Energy and Process Engineering.

During my work with this thesis a number of people have contributed with support, encouragement and constructive feedback. First I want to thank my supervisors Edgar Hertwich and Anders Arvesen for their guidance and encouragement throughout the process. A special thanks to Anders Arvesen for helping me with my models and discussing the challenges I have faced during my work. Your advices and support have been invaluable. I also want to thank Guillaume Majeau-Bettez for great work in improving the LCA GUI software, and for supervising me in how to organize my excel models in order to use them in the LCA GUI.

The opportunity is also taken to thank my fellow students Kari Sørnes and Ida Lund Segtnan, for inspiration and enlightening discussions throughout the semester. Thank you to Steinar and Berit Birkeland for motivation when needed and for proofreading my work. To Jan Olav Owren; thank you for support, patience and encouragement throughout the process.

Trondheim, June 2011

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Abstract

An integrated approach to climate and energy policy is required to meet the challenges associated with climate changes caused by anthropogenic emissions. At the same time, the demand for electricity is increasing. Wind power is considered as part of the solution in solving these challenges, as this is renewable energy. By relocating wind power production offshore, stronger winds are achieved that increases electricity production without having emissions of GHG during power production. Europe's ambitious goals and plans for development of offshore wind power development in the North Sea have also raised questions about how to integrate wind power into existing power systems in Europe. In this study the environmental impacts of offshore wind power production and development of an offshore grid in the North Sea, have been considered.

To quantify the environmental impacts associated with offshore wind power generation and power transmission in the North Sea, several LCA's have been carried out. Four LCA's were conducted, whereof three of them were analyses of various submarine cables used either in offshore wind farms or long-distance power transmission. The cables studied were; 33 kV HVAC cables used internally in offshore wind farms, 132 kV HVAC cables used to transmit power from a wind farm to the grid onshore and 450 kV HVDC cables used for long-distance power transmission between for instance countries. A fourth LCA was conducted of an entire offshore wind farm, including the inventories of the 33 kV and 132 kV cables.

The emissions from a 390 MW offshore wind farm with bottom-fixed windmills, were calculated to be 20.6 g CO_2 -equivalents/kWh_{el}. Cabling constituted only 1.5 % of the total impacts to climate change from the wind farm. A larger wind farm of 9000 MW had lower estimated emissions of 19.8 g CO_2 -equivalents/kWh_{el} due to a higher electricity production. The LCA results of the 450 kV cables were used in estimating the environmental impact caused by different designs of offshore power grids in the North Sea. Several alternative grids were investigated, both with and without wind farms. For instance, a power grid in the North Sea where the two wind farms above were implemented, had estimated emissions of 84 million tonnes of CO_2-equivalents throughout lifetime. This represents approximately 2% of the EU-27 countries' total GHG emissions from 2007. In addition to the quantification of environmental impacts, a qualitative discussion was conducted of the various environmental costs and benefits associated with large-scale development of power generation and transmission in the North Sea. The results from this study indicate that the expected environmental impacts from developing offshore wind farms and power grids in the North Sea are not insignificant. The positive environmental effects are large because the increased transmission capacity between power markets allows for increased development of electricity generation from intermittent renewable energy sources like wind power. Increased share of renewable energy reduces the need for power generation from fossil fuels, thus there will be an environmental gain. The study seeks to emphasize the complexity and the important aspects of the assessment of environmental impacts associated with large power systems.

Sammendrag

En integrert tilnærming til klima- og energipolitikk er nødvendig for å møte utfordringene tilknyttet klimaendringer på grunn av menneskeskapte utslipp. Samtidig er behovet for elektrisitet stadig økende. Vindkraft er fornybar energi og ansett som en del av løsningen. Ved å flytte vindkraftproduksjonen til havs, vil man oppnå jevnere og sterkere vind som gir økt elektrisitetsproduksjon uten utslipp av drivhusgasser under kraftproduksjon. Europas ambisiøse mål og planer for utvikling av havbasert vindkraftutvikling i Nordsjøen, har også reist spørsmål om hvordan man kan integrere vindkraft i eksisterende kraftsystemer i Europa. I dette studiet, er de miljømessige konsekvensene av havbasert vindkraftproduksjon og utvikling av et offshore kraftnett i Nordsjøen, for å koble sammen offshore vindparker og de ulike kraftmarkedene i Europa, blitt vurdert.

For å kvantifisere de miljømessige konsekvensene assosiert med vindkraftproduksjon og overføringsnett for elektrisitet i Nordsjøen, er det gjennomført ulike livssyklusanalyser. Fire LCA'er ble gjennomført, hvorav tre av dem var analyser av ulike sjøkabler brukt i enten havbaserte vindparker eller ved langdistanse kraftoverføring. Kablene som ble studert var; 33 kV HVAC kabler brukt internt i vindparker, 132 kV HVAC kabler brukt for å overføre kraft fra vindpark til nett på land og 450 kV HVDC kabler brukt til langdistanse kraftoverføring mellom land for eksempel. En fjerde LCA ble gjort av en vindpark utfor Norges kyst, hvor analysene av 33 kV og 132 kV kablene ble inkludert.

Utslippene fra en havbasert vindpark på 390 MW med bunnfaste vindmøller, ble beregnet til å være 20.6 g CO_2-ekvivalenter/kWh_{el} hvorav kabling utgjorde kun 1.5 % av de totale utslippene fra vindparken. En større vindpark på 9000 MW, hadde noe reduserte utslipp på 19.8 g CO_2-ekvivalenter/kWh_{el} ettersom mer elektrisitet ble produsert. LCA resultatene for 450 kV kablene ble så brukt for å lage estimater av miljøpåvirkningene fra ulike design av offshore kraftnett i Nordsjøen. Flere ulike design til kraftnett ble studert, både med og uten vindparker. Et kraftnett hvor de to vindparkene over ble implementert på en kraftlink mellom Norge og Storbritannia, fikk estimert utslippene til å være 84 millioner tonn CO_2-ekvivalenter gjennom livstiden. Dette tilsvarer omtrent 2 % av EU-27 landenes totale klimagassutslipp fra 2007. I tillegg til kvantifiseringene av miljøkonsekvenser, ble en lengre kvalitativ diskusjon gjennomført av de ulike miljømessige fordeler og ulemper som er assosiert med storskala utvikling av kraftproduksjon og overføring i Nordsjøen. Resultatene fra dette studiet indikerer at de forventede miljøkonsekvensene fra å bygge havbaserte vindparker og kraftnett, ikke er ubetydelige. Man vil ha store negative og positive ringvirkninger. De positive miljøeffektene er store ettersom økt overføringskapasitet mellom ulike kraftmarkeder gir mulighet for økt utbygging av elektrisitetsproduksjon fra uregelmessige fornybare energikilder som vindkraft. Økt andel fornybar energi reduserer behovet for kraftproduksjon fra fossile brensler og man vil oppnå miljøgevinster. I studiet diskuterer positive og negative miljøkonsekvenser ved utbygging av kraftproduksjon og -overføring i Nordsjøen, fra ulike innfallsvinkler. Dette for å få frem kompleksiteten i og belyse viktige aspekter ved vurdering av miljøkonsekvensene tilknyttet store systemer som dem betraktet her.

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Abbrevations

AC	Alternating current
CSC	Current Source Converters
CTA	Commodity Technology Assumption
DC	Direct current
E	Egalitarian
EE-IOA	Environmentally Extended Input-Output Analysis
GHG	Greenhouse gases
GWh	Gigawatt hour
H	Hierarchist
HV	High Voltage
HVAC	High Voltage Alternating Current
HVDC	High Voltage Direct Current
I	Individualist
IO	Input Output
IOA	Input-Output Analysis
ITA	Industry Technology Assumption
kWh	Kilowatt hour
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
MWh	Megawatt hour
NTNU	Norwegian University of Science and Technology
SIOT	Symmetric Input-Output Tables
SNA	System of National Accounts
SUT	Supply and Use Tables
TSO	Transmission System Operator
TWh	Terrawatt hours
VSC	Voltage Source Converters

Chapter 1

1 Introduction

This study will assess the life cycle environmental impacts from power generation and transmission associated with large-scale expansion of wind power in the North Sea.

Europe and the world are at a crossroad concerning the future of energy. The challenges of climate changes due to anthropogenic emissions need effective and immediate action. An integrated approach to climate and energy policy is required given that energy production and use are primary sources for greenhouse gas emissions (Commission Of The European Communities 2008).

Development of renewable energy resources is a prioritized assignment in all European countries. The EU Renewable Energy Directive 2009/28/EC of the European Parliament and the Council of the European Union, puts national demands on the share of renewable energy in consumption of electricity (The European Parliament and the Council of the European Union 2009). EU has decided a so-called 20:20:20 goal in this directive, deciding that EU shall reduce the CO_2 emissions by 20 %, decrease energy consumption by 20 % and increase the share of consumption coming from renewable energy sources from 8.5 % to 20 % before year 2020 (Landssamanslutninga av Vasskraftkommunar 2009). The national requirements assume that all member states must increase the renewable share by 5.5 % (Adapt Consulting AS 2010). The European Wind Energy Association (EWEA) states that this directive calls for more than one third of the European electricity demand coming from renewable sources, with wind power expected to deliver 12 -14 % (The European Wind Energy Association 2008). EWEA predicts that the EU-27 countries have to have 80 GW installed capacity of wind power, including 3.5 GW from offshore wind power by 2010 (European Environment Agency 2009). EU also have to set a target of 180 GW in installed capacity, including 35 GW from offshore wind power, to reach this goal by 2020. The directive is relevant for Norway through the European Economic Area (EEA- agreement). In addition to this directive, EU is obliged to reduce greenhouse gas emissions under the Kyoto protocol (European Environment Agency 2009a). Also Norway is committed to the Kyoto protocol, and have to reduce the emissions of greenhouse gases to being maximum 1 % higher than the total greenhouse gas emissions from Norway in year 1990 (United Nations 1998). The Kyoto agreement came into force in 2008 and ends in 2012.

It is the electricity consumption, and not the production of power from renewable energy resources, that is important when it comes to establishing goals for the level of electricity that should come from renewable energy in a country. This result in countries wanting new electricity production to come from renewable energy resources, and that import of electricity should preferably be from renewable energy. To meet demands like these, development of renewable energy resources such as wind power is expected to be a part of the solution. Great Britain will for instance have to increase the share of renewable energy in their final electricity consumption from 1.3 % in 2005 to 15 % within 2020 (Adapt Consulting AS 2010). Great Britain plans to develop 31 GW of new production capacity from renewable energy between 2010 and 2020. 23.9 GW is wind power, of which 12.1 GW is offshore wind power. Total production in Great Britain coming from wind power is expected to be nine times higher in 2020 than in 2009, increasing from 9.3 TWh in 2009 to 78 TWh in 2020 (Adapt Consulting AS 2010). Today, a great share of Europe's power production is coming from thermal power, such as coal, but the trend of building more power production such as wind power, is expected for North Europe in general. This gives a high amount of intermittent power production in the power system, which is not easy to regulate.

Development of renewable energy resources in Europe, such as wind power, will increase the demand for regulating power. Hydropower is considered to be best energy resource to use as regulating power. Wind and hydropower are complementary energy resources. Hydropower can easily be regulated and stored in reservoirs when it is windy and the wind power production is good. If the wind power production is reduced, this can quickly be compensated for by increasing the hydropower production. This can be utilized in the European power market, and is today already made use of in Denmark (Adapt Consulting AS 2010). Hydropower will also work well as regulating power in a system of much thermal power production, as thermal power plants are expensive to switch on and off and it takes some time to start up these power plants. Regulating power is hence something Norway can offer to the European power market. The Norwegian electricity production is in a unique position when it comes to the share of electricity produced from renewable energy resources. The Norwegian power market is dominated by hydropower. In 2009, the hydropower production made up 96 % of total electricity production in Norway. This means that the Norwegian electricity production is mainly based on renewable energy resources. Norway is the 6th largest hydropower producer in the world (Norges vassdrags- og energidirektorat 2011). In comparison, around 17 % of all electricity produced in the EU is based on renewable energy resources. In Sweden, renewable energy constitute about half of the electricity production, and corresponding share in Denmark is about 29 % (Norges vassdrags- og energidirektorat 2011).

For future development of new renewable energy resources, the countries around the North Sea are particularly interesting for wind power production. Norway's long coastline and excellent wind conditions make it suitable for wind power production, and especially for offshore wind power. Wind maps for Europe show that Norway and the northern parts of United Kingdom are the areas having the best wind conditions in Europe. For offshore wind power production, wind speeds between 4 and 25 m/s are needed. In Norway, wind speeds are 7.5 - 8.5 m/s in coastal areas and >9.0 m/s in open sea areas. Wind conditions at the coast of the UK, and in open sea, is similar to the Norwegian conditions (Global Energy Network

Institute (GENI) 2010). For maximum electricity production in wind turbines, wind speeds between 10 to 14 m/s are desirable, which makes Norway and UK very suitable for offshore wind power production.

Power connection between the hydro dominated Nordic power system and the European thermal dominated power system is expected to be both necessary and profitable in the near future, due to changes in the power market and power demand (Statnett 2010). Many parties involved mean that development of power transmission capacity between different power markets is a requirement if EU shall succeed in its energy and climate policy. If European countries want to concentrate on developing wind power production, security of power supply will be important as wind power is very intermittent. To handle the problem of intermittency, hydropower will be an important remedy as explained. Further development of transmission capacity will be necessary if Norway shall work as an exporter of regulating power to the continent. A project called “OffshoreGrid” is now being carried out by the Intelligent Energy Europe program, studying the possibilities of making an offshore power grid in the Baltic and the North Sea. The objective is to develop a scientifically based view on an offshore grid in the Northern Europe along with a suited regulatory framework considering economic, technical, policy and regulatory aspects (Intelligent Energy Europe 2011). A power transmission grid will make it easier to transmit power between different power markets, and hence make power production more flexible and easier to plan in different regions. These topics will be further discussed and analyzed towards the end of this report under chapter 5.

1.1 Objective

In this study an assessment will be made of the life cycle environmental impacts of electricity transmission associated with offshore wind power development in the North Sea. The main focus of this study will be on environmental impacts caused by offshore wind power generation and submarine power transmission between countries across the North Sea. Quantification and assessment of the environmental impacts associated with offshore wind power generation and power transmission in this area, will be carried out by using the mathematical method; life cycle assessment (LCA). LCA is a method which makes it possible to quantify the environmental impacts throughout the life cycle of a system, from “cradle-to-grave”. A discussion will also be given on what are the environmental costs and benefits associated with large-scale expansion of power generation and transmission in the North Sea, and what the role of submarine cables are on smoothing intermittent wind power.

Wind power is a renewable energy resource and hence does not have any direct emissions during power production. Non- renewable resource inputs and emissions will nevertheless occur in the life cycle of wind energy systems. Extraction of raw materials, manufacturing of components, installation, maintenance and dismantling of a wind farm, will all result in the need for non- renewable inputs and thus cause environmental stress. In addition to the actual wind turbines in a wind farm, a transmission grid both internally in the wind farm and from the wind farm to the grid onshore is required. This will also call for non- renewable resources and cause environmental stress. Large- scale expansion of wind power generation in the North Sea can probably also increase the likelihood of developing a transmission grid across the North Sea, which will call for great resources. Building a transmission grid of this size, demand great use of materials, especially metals, and vessels using fossil fuels. In this study, electricity transmission connected to expansion of offshore wind power in the North Sea will be focused on, including long distance transmission alternatives interconnecting countries across the North Sea. The report will contain two parts; one part containing LCA's of electricity transmission cables (chapter 4) and one discussion part (chapter 5).

In the first part there will be carried out four LCA's. Three of the analyses are of different submarine cables; 33 kV HVAC cables used typically for the collection system in an offshore wind farm, 132 kV HVAC cables normally used in transmission from an offshore wind farm and to the grid on shore and 450 kV HVDC cables for long distance submarine power transmission for instance across the North Sea. A fourth LCA of an entire offshore wind farm is finally performed. In this LCA, the transmission and collection systems for a wind farm are included to see what the environmental impacts are from an offshore wind farm. The four LCA's are;

1. Cables for the collection system in the offshore wind farm: 33 kV HVAC cables.
2. Cables for the transmission system in the offshore wind farm: 132 kV HVAC cables.
3. Cables for interconnection between Norway and Great Britain: 450 kV HVDC cables.
4. LCA of an offshore wind farm, implementing data on 33 kV and 132 kV cables.

The aim of these life cycle assessments is to assess the environmental impacts associated with large-scale expansion of power generation and power transmission in the North Sea. Functional unit for the life cycle assessments of submarine cables will be 1 MW*km, whereas MW refer to the transmission capacity needed in the cable and km is the length of the cable. For the life cycle assessment of the entire wind farm, a functional unit of 1 kWh of electricity delivered to the grid onshore is chosen.

In the second part of this study, a discussion will be performed on environmental costs and benefits associated with a large-scale expansion of power generation and transmission in the North Sea, and what can be concluded with respect to system designs and strategies for maximizing net environmental benefits. Also, the role of submarine cables on smoothing intermittent wind power and the challenge of power scheduling and standby requirements will be discussed.

The problem description of this master thesis is to a large extent answered from a Norwegian point of view. Norway's role in the development of offshore wind power and an offshore power grid in the North Sea are therefore emphasized.

1.2 Previous work

During fall semester 2010, I carried out a specialization project investigating the environmental impacts caused by an offshore wind farm located outside the coast of Møre og Romsdal in Norway. This study delved deeply in what was required of material, energy inputs to the system throughout the lifetime of the offshore wind farm, and what the environmental impacts were when delivering 1 kWh of electricity to the grid onshore. The study emphasized the investigation of the share of environmental impacts caused by the requirements for installation, operation and maintenance in an offshore wind farm. The present study will be based on data from this specialization project, but the inventory for the wind farm will be improved and updated.

Studies performed earlier of *offshore wind farms* have found that offshore wind farms emits typically between 5.0- 20.0 g CO_2 -eq/kWh$_{el}$ (M Lenzen & Munksgaard 2002), (Martínez et al. 2009). A LCA study undertaken by Vestas found a contribution of 5.3 g CO_2-eq/kWh$_{el}$ to climate change from an offshore wind farm with the Monopile foundation type (Vestas 2006). Lentzen et al. found an impact of 16.5 g CO_2 -eq/kWh$_{el}$ from an offshore wind farm located in Denmark (M Lenzen & Munksgaard 2002), Martinéz et al. found a contribution of 6.6 g CO_2 -eq/kWh$_{el}$ from offshore wind power (Martínez et al. 2009), while a LCA done by Elsam found a contribution of 7.6 g CO_2/kWh$_{el}$ (only contribution of CO_2) from the wind farm Horns Reef in Denmark (Elsam Engineering A/S 2004). Weintzettel et al. found a contribution to climate change of 11.5 g CO_2 -eq/kWh$_{el}$ for a floating windmill, and states that the largest contribution to climate change comes from the low- alloyed steel in production of the tower, followed by cable production and chromium steel in production of wind turbine (Weinzettel et al. 2009). The study done by Weinzettel et al. is of a floating offshore windmill, and thus there will not be any impacts associated with the foundation. Instead, much more steel will be used in the tower, thus the large contribution from steel.

Few LCA's are performed for cables used within an offshore wind farm and cables used for long distance power transmission across the North Sea. Some LCA work on power cables is at the moment undertaken by Nexans, but the results are not available yet [1]. Hence, this study will contribute to a better understanding of the environmental effects caused by submarine power cables both in an offshore wind farm and in a power grid in the North Sea. In addition the environmental impacts caused by an offshore wind farm are investigated as the problem description asks for quantification and assessment of environmental impacts associated both with offshore wind power generation and power transmission in the North Sea.

[1] Information given by professionals in Nexans. Dated 16.02.11.

1.3 Structure of report

This report will be structured in the following way;

Chapter 1 gives the introduction and objective of this study. Chapter 1 describes the methodology and what are the technicalities of the life cycle assessments. Both the methodologies for LCA and IOA are presented. The characterization method ReCiPe and the IO framework by EXIOPOL are explained briefly, as well as what software tools are used in order to perform the assessments.

Chapter 3 presents the technical aspects and background information about the power market and mechanisms for power trade, offshore wind power generation and electrical power transmission. This chapter explains what happens to the market prices for electricity if a power cable is installed between two power markets. Also an explanation of offshore wind power and power transmission with submarine cables is given.

In chapter 4 the different LCA's that are carried out are presented. This chapter includes the life cycle inventory analyses, life cycle impact assessments, presentation, analysis and discussion of the results for all four LCA's completed. Chapter 4 also gives an account of and assesses the data quality and uncertainties associated with the analyses. Chapter 5 is the discussion chapter that seeks to answer part two of the problem description. Questions that are answered here are; what are the environmental costs and benefits associated with large-scale expansion of power generation and power transmission in the North Sea? What can be concluded with respect to system designs and strategies for maximizing net environmental benefits? What is the role of sea cables on smoothing intermittent wind power? What are the challenges associated with power scheduling and standby requirement?

In chapter 0 the conclusion of the study, including need of further work is presented.

Chapter 2

2 Methodology

In this study, mainly the framework of Life Cycle Assessment (LCA) is used. Because of lack in data input for some processes, the monetary Input-Output Analysis (IOA) framework has been utilized for these processes/sectors. This gives a better coverage of the inputs to the process, than if only the LCA inputs were included. It is nevertheless selected not to conduct a full hybrid LCA, due to the difficulties of obtaining the correct prices in basic prices and the timeframe of this study. Many assumptions would have to be made in order to do a full hybrid analysis, using both the LCA and IO frameworks. These assumptions, as for instance assumptions of prices, would bring new uncertainties into the analyses which could remove much of the advantage of doing the hybrid analyses in the first place. Doing a full hybrid LCA would also be very time consuming. This study has a timeframe of 20 weeks, so conducting a full hybrid analysis in addition to answering the other assignments given would be difficult to do properly and throughly. To conduct a hybrid LCA within this timeframe, would call for crude assumptions as the data required were not made available on forehand. These are the main reasons why a LCA is performed, but using the IO framework to cover the processes that are poorly covered by the LCA framework. For these processes, the basic prices have been obtained. In this methodology part, primarily the LCA framework will be presented. A short presentation of the basics in the IOA framework will also be given.

While LCA is a tool used to assess the environmental aspects and impacts of a product system in physical terms, the IOA is a more comprehensive framework built on the possibility to analyze a system in monetary terms. IOA models the flows to and from all economical sectors in a region. LCA uses the physical data specific for the system under consideration, but may suffer from inflexibility, aggregation, data confidentiality and cut-off errors due to defining the system boundary (Joshi 2000). IOA has the advantage of a more complete system boundary, but it does not have the same precision level as LCA. By combining these two frameworks, and making a hybrid LCA, more complete system coverage can be achieved. The advantages from both frameworks can be exploited (Arvesen & E. Hertwich 2011). The mathematical formulations of IOA and LCA are the same, derived from the work of Professor Wassily Leontief in the late 1930's. He constructed the first IO tables for the United States for year 1919 and 1929 (United Nations 1999). His work was based on the work of the French economist Francois Quesnay, which already in 1758 published a "Tableau Economique". This was a systematic way of representing how expenditures could be traced through an economy (Miller & Blair 1985). LCA and IOA can easily be combined mathematically in an environmental systems analysis purpose, as the methods are mathematically equally constructed only with some minor differences.

Representation and explanations of the LCA and IOA frameworks are to a large extent based on lectures given and material supplied by Anders H. Strømman in the courses "Life Cycle Assessment" (fall 2009) and "Input- Output Analysis" (fall 2010), at NTNU.

In performing the LCA's in this study, presented in this report, the required models were made and compiled in excel. The emission intensities calculated for the IO system were included in the LCA model as "dummy" processes. Then a Matlab script was written in order to read the tabulated data properly into the LCA software tool called LCA GUI, developed by Guillaume Majeau-Bettez at the study program of Industrial Ecology at the Norwegian University of Science and Technology (Majeau-Bettez 2010). This is a graphical user interface that performs life cycle impact assessment (LCIA) calculations including Taylor series expansion and structural path analysis. This software was preferred because it uses the Ecoinvent 2.2 database, as well as calculating Taylor series expansion and structural path analysis.

2.1 Tools used

The characterization method used in this study to perform the life cycle impact assessment (LCIA), is the ReCiPe method. This method is used in LCIA to convert the emissions of hazardous substances and extraction of natural resources, into impact category indicators. For further reading about characterization and impact categories in ReCiPe, see (Goedkoop et al. 2009). The results can be offered both at midpoint level (such as Acidification and Eco-toxicity) or at endpoint level (such as for instance Damage to human health and Damage to ecosystem quality). Whether it is best to use midpoint indicators or endpoint indicators is a widely discussed topic in the LCA research community. For further reading see (E. G. Hertwich & Hammitt 2001).

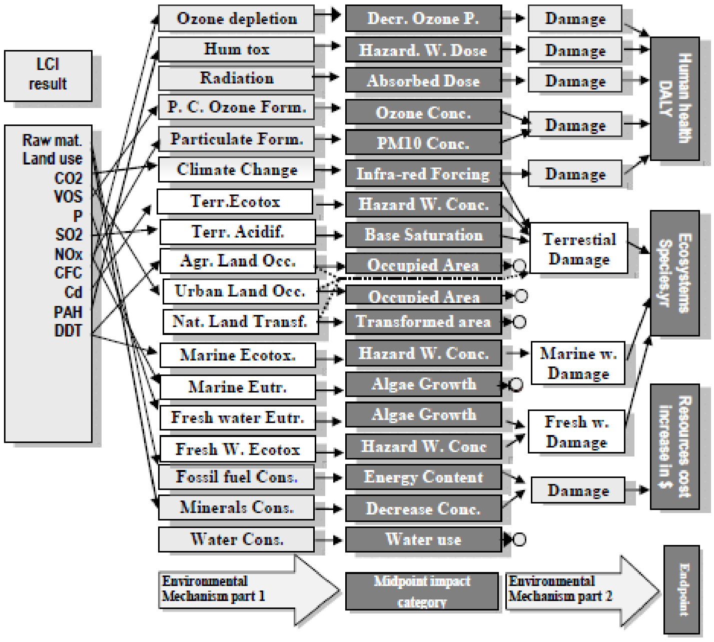

Figure 2-1 Relationship between life cycle inventory parameters (left), midpoint indicators (middle) and endpoint indicators (right) in ReCiPe.

In this study, midpoint indicators are used, having 18 impact categories in the impact assessment results. By converting emissions and stressors into impact categories, higher uncertainty is given to the results. For some of the conversion and aggregation steps, uncertainties have been incorporated in the form of three different perspectives: Individualist (I), Hierarchist (H) and Egalitarian (E) (Goedkoop et al. 2009);

- **Individualist perspective** has a short term perspective (100 year or less). Substances are included if there is complete proof regarding their effects.
- **Hierarchist perspective** has a long term perspective. Substances are included if there is consensus regarding their effect.
- **Egalitarian perspective** has an extremely long term perspective and is the most conservative. Substances are included if there is just an indication regarding their effect.

In this study, the hierarchist perspective at midpoint level is chosen.
There is also uncertainty connected to the midpoint impact categories themselves. Especially the toxicity categories have high uncertainties associated. It is not always evident what the exposure routes for toxic substances are. For marine eco- toxicity it is hard to find what the consequences of metals in ocean systems are, and to what extent different processes contribute. For human toxicity it is difficult to decide the impacts from hazardous substances on humans, as these substances should not be tested (Althaus et al. 2010). The uncertainties in impact categories will affect the results in the impact assessment throughout the analysis, and should therefore be kept in mind when performing the LCIA's and interpreting the results.

2.2 Life Cycle Assessment

ISO14040 named: "Environmental management. Life cycle assessment, principles and framework", states that LCA is a tool used to assess, in a systematic way, the environmental aspects and impacts of product systems, from raw material extraction to final disposal, in accordance with the stated goal and scope. The relative nature of LCA is due to the functional unit feature of the methodology (ISO 14040 2006). LCA has the same mathematical framework, and is built on the same principles, as the IOA framework. While IOA takes a top-down approach and treats a whole economy as a system boundary (Joshi 2000), the process-LCA takes a bottom-up approach defining and describing processes relevant for the system in physical terms (Arvesen & E. Hertwich 2011). This makes LCA more specific than IOA.

A LCA comprises four phases which are; the goal and scope definition, inventory analysis, impact assessment and interpretation. These following brief explanations of each phase are based on ISO 14040.

The goal and scope determine the context for the study. The goal tells us what the reasons for carrying out this study are and what the intended application is. The scope decides where the system boundary is set, what the functional unit of the system will be and what assumptions and limitations that exist. Also potential allocation procedures must be clarified. The functional unit is a quantified performance for a product system for use as a reference unit. Hence, all following LCA's are related to a functional unit. It defines what is studied (ISO 14040 2006). Selecting an appropriate functional unit and a system boundary, including all important processes, is essential as this may influence the results. One of the main shortcomings in LCA is the cut-off of system boundaries as it is not possible to include *all* relevant processes in detail. This will result in uncertainties throughout the analysis and is thus important to beware of.

Life cycle inventory analysis (LCI) involves data collection and calculation procedures to quantify the relevant input and output flows in the production system. The LCI is a time-consuming and iterative process. Collection of data can result in new knowledge and thus actuate a new collection process. All data calculations, validation of data and potential allocation procedures are carried out in the LCI. The material and energy inputs and output, and related emissions, are calculated and tabulated in order to carry out the mathematical calculations of the LCIA.

The life cycle impact assessment (LCIA) aims to evaluate the significance of potential environmental impacts by using the LCI results. These data tabulated in the LCI are in the LCIA connected with specific environmental impact categories and category indicators. The emissions and stressors found in calculations are in the impact assessment gathered and converted to an equivalent quantity of a reference compound, and divided into environmental impact categories such as for example "climate change" or "marine eco-toxcicity". Results (impacts) given from this are then attempted understood and interpreted.

Eventually, all results from the LCI and LCIA will be interpreted and evaluated. The interpretation is the phase where findings from inventory analysis and impact assessment are considered together. Interpretation itself is done throughout all phases in the LCA, but a unifying presentation of results, understanding and limitations, in accordance with the goal and scope definition of the study, should be provided. The results are based on a relative approach, thus it is needed to elucidate that the results indicate potential environmental effects and do not predict impacts on humans, environment, on safety risks or similar. Interpretation gives the results and the system meaning and context. A final conclusion about the meaning of the results, in accordance with the goal and scope, is stated.

2.2.1 Formal framework

Table 2-1 presents the nomenclature for the LCA framework.

Table 2-1. Nomenclature for the different matrices used in the mathematical framework of LCA.

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 of process
	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	*(str 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 LCA model is built upon the assumption that the interdependences between processes in life cycle assessments can be modeled by linear equations. For each process, information about requirements of inputs to the production is collected. From this, the requirement matrix (A) is established which contains the "cooking recipe" for the product's system outputs. Each column represents a product and the quantities required from the other processes to produce one unit output of this product. For instance will the coefficient a_{13} tell how much of process 1 is required by process 3 in order to produce one unit of output from process 3. The production balance for each node in a product network becomes similar to;

$$x_{11} = a_{11}x_1 + a_{12}x_2 + a_{13}x_3 + y_1 \qquad 2.1$$

x_{11} is the total output from node 1. $a_{11}x_1 + a_{12}x_2 + a_{13}x_3$ is the intermediate demand node 1 has from node 2 and 3, and y_1 is the external demand upon node 1.

Here, the production output, x, and the external demand, y, are introduced. The production system can be represented by a set of linear equations and thus be systemized into a set of matrices and vectors, giving;

$$x = Ax + y \Leftrightarrow x = (I - A)^{-1} y \Leftrightarrow x = Ly \qquad 2.2$$

The L matrix is known as the Leontief inverse. Coefficient l_{ij} in the L matrix represents the amount of output from process i that is required per unit of final delivery of process j. For the Leontief inverse to be invertible, it has to satisfy the Hawkins-Simon condition which says that the determinant of (I-A) must be positive and unequal to zero.

Basic contribution analysis

To calculate total emissions from the production system, the stressor matrix (F) has to be determined. In LCA this is in physical terms. The stressor matrix is multiplied with total output from the system, which gives the vector of total emissions (e) associated with the external demand given by the y vector;

$$e = Fx = FLy = F(I - A)^{-1} y \qquad 2.3$$

By relocating the elements of the y vector to the diagonal and put the other elements equal to zero, investigations of how much the various processes contribute to the total stressor load can be implemented. This gives the E matrix;

$$E = F\hat{x} \qquad 2.4$$

Then, the vector of total impacts (d) for a given external demand can be calculated;

$$d = Ce = CFx = CFLy \qquad 2.5$$

How different processes contribute to the environmental impacts is also important to understand. This is given by the D_{pro} matrix;

$$D_{pro} = CE = CF\hat{x} \qquad 2.6$$

By using matrix manipulation, it is possible to calculate the contribution to impacts from stressors as well;

$$D_{str} = C\hat{e} \qquad 2.7$$

$$d = D_{pro} + D_{str} \qquad 2.8$$

Structural path analysis

The goal of structural path analysis is to systematically extract important supply chains, structural paths, which contribute to the various environmental impacts (G. Peters & E. Hertwich 2006). The resulting structural path analysis will reveal which processes in the production system are having the main responsibility for the environmental impacts associated with a foreground process. It will also reveal which processes are causing a demand on whom. A structural path analysis is mathematically closely related to the Taylor series expansion, and can be useful in a life cycle assessment. This study only made use of Taylor series expansion very simple for studying emissions associated with purchases done by one sector studied (see chapter 4.2.3). It is a tool which can be useful in cases where it is interesting to study how far downstream emissions occur, and similar.

Geometric series expansion

The external demand on the system will trigger a chain of processes in the production system. In this study a demand for 1 kWh from offshore wind power will trigger the construction of a windmill, which again will require steel for the tower. To make steel, raw materials need to be extracted and processed, which put up a demand for energy. Using geometric series expansion, here Taylor series, reveals the relative amount of impacts associated with each tier of the production system. It gives the analyst a possibility to investigate whether the majority of environmental impacts occur upstream or downstream in the production system.

This analysis method is based on basic mathematical expansion of geometric series. Doing an expansion of the total output gives;

$$\sum_{t=0}^{\infty} A^t y = y + Ay + A^2 y + A^3 y + ... + A^n y = Ly = (I - A)^{-1} y = x \qquad \text{if } \rho(A) < 1 \qquad 2.9$$

Where ρ(A) is the spectral radius of the matrix A and ρ(A) = max| λ |, λ is the eigenvalue.

Each term of the series in equation 1.9 represents the output from one tier of the system. Summing all outputs gives the total output, x.

Calculating impacts associated with the different tiers is done by using the production outputs in every tier. Output in one tier is given by the product of the external demand and the requirement coefficients in all previous tiers. The contribution of impacts in each tier is calculated by;

$$\sum_{t=0}^{\infty} CFA^t y = CFy + CFAy + CFA^2 y + ... + CFA^n y = CFLy = d \qquad 2.10$$

2.3 Input Output Analysis

One of the main purposes of the IO framework is to analyze the interdependence of industries in an economy (Miller & Blair 1985). Matrices are used to model the economy of a country or a region. It gives us a tool for modeling the flows from all economical sectors to all other economical sectors in a given region. The fundamental information with which one deals in IOA concerns the flows of products from each industrial sector considered as a producer, to each of the sectors considered as consumers. In recent years the IO framework has been extended to deal more explicitly with topics as accounting for environmental pollution, energy consumption, interregional flows and employment associated with industrial production (Miller & Blair 1985). This is being used in an Environmentally Extended Input-Output Analysis (EE-IOA).

The mathematical structure of an IO system consists of *n* linear equations with *n* unknowns as in LCA. This makes it possible to use matrix representation to solve and analyze the system mathematically. The main matrices in IO analysis are; the inter-industry flow matrix (Z), the inter-industry requirement matrix describing the intermediate inputs required to produce one unit output (A), exogenous final demand (y) and total output (x). These are all in monetary units. In an EE-IOA, a stressor and characterization matrix is used to connect the economical flows to the environmental impacts caused by the system.

The IO tables are derived from what is called the supply and use tables (SUT) which are a part of the System of National Accounts (SNA). SNA is an integrated national accounting structure, and a comprehensive framework including basic statistical data on transactions among micro-producing units (United Nations 1999).The SUT’s are used to derive the symmetric IO coefficient table (SIOT). For further reading on how to derive the SIOT’s, see (United Nations 1999).

2.3.1 Formal framework

Table 2-2. Nomenclature for the different matrices used in the mathematical framework of IOA.

Sets	**Prod (*m*)**		**Products**
	Ind (*n*)		**Industries**
	Str		**Stressors**
	Imp		**Impact category**
Matrices and variables	A	*(prod x prod) or (ind x ind)*	Matrix of inter industry requirements.
	y	*(prod x 1) or (ind x 1)*	Vector of external demand.
	x	*(prod x 1) or (ind x 1)*	Vector of outputs for a given external demand.
	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
	Z	*(prod x prod) or (ind x ind)*	Inter industry flow matrix.
	C	*(imp x str)*	Characterization matrix
	q	*(prod x 1)*	Total commodity output.
	g	*(ind x 1)*	Total industry output.

Some of these vectors and matrices are the same as in LCA, and some are only used in IOA. In IOA we have the inter-industry flow matrix (Z) which keeps track of the total inter-industry transaction flows between sectors over a given time period (often a year). The final demand vector (y) represents the consumption of goods. By normalizing the Z matrix, the A matrix can be constructed. It is the A matrix that is the core of this framework, as in LCA. This is the matrix giving the inter-industry requirements. This matrix is constructed by mapping inter process or - industry flows, Z, in any unit and then dividing each column of inputs with the total output (x) of the respective industry or process (Strømman 2009). This gives the relation;

$$Z = A\hat{x} \Leftrightarrow A = Z\hat{x}^{-1} \qquad 2.11$$

The formal framework of IOA also has, as we see, its basis in the open Leontief model. The A matrix is a square per unit matrix, having the same number of producers and consumers. It has to be either a product-by-product matrix or an industry-by-industry matrix. If A is a product-by-product matrix, the coefficient a_{ij} tells us how much money is needed from *i* to produce one monetary unit of output from *j*. A column in the matrix represents a product technology and a row represents the distribution of a product to intermediate inputs and as final use (United Nations 1999). If A is an industry-by-industry matrix, a_{ij} gives how much money from industry *i* is required to meet the requirements for output of one monetary unit from industry *j*. A column represents an industry technology containing all inputs required by that industry, and a row represents the distribution of the industry output to all industries and to final consumers (United Nations 1999). By adding an exogenous external demand (y) to the system, the total output (x) can be found by the open Leontief;

$$x = Ax + y \Leftrightarrow x = (I - A)^{-1} y \Leftrightarrow x = Ly \qquad 2.12$$

Constructing symmetric A matrices in IO is done from supply and use tables (SUT) and is challenging and necessary work when performing an IOA. There are two different assumptions that can be undertaken when constructing the A matrix; the industry technology assumption or the commodity technology assumption. The industry technology assumption assumes that the input structure will be decided by the industry producing a commodity. This means that all primary and secondary products produced by a given industry, are produced using the same technology. The commodity technology assumption assumes that it is the product produced that decides which technology is used in production, and hence the input structure. The input structure and technology used for a product is thus the same no matter where the commodity is produced. For both of these assumptions, either a product-by-product *(m x m)* A matrix or an industry-by-industry *(n x n)* A matrix can be made. This will not be further elaborated on here, but more can be read about this in (United Nations 1999).

Another attribute to the IO data is the value added vector (V). Included in the value added vector are salaries of employees and shareholders profits. For a given purchase, we can find the total amount of salaries and operating surplus that is generated. Value added can also be used in calculating the Gross Domestic Product (GDP) of a region. The vector v is value added per unit;

$$GDP = vx = v(I - A)^{-1} y \qquad 2.13$$

EXIOPOL

In this study, the EE-IO database from EXIOPOL is used in order to cover required data input to manufacturing of cables in the different life cycle inventories. According to Tukker et al., the EXIOPOL is “a new environmental accounting framework using externality data and input-output tools for policy analysis” (Tukker et al. 2009). It covers relevant research on environmental valuation and Environmentally Extended Input Output Assessment (EE-IOA). The aim is to support cost-effectiveness and cost-benefit analysis of technologies, policies and standard setting, on micro, meso and macro level (EXIOPOL 2011). EXIOPOL has in its research set up an EE-IOA framework in order to get estimations of the environmental impacts and external costs of different economic sector activities, final consumption activities and resource consumption for countries in the EU (EXIOPOL 2011). The EE-IOA work in the EXIOPOL has an objective of giving EU a fully developed, detailed, public, transparent and global multiregional EE-IO framework that includes externalities. With a multiregional database means that several economic regions are included and that trade between these regions are accounted for.

By using the symmetric input-output tables provided by the EXIOPOL project, an analysis of the economical sector covering cable manufacturing is carried out. It is the sector "Manufacture of electrical machinery and apparatus n.e.c. (31)" which covers manufacturing of power cables in the EE-IOA tables. In this study, the material requirements for the cables (metals and plastics) are known. Processes from the Ecoinvent 2.2 database are used to represent these inputs. This makes it necessary to adjust the IO A matrix in order to avoid double counting. This must be done by either subtracting the material amounts from the respective IO sectors, or by putting the respective sectors to zero. Either two of these methods have their advantages and disadvantages. In reality some of these materials, for instance steel, will also be used for other processes than directly as inputs to manufacturing of the cable. Putting the respective sector to zero will hence underestimate the amounts of materials used. On the contrary, by subtracting the amounts of materials used in manufacturing of cables directly from the respective sectors, new challenges and uncertainties occur. To do this, a price must be found for the different materials. This might be difficult as there are big price variations on these types of materials. This uncertainty may at worst result in having to subtract more materials than available in the A matrix, leaving negative numbers in the A matrix. The A matrix cannot hold negative numbers, so this has to be handled. In this study, the sectors representing the respective materials will be set to zero.

By analyzing the environmental impacts caused by 1 Euro of cable, the emission intensities associated with this demand was found. The emission intensities were then included in the stressor matrix in the life cycle inventory analysis, in order to include the environmental stress caused by the manufacturing of cables. Then, a "dummy process" denoted "Cables manufacturing (IO)" was made in the life cycle assessment of cables, to be able to calculate the environmental impacts caused through the entire lifetime.

In the IO dataset, 28 stressors are included whereof all are emissions to air. These are;

Ammonia (NH^3)
Arsenic (As)
Benzo(a)pyrene
Benzo(b)flouranthene
Benzo(k)flouranthene
Benzene, hexachloro- (HCB)
Cadmium (Cd)
Carbon dioxide (CO_2)
Carbon monoxide (CO)
Chromium (Cr)
Copper (Cu)
Dinitrogen monoxide (N_2O)
Dioxins
Sulfur oxides (SO_x)

Indeno
Lead (Pb)
Mercury (Hg)
Methane (CH_4)
Nickel (Ni)
Nitrogen oxides (NO_x)
NMVOC
PAH
Particulates, > 10 um (TSP)
Particulates, < 2.5 um
Particulates, > 2.5 um, and < 10um
Polychlorinated biphenyls (PCB's)
Selenium (Se)
Zinc (Zn)

Environmental extensions of the IO system

The input-output system can be extended to account for direct and indirect environmental impacts. This is taken advantage of in this study. IOA describes economical trade between different sectors, and can be exploited to study what the environmental effects are caused by these economical transactions. This can be done by making a stressor matrix (F), which takes care of including the environmental burden by the economical transactions. F_{ij} is the environmental burden *i* per monetary output from sector *j*. This makes it possible to calculate the total emissions caused by the system (e), due to total monetary output. As in LCA, a characterization matrix (C) can be made, which makes it possible to calculate the vector of total environmental impacts from the system (d). The mathematics and matrices are the same as explained under LCA, just in monetary units.

$$e = FLy \tag{2.14}$$

$$d = Ce = CFLy = CF(I - A)^{-1} y \tag{2.15}$$

Chapter 3

3 Background

3.1 Power markets and trade mechanisms

A power cable will be installed between two power markets or price areas if the prices for power differ in these two regions. If there is a price difference, power will be transmitted between markets since a profit through purchase and sale of power can be achieved. The profit motivates development of cables and consists of the *trading revenue, producer's surplus and a consumer's surplus.* The prices of electricity and hence how the power market function, is useful knowledge when discussing development of submarine power cables in the North Sea. A brief introduction and explanation of the power market and of relevant mechanisms for power trade, is therefore given in this subsection. In chapter 5, a deeper discussion will be provided, of the environmental costs and benefits associated with power cables between different regions across the North Sea.

A power market is a market for sale and purchase of power. How the power market is structured, and how purchase and sale is organized, will vary within the different markets. European power markets are often divided into five regions; Continental Europe (former UCTE), Great Britain, Ireland, the Nordic regions (former Nordel) and the Baltic regions (Svendsen et al. 2010). These five regions are today gathered into one organization called The European Network of Transmission System Operators for Electricity (ENTSO-E). ENTSO-E is an organization consisting of all the electric Transmission System Operators (TSO's) in EU and others connected to their networks. The organization coordinates and speaks for all the TSO's in order to ensure reliable operation, have an optimal management, ensure security of supply and attain a sound technical evolution of the European electricity grid (ENTSO-E 2011). ENTSO-E communicates the different TSO's needs and positions on European and regional issues. Still, the different regions have their own market places for trading of power.

The Nordic regions for instance, have a common Nordic wholesale market for power, called the Nord Pool Spot market. A wholesale market is where the sale and purchase of large power volumes take place. The market participants are power producers, power suppliers, traders and large end-users. In the wholesale market physical trading, financial trading and clearing of contracts take place. The spot market offers trade for day-ahead physical delivery of power. Prices are decided through auctions for each hour in the day. The system price is the unconstrained price in Elspot and is the reference price for financial trade in the Nordic market. The system price is determined based on supply and demand for power in the market.

The Nord Pool Spot AS is owned 20 % each by the TSO's in Sweden, Norway, Finland and Denmark, and manages the physical power sales in the Nordic regions. The remaining 20 % is owned by Nord Pool ASA, which is owned 50 % by Statnett SF in Norway and 50 % by Svenska Kraftnät in Sweden (Wangensteen 2007). How the various power markets are constructed vary somewhat in the different regions in Europe.

A relevant question is; how will trade be affected by a power cable between different power markets? A power cable enables power transmission between two different price areas. Development of cables is dependent on differences in the power system and the prices in both ends of the cable. In principle new transmission capacity can be developed as long as the expected price differences cover the cable costs. Profit is made by buying cheap power in one market and sell the same power for a higher price in another market (Adapt Consulting AS 2010). Both trading incomes (due to "bottlenecks" in the grid) and producer's and consumer's surplus are earned by connecting two power markets.

The reason why there are price differences between power markets is because the costs of producing power differ between countries. It is the difference in production costs in for instance Germany and Norway that gives the trading revenues. The yearly trading revenue (often called the congestion rent, but denoted TR in figure 3-1) on a foreign power cable connection is decided by the absolute price difference in every hour between the two markets that are connected, multiplied with transmitted power volume (excluding transmission losses) and summed over all hours throughout the year. The power exchange can also affect the prices in the two markets, and hence cause negative or positive changes in the producer's and consumer's surpluses (denoted CS and PS in figure 3-1). Power trading is illustrated in figure 3-1 below. This figure is gotten through personal communication with specialists in Statnett. The explanation of coherences between power markets and power transmission is based on information gotten through personal communication with Statnett [2] and the book *Power System Economics – the Nordic Electricity Market* by Wangensteen (Wangensteen 2007).

[2] Information about the gains from spot trading, including Figure 3-1, are got through personal communication with specialists in Statnett. Dated 03.05.11.

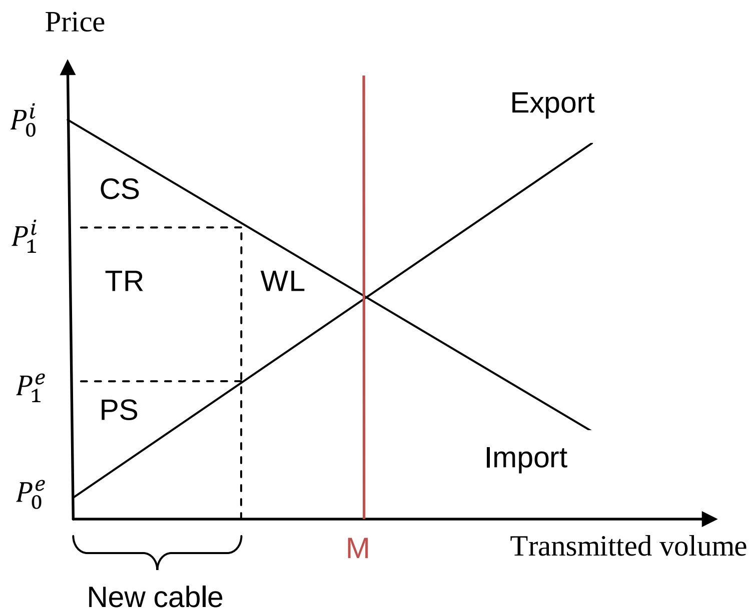

Figure 3-1. Profitable power trade between two price areas.

In an efficient market, all cost and benefit components associated with an international power cable will in principle be reflected in the market prices. Figure 3-1 shows the potential of trade between a power market with available power for export and a market with import requirements, in a given hour. The county with the lowest price will be the country exporting power. P_0^i is the price in the market being a potential import market, and the price P_0^e is the price in the market having the potential of being the exporter. These are the prices when there is none trading connection between these markets. If a power cable is installed between these two markets, the power will flow from the market with low price and to the market with a high market price. This cable has the capacity denoted "New cable" in the figure. When this occurs, the price in the import market will be reduced to P_1^i, while the price in the export market will increase to P_1^e. The socio-economic surplus will become the sum of the areas denoted TR (congestion rent/trading revenue), CS (consumer's surplus) and PS (producer's surplus). For this power link to be profitable, the total surplus must exceed the investment costs and other possible socio-economic costs after they have been aggregated over all hours of the year and discounted throughout the lifetime of the power link.

Before the power link is installed, the areas denoted CS, PS, TR and WL (welfare losses) constitute a cost due to lack of transmission capacity between areas. By investing in new transmission capacity, this cost is reduced to the area denoted WL. This welfare loss exists because there is insufficient transmission capacity between these areas. The vertical line, M, is the transmission capacity that gives an equal price in both price areas. If the capacity is increased to this level, the TR becomes zero, and all surpluses will be divided between consumers or producers. The socio-economic gain hence increases.

This figure illustrates what can be a challenge and problem if Norway is expected to produce more power than the demand in Norway suggests, and then export the surplus to other European countries. Norway already has a very low electricity price, as the Norwegian hydropower is very cheap. If Norway is in an export situation, the market price will increase (for example from P_0^e to P_1^e). This implies that the electricity price increases and there is a redistribution between domestic producers and consumers so that the producers win and the consumers loose. In the hours of import to Norway, it will be opposite. Then the consumers win while the producers loose due to a lower electricity price. How great the price effects are from trade of electricity, depend on the gradient of the supply and demand curves and hence how elastic the prices are. The price effects from trade of electricity also depend on the total transmission capacity between the different power markets.

Some other points worth noticing are; that the trade revenue depends on the price differences after the connection is built and that changes in consumer’s and producer’s surpluses depends on price differences both before and after the connection is built and installed.

3.2 Offshore wind power

An offshore wind farm is a power plant consisting of several windmills that convert wind power into mechanical power. A windmill is made up of different components, such as foundation, tower and wind turbine. The wind turbine is a machine which converts the power in the wind into electricity which can be utilized. A wind farm consists of windmills, high-voltage transformer stations and transmission grid. Onshore, there is a Substation situated to feed the electricity produced into the electricity grid. The electricity can either be transferred onshore or be used to supply offshore oil and gas installations with power.

Making use of wind power is not a new idea. The first windmills known were built by the Persians around year 900 AD (J.F. Manwell et al. 2002). However, the re-emergence of wind energy was considered to find place in the late 1960’s, when an important change in people’s opinion and awareness about environmental issues took place. This is sometimes referred to as “the environmental revolution”, and was a reaction to the increasing pollution levels in the industrialized countries. This awareness was triggered much by the book *Silent Spring* written by Carson and published in 1962. In 1972 the book *The Limits to Growth* was published, examining possible world development models based on system dynamics techniques (Brattebø et al. 2007). The conclusion was that planet Earth has a limit to growth which would be reached within a hundred years if pollution, world population, industrialization and resource depletion continued unchanged. Fossil fuels hence became one of the culprits, and a new interest in wind power emerged. Several wind concepts have been developed since that; horizontal axis turbines with one, two, three or multi- blades, up-, down- or cross-wind concepts, concepts with multiple rotors and concepts of rotors using drag instead of lift (J.F.

Manwell et al. 2002). Today, windmills are normally three-bladed horizontal axis wind turbines. These are the windmills studied here.

As more power is needed in our society, the wind power industry moves towards larger windmills with higher installed effect. By developing wind farms offshore, better wind conditions can be achieved and larger windmills can be built. At present, offshore windmills are typically bottom fixed constructions often using Monopile or Gravity based substructures. Most of today's, and the near future's, wind farms will be located 10 - 30 km from shore on water depths between 5 - 30 m. A typical wind farm has a capacity of 50 - 200 MW with wind turbines of a nominal effect of 1 - 3 MW (Rademakers et al. 2009). In the future, wind turbines are expected to increase in rated power, typically to 5 MW and higher, and the wind farms are expected to be located further offshore (Rademakers et al. 2009). In this section a rough description of the technological aspects for an offshore wind farm will be given. This is to give a basic understanding of what is included in the term *offshore wind farm*.

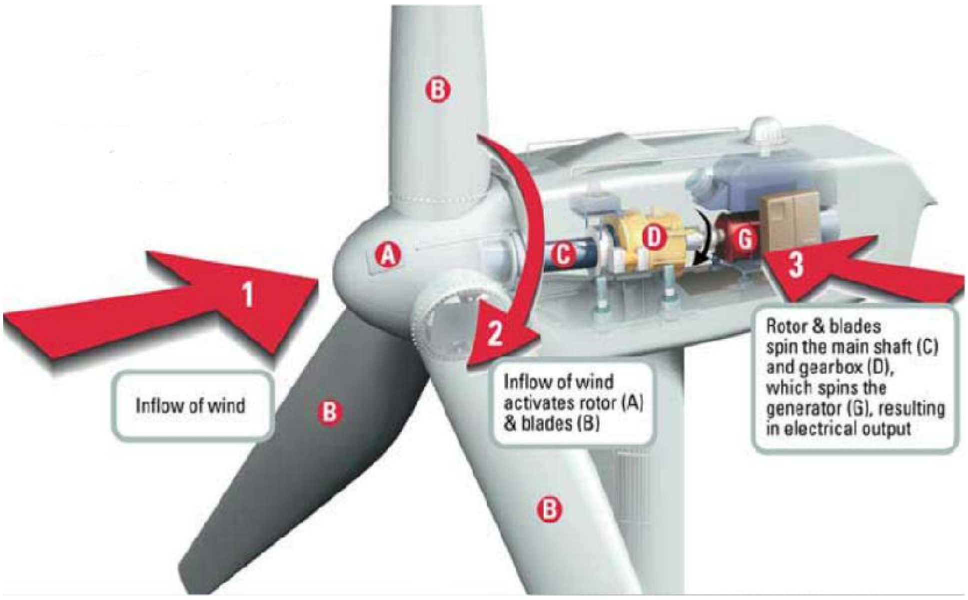

Figure 3-2. Illustration of how a wind turbine work and what technical components that constitute the wind turbine.

Modern wind turbines are horizontal axis wind turbines, as the ones in figure 3-2. These utilize lift forces to make the rotor turn, which then makes the drive train rotate. The drive train consists of all rotating parts of the turbine; a low-speed shaft (on the rotor side), a gearbox, a high-speed shaft (on the generator side), support bearings, brake and the rotating parts of the generator. The gearbox speeds up the rate of rotation (rpm) of the rotor from a low value to the high value required in the generator. The generator then converts this mechanical power into electricity which can be transferred to the main grid. All these components are parts of the windmill's nacelle. The yaw system is also a part of the nacelle, and is required to keep the rotor shaft properly aligned with the wind. A bearing in the yaw system connects the main frame of the wind turbine, to the tower of the windmill (J.F.

Manwell et al. 2002). The tower of a windmill is normally 1 to 1.5 times the rotor diameter, and for offshore windmills it might be higher, depending on water depths. The tower is usually a steel tube, supporting the rotor and machinery. The tower is then fixed to the windmill foundation, often called the substructure of offshore windmills. The substructure stabilizes the wind turbine, and must for offshore windmills have the strength to resist the great weather forces acting upon the windmill. Hence, they are either heavy concrete foundations (Gravity based substructures), or they're anchored to the seabed by for instance drilling the substructure into the seabed (Monopile foundations) or by using mooring. The windmills are connected to one or several high-voltage transformer stations through the internal collection grid. The task of a transformer station is to transform the medium-voltage electricity delivered from the wind turbines, up to high-voltage level in order to transfer it to the grid onshore. The high-voltage transformer transforms typically electricity of 33kV delivered from the wind turbine, up to 132kV for transmission from the wind farm and onshore (Rasmussen et al. n.d.).

Operation of an offshore wind farm is typically done by remote control onshore. As many functions as possible are remote controlled. This reduces the need for offshore work (Havsul 1 AS 2006). The further offshore a wind farm is located the less accessible will it be. Weather conditions are among the most important aspects when choosing operation and maintenance strategy. The weather conditions offshore can give limitations on accessibility and hence reduce the regularity of the plant. Waiting for access to the wind farm and the costs for work on site, are among the most important reasons to optimize the strategy used for operation and maintenance work (Bussel & Schontag 1997). Maintenance of an offshore wind farm will depend upon several aspects such as reliability of turbines, maintainability of turbines and weather conditions (Rademakers et al. 2009). The goal is a cost effective maintenance and securing high regularity on the wind turbines (Faulstich et al. 2006). In general, maintenance work of an offshore wind farm can be separated into two categories; preventive and corrective maintenance. Preventive maintenance is performed on a regular basis, to prevent equipment breakdown, replacement of parts etc. Corrective maintenance is performed when failures or break down occur on wind farm (Rademakers et al. 2009).

During installation, operation and dismantling of an offshore wind farm, a lot of transportation is required. Special vessels and equipment are required as the wind farm is located offshore and the constructions are large and heavy. Doing the same operations offshore, using floating vessels, is challenging both because of heavy lifts and need for precision. This makes it desirable to place cranes and excavators on solid ground, as the operations then become easier to accomplish and more stable. As much pre- assembling as possible should also be performed before installation on final location. All activities that have to be carried out by personnel in the wind farm are sensitive to weather conditions. It is therefore preferable to do this kind of work during spring and summer months (Havsul 1 AS 2006).

3.3 Electrical power transmission offshore

Electrical power generated by offshore wind farms requires submarine cables in order to transmit the power from the power plant and to the onshore utility grid. Power from wind turbines is generated as an alternating current (AC). The onshore grid is also AC, which makes an AC cable system the most straight forward transmission system to apply (ESS Group Inc. 2004). A direct current (DC) cable system can also be used, which will require converters in both ends and also result in lower transmission losses than for AC. DC is normally used for long distance power transmission.

Large- scale expansion of power generation in the North Sea is expected to open up for an expansion of the transmission grid in the North Sea as well, as for instance with power cables between Norway - the United Kingdom and the United Kingdom – the Netherlands. For power links across the North Sea, HVDC power cables are used.

3.3.1 High- voltage alternating current (HVAC) and high-voltage direct current (HVDC)

Which technology should be chosen for the different types of cables? High- voltage alternating current (HVAC) or high-voltage direct current (HVDC)? AC and DC will in this study mainly be discussed in the context of submarine power transmission.

Direct current can be explained as electricity flowing in a constant direction, possessing a voltage with constant polarity. Alternating current is electricity made by the current switching direction back and forth, or the voltage switching polarity. Using alternating current makes it possible to build electric generators and power distribution systems that are more efficient than if using direct current. This has made AC more used in high power applications worldwide (All About Circuits 2011). Compared to HVAC technology, using HVDC technology allows electricity to be transmitted through subsea power cables over substantially longer distances, with fewer cables than HVAC, reduced power losses over long distances and without requirements of compensation equipment to be installed to the cable in order to maintain power transfer (The Crown Estate 2008). These are some reasons why HVDC is used for longer power transmission distances than HVAC. Since the existing onshore transmission system utilizes AC technology, converter stations are required to interface the AC and DC electricity transmission systems (The Crown Estate 2008).

In the context of submarine power transmission, the most significant difference between DC and AC is that AC cables have high capacitance which results in considerable generation of reactive current (ABB 2010). Capacitance is explained as the ability of an insulating material between conductors to store electricity when there is a voltage difference between the two conductors (ABB 2010a). Reactive power is made by reactance through the relation: Q =

U^2/X. Q is the reactive effect [VAr], U is the voltage level [V] and X is the reactance [Ω]. Reactance is essentially inertia against the motion of electrons (All About Circuits 2011a). Reactance is most notably present in inductors and capacitors, and if AC flows through a pure reactance there will be a voltage drop which is out of phase with the current (All About Circuits 2011a).

Another characteristic of an AC cable is the charging current induced in the cable due to the capacitance between each phase conductor and earth. The capacitance of a HVAC insulated cable plays a role in limiting the technically feasible length of the cable (Wright et al. 2002). The cable itself acts as a long capacitor, and this charging current will be induced along the cable's length. Longer cable, give more reactive power generated (All About Circuits 2011a). The cable must carry this charging current in addition to the useful load current. This physical limitation will reduce the carrying capability of the cable as the active current- carrying capacity of the cable is reduced. If the cable is longer than 10 km, a plan on how to compensate for reactive power is required for the cable (Wright et al. 2002). Higher voltage level for transmission will result in higher charging currents. This will make the challenge of reactive power and transmission losses even more difficult. Typical amounts of reactive power generated in 33 kV HVAC XLPE cables is in the range of 100-150 kVAr/km. For 132 kV HVAC XLPE cables the range is 1000 kVAr/km (Grainger & Jenkins 2000). In DC transmission a charging current only occur during the instant switching on and off. Therfore this current has none effect on the continous current rating of the cable. This is why HVDC transmission does not have any issues with the length and voltage level limitations, such as AC has, and is preferred used in long distance subsea cable interconnections (such as UK-Norway, UK-Netherlands etc) (The Crown Estate 2008).

Figure 3-3 below is from The Crown Estate's report *East Coast Transmission Network Technical Feasibility Study* and compares HVAC and HVDC cable power capacity. It shows how essentially much better HVDC is for long distance power transmissions, than HVAC is.

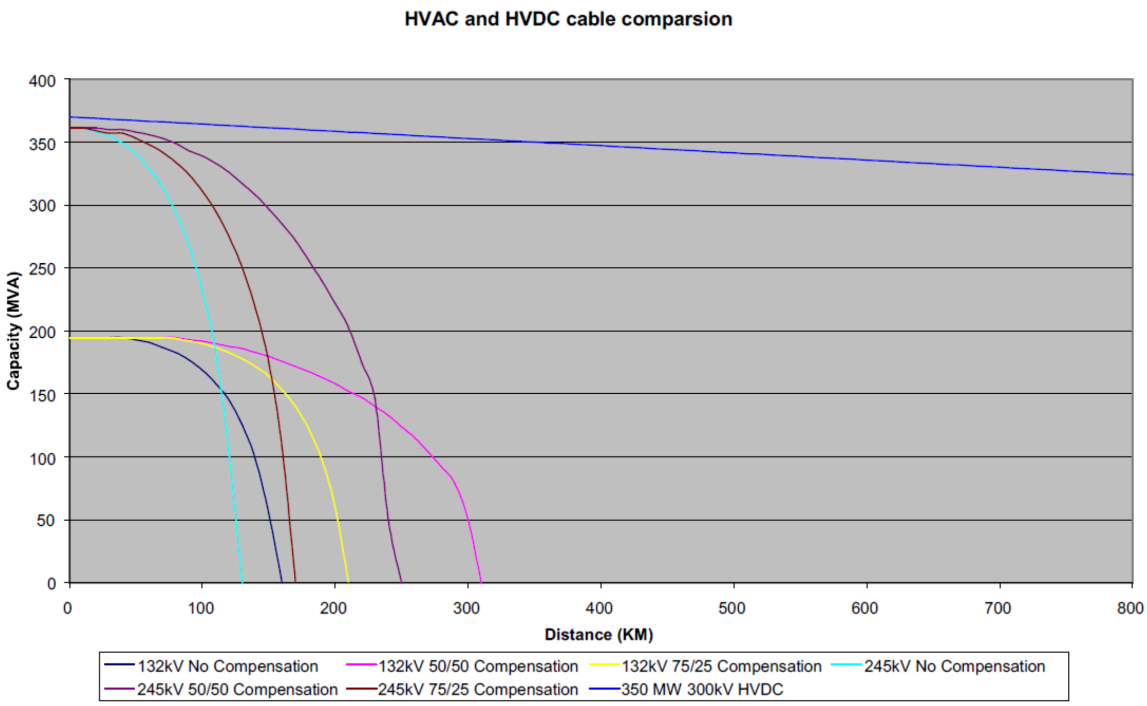

Figure 3-3. This figure shows a comparison of HVAC and HVDC cable power capacity (The Crown Estate 2008).

Figure 3-3 shows that the capacity of HVAC power cables decreases with increasing distances. Up to about 100 km, the capacity is kept on an accepted level, but with longer transmission distances the capacity decreases rapidly. For HVDC on the other hand, there is only a small decrease in capacity, when increasing the transmission distances. The figure illustrates that there are almost none limitations in distances for HVDC power transmission.

For HVAC cables, shunt reactors are required connected to the circuit at either end of the HVAC cable. These are located either 50:50 offshore and onshore, or 75:25 onshore and offshore. HVAC cable capacity is limited mainly by the charging current, while the HVDC cable capacity is limited mainly by resistive voltage drop (The Crown Estate 2008). The graph shows several scenarios of cable transmission. It is very obvious that for long distance transmission, HVDC cables will be the best option having less capacity loss. For offshore wind farms, 132 kV power cables are often used for transmitting power from the wind farm an onshore. Until now it has been normal to use HVAC technology for this, as the wind farms are not located very far from the coast. The graph shows that AC cables can be used for this as long as the distances are shorter than ~ 100 km and the 132 kV cable has 50/50 compensation. If the wind farm is located further offshore, HVDC transmission will become a realistic choice for transmission. AC is usually the most cost-effective alternative if the charging current is less than the active current, and losses and voltage drop are kept under an acceptable limit. Wright et al. states that as a rule of thumb, economic cut-off point for AC vs. DC is estimated to be between 30 and 250 km (Wright et al. 2002).

In HVAC cables the main challenge is transmission losses in the cable. AC cables suffer from what is called the “skin effect”. The “skin effect” concentrates the currents at the outside edges of the conductor, meaning that HVAC cables only uses the outer of the conductor to carry the current. This may lead to a requirement of very large conductors in AC transmission, or use of several smaller conductors, in order to transfer a given amount of power. In HVDC transmission, however, the entire cross-section of the conductor can be utilized. This makes it possible to use smaller conductors for same level of power transferred. Transmissions losses are higher for AC transmission than for DC transmission, because the AC resistance is higher than the DC resistance due to the skin effect in cables (Meah & Ula 2007). DC cables lack both the charging currents in the conductor and the induced current in the shielding, so even though there will be electrical losses in the converters the overall losses will be lower for a DC than for an AC alternative (Wright et al. 2002).There are several components that make up the losses in the cable:

Table 3-1.Different losses in a HVAC transmission cable (ESS Group Inc. 2004).

Type of loss	Comment
Dielectric losses	Results from the heating effect on the dielectric material between the conductors. These are relatively small.
I^2R losses n the conductor	Usually the largest component of losses.
I^2R losses in the metallic shield	Current flow is induced in the shield by the current in the conductors; shield losses can be on the order of one-third of conductor losses.
I^2R losses in the steel wire armor	Current flow is induced in the armor by the current in the conductors; armor losses can be on the order of one-half of conductor losses.

For HVDC transmission, there are mainly two technologies that are used for converters; Current Source Converters (CSC) and Voltage Source Converters (VSC). To drive the CSC’s an external voltage source to drive the converter and feed its inherent reactive power demand is required. CSC HVDC systems are able to control large amounts of real power flow, but unable to dynamically control reactive power injected to (or absorbed from) the AC network in contrast to a VSC HVDC converter station. A CSC HVDC system hence requires reactive compensation to be connected to the AC side of the converter, in order to compensate for the reactive power drawn by the converter and to provide the required reactive power to the grid (The Crown Estate 2008). VSC’s does not require any external power source as it is an independent voltage source that can supply or absorb reactive and/or active power. VSC converters are able to form their own AC voltage wave form, and act as a true voltage source, because they utilize the high power Insulated Gate Bipolar Transistor (IGBT) technology. Unlike the thyristors used in the CSC technology, the IGBT's are self commutated which means that they are switched on and off rapidly to modulate a voltage waveform (The Crown Estate 2008). This gives flexibility on where the converters are located in the system, which makes it well suited for transmitting power from for instance offshore wind farms. VSC's are the most ideal to use in offshore installations. A more detailed and thorough description of CSC and VSC technology will not be given in this report. For further reading about this see for instance (The Crown Estate 2008), (Reidy & Watson 2005).

Even though AC will result in higher losses than DC, the AC cable systems are well understood and a mature technology. AC technology is the most cost-effective alternative unless the voltage level is very high or the transmission distances are long (Wright et al. 2002). In most cases, HVDC transmission will be more expensive than HVAC transmission due to the need for the extra converters. The cables themselves are less expensive than for AC, because they with the same amount of insulation can be operated at a higher current and therefore allow more power per cable. Still, the HVDC alternative is often more expensive due to the converters needed in both ends of the cable, that are very expensive and resource demanding. This is the key component to make an economical comparison between a DC and an AC transmission system (Meah & Ula 2007). Some advantages and disadvantages of HVDC transmission are listed (Meah & Ula 2007), (Wright et al. 2002):

Advantages of HVDC:

- The power flow can more easily be controlled, both in respect of power direction and in amount.
- Greater power per conductor. A set of cables which now is used in a medium-sized AC wind farm, can later be used in a wind farm four times the size if you add a converter and more wind turbines.
- Simpler line construction.
- No charging current.
- No skin effect.
- Cables can be worked at a higher voltage gradient.
- Line power factor is always unity: line does not require reactive compensation.
- Synchronous operation is not required. The frequency and voltage at either end can differ.
- May interconnect AC systems of different frequencies. Does not transfer short-circuit current on DC line.
- Does not contribute to short-circuit current of an AC system.
- Avoids the resonance between the cable capacitance and the inductive reactance of the grid.
- The direction and magnitude of the power flow can be controlled.

Disadvantages of HVDC:

- Converters are expensive.
- Converters require much reactive power.
- Converters generate harmonics, require filters.
- Multi-terminal or network operation is not easy.

3.3.2 Composition of a submarine cable

A submarine cable is primarily constructed by a conductor, insulation and outer protection. The conductor is either aluminium or copper, and the insulation type will vary depending on type of cable and what it is used for. Outer protection of the cable is normally a type of plastic, as polypropylene. Figure 3-4 below shows a single-core cable, and a three core cable.

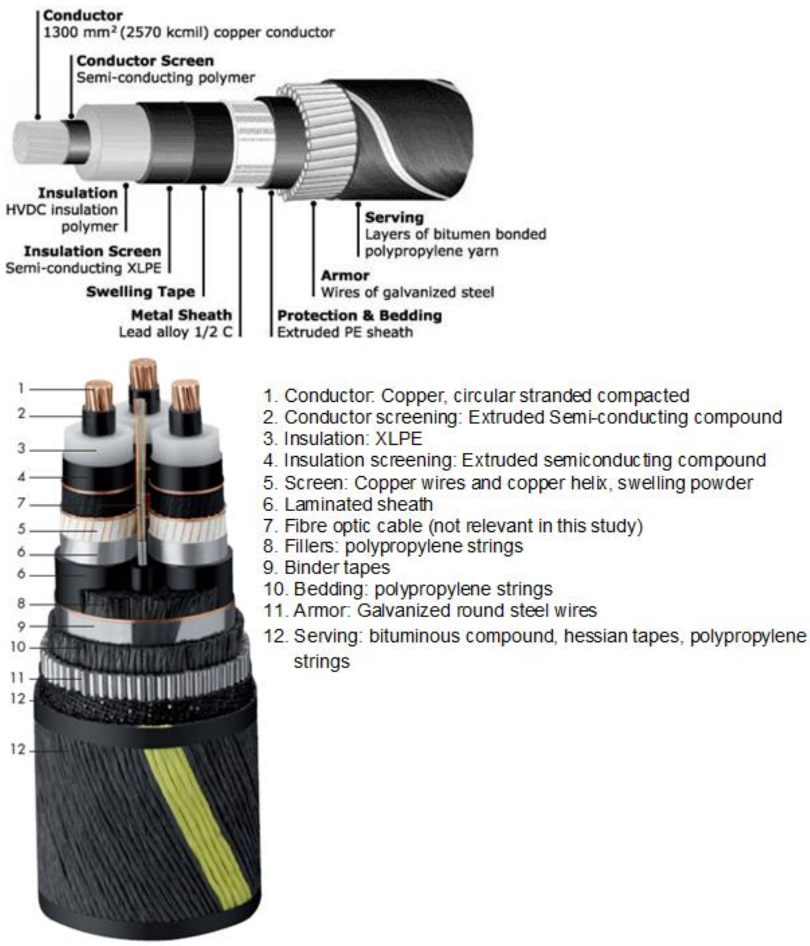

Figure 3-4. On top: Construction of a single-core XLPE cable (Wright et al. 2002). Below: Construction of a three-core cable (Nexans 2008).

Conductor

For medium and high-voltage cables it is most normal to use a copper conductor. Also aluminium conductors are common to use, but this is preferably used in underground cables. Copper is normally the material chosen in conductors for submarine cables because it has the best conductive properties and the greatest mechanical strength. Aluminium has a lower current-carrying capacity (ampacity), and thus requires a greater diameter (Wright et al. 2002). Then, more insulation will be needed as well. As aluminium will corrode in contact with seawater, cables with aluminium conductors can be more problematic to use in subsea cables than copper conductors. On the contrary, an advantage with aluminium is that it's lighter than copper. This provides us with a lighter cable which will be an advantage, both physically and in costs, when transporting the cables and installing them under sea. The disadvantage in a light weight cable used subsea is that it is more sensitive to buoyancy (Ildstad 2009).

In AC cables it also has to be decided whether all three phases are supposed to be "bundled" into one three-core cable, or if these shall be made in three separate cables. By gathering all three phases in one three-core cable, cable and cable laying costs are reduced. It will also produce weaker electromagnetic fields and have lower losses from the induced current, than if all three phases were laid separately.

Insulation types

This section is to a great extent based on lecture material from the course TET 4195, *High-voltage equipment*, lectured at NTNU spring 2010 (Ildstad 2009). There are two main types of insulation used in cables: Oil impregnated paper and polymer solid materials.

Oil impregnated paper

This insulation consists of wound paper impregnated with oil. The paper used is made from cellulose, which are chain molecules that are linked by chemical bonds. This creates paper fibers and has a density of about $1.54*10^3$ kg/m^3. Cable paper typically obtains a density of around $0.75*10^3$ kg/m^3, which implies that the content of pores is high. These pores need to be filled with impregnating agent. Well dried and impregnated paper will reduce the amount of dielectric losses.

Main types of impregnations are mass- impregnation and oil- impregnation. Cable mass is based on mineral oil. It will be thinly liquid while the impregnation is carried out because of high temperatures. When it is cooled down to normal operating temperatures, the cable mass will be viscous. This is an advantage if the cable trace has varying altitudes. When the cable has higher load, there will be a heat expansion in the cable. This will lead to a thermal expansion of the insulation. This can lead to deformation in plastic and in lead sheathing (or similar). When the cable is cooled down again, cavitations might have been created. If there are varying altitudes in the cable trace, and the impregnating agent is thinly liquid, then the insulation might be drained away from the high lying parts and concentrated in the lower parts. If the impregnating agent is viscous at all operating temperatures, this can be avoided. Still, there will be a challenge in avoiding cavitations (Ildstad 2009). The mass-impregnated paper-insulated cables are traditionally used for HVDC transmission and are available for voltages up to 500 kV (Wright et al. 2002).

Oil impregnation is a thin liquid that is either made from mineral oil or from synthetic oil. This is kept under over pressure in order to avoid the cavitations that occur during variations in temperature. If temperature increases in the cable, the oil is pressed out of the insulation and into small longitudinal oil passages made in the cable. Then, the oil is directed back to the reservoir where the oil is kept. In case of cooling, the opposite will happen.

Polymer solid materials

These are insulation materials made from plastic types. The most common insulation material used in high voltage cables in Norway is cross-linked polyethylene (XLPE). There are several types of solid materials that can be used.

Polyethylene, PE, consists of areas of crystalline and amorphous and is a non-polar material. Crystalline is when the structure in polyethylene is ordered, while an amorphous structure is when the chains of molecules are disordered. This makes the material have a melting point over a certain temperature area, as ordered and disordered molecules will have different melting point. Because of these characteristics of polyethylene, the density in PE will vary depending on whether the proportion of crystalline is high or not. A high level of crystalline, gives high density. Lower densities ($0.91\text{-}0.925^3$ kg/m^3) is called low density PE (LDPE), then you have medium density PE (MDPE) for a little higher densities and finally high density PE (HDPE) for the highest densities ($0.941\text{-}0.959*10^3$ kg/m^3). LDPE is most commonly used in cable insulation. The relative permittivity of PE is 2.3, and due to its non-polar property, the dielectric losses are low of about 0.0002 at 50 Hz.

Cross-linked polyethylene, XLPE, is made by vulcanizing polyethylene. Then chemical cross links are made in the material between the molecule chains. By doing this, the material will not transform into liquid even if it is heated up above the melting point. This makes it very strong and opens for keeping operating temperatures above 90 ºC for PEX. As polyethylene has low tolerance for partial discharges, it is very important to avoid cavitations in the cable. Small quantities of water dissolved in the polyethylene can result in a situation where tree like structures appear in the insulation and thus harm the cable. There are several ways of cross-linking polyethylene: radiation, silane cross-linking and peroxide cross-linking. This insulation type is normally used in HVAC cables, and is available for voltage levels up to 300 kV (The Crown Estate 2008). For more reading see Ildstad’s book *Cable technology* (Ildstad 2009).

Screening, sheathing and armor

Screening is a semi-conductive screening layer. This is made of paper or extruded polymer and is placed around the conductor. The point is to smooth the electric field and avoid concentrations of electrical stress, among other things (Wright et al. 2002).

A metallic sheath is placed outside the screening of the conductors in a submarine cable. This helps in grounding the cable, and it carries the fault current if the cable is damaged. In AC cables a current will be induced in the sheath, leading to circulating sheath losses (Wright et al. 2002).

Armoring, together with the outer protection (jacket), completes the cable construction. The armor is corrosion protected and has the function of protecting the cable. Sometimes, two layers are used in order to avoid twisting of the cable when it is lifted from the sea bottom and to water level. This is mainly a problem with deep waters. For HVDC cables steel can be utilized as protective armor around the insulation to help prevent damage on the cable.

The electrical system of an offshore wind farm consists of a medium- voltage collection system between the wind turbines, and a high- voltage transmission system to deliver the power to the onshore grid (Green & Schellstede 2007). For these electrical systems it is today most common to use solid dielectric cables with cross-linked polyethylene (XLPE) insulation which makes the cables robust and strong. This cable technology is presently used for all offshore wind farm constructions (ESS Group Inc. 2004).

3.3.3 Transmission of power related to an offshore wind farm

The electrical collection system is the grid which connects the wind turbines. In each wind turbine there is a low-voltage transformer which transforms the voltage from the generating voltage around 700 V, up to a medium- voltage level between 30-36 kV (Negra et al. 2006). For the internal power grid in an offshore wind farm, typically 33 kV HVAC cables are utilized. These are buried in the seabed, and connected to offshore high- voltage substations on site (Green & Schellstede 2007).

The substation is a high-voltage transformer station that steps- up the voltage to high-voltage level of around 130-150 kV, before transmission on shore. From the offshore transformer station, a submarine cable will transmit the power to grid onshore at a voltage level of typical 132 kV. This is called the transmission system of an offshore wind farm. If the distance is below 100 km, it can be expected that HVAC technology will be used. Transmission of power from the offshore substation in a wind farm and on shore has until now only been done by HVAC cables. Nevertheless, it is also possible to use HVDC cables and converters, especially when the transmission distance increases to above 100 km (ESS Group Inc. 2004). It can nevertheless be possible to use HVAC up to distances of 300 km, but then advanced compensation systems, larger conductors and similar must be utilized. In practice, the limit of utilizing HVAC is at 100 km [3] (see chapter 3.3.1 for explanation). On shore there is situated another substation that, if necessary, will step up the voltage to match the existing transmission grid onshore.

3.3.4 Long distance transmission across the North Sea

Possibilities for long distance interconnections between countries across the North Sea is widely discussed and studied. To this, advanced HVDC technology must be utilized due to long distances and deep water depths. There are already several electricity interconnections between the Northern European countries in both the North Sea and the Baltic Sea. Between Sweden and Germany we find the 250 km long Baltic cable HVDC link of 600 MW and between Norway and Denmark the Skagerrak HVDC link of 1000 MW is installed, including 127 km of submarine cable. Between Sweden and Poland we also find the 600 MW and 245 km long SwePol HVDC link, and between the Netherlands and Norway the NorNed interconnection of 700 MW and 520 km is installed (the longest submarine cable in the world) (ABB 2011). Common for all these links is that the transmission distances are long. Hence, HVDC technology is used.

If development of an offshore grid in the North Sea shall be carried out, HVDC cable technology will be utilized. Some of the links considered to be very useful if interconnecting countries across the North Sea, are interconnections between Norway-UK and UK-Netherlands. The BritNed cable between Great Britain and the Netherlands is a 1000 MW and 260 km long cable already in operation. Together with a possible link between Great Britain and Norway, this can be an important fragment of a future grid in the North Sea. Also, it connects the power market in United Kingdom to the European power markets, opening for new power transmission and trade. Several interconnection options between the Norwegian and the Great Britain electricity systems have been investigated the last years. This includes direct onshore to onshore connection, connection via Dogger Bank, connection via the Shetland Islands and a three way UK-Norway-Benelux option with Dogger Bank as a “hub” (Sinclair Knight Merz 2010). Alternatives of having a connection via oil drilling platforms have also been discussed. This will be further discussed later in this report.

[3] This is what large companies operate with today. The information is given by professionals in Statoil. Dated 09.05.11

Chapter 4

4 Life Cycle Assessments

This chapter will include the life cycle inventory analyses (LCI) and life cycle impact assessments (LCIA) for the cables and the entire offshore wind farm referred to under the explanation of the objective in chapter 1.1. This includes results from the basic contribution analyses and some selected structural path analyses. In the end a review of uncertainties is given together with an analysis and discussion of the results for this study.

4.1 Life Cycle Inventory Analysis (LCI)

To obtain the inventories for these cables, actual cables were used as models. The inventories for the 33 kV and the 132 kV were based on the cables planning to be used in the collection and transmission system of the offshore wind farm Havsul 1. This wind farm has got the concession approved, and is planned to be developed outside the coast of Møre og Romsdal in Norway. For the 450 kV cable, the inventory was based on data for the NorNed cable which is in operation between the Netherlands and Norway. This is the world's longest submarine power cable (Statnett 2008). Cables for transmission between European countries as Germany, United Kingdom, Norway and the Netherlands are expected to be similar to the NorNed cable [4].

The cables studied are;

- 33 kV HVAC cables used for internal connection of wind turbines and the high voltage transformer station situated in an offshore wind farm. These are three-core copper conductor cables with XLPE insulation, lead sheath and one layer of steel armor.

- 132 kV HVAC cables used for transmission of electricity from an offshore wind farm and to the grid on shore. These are three- core copper conductor cables with XLPE insulation, lead sheath and one layer of steel armor. Also HVDC cables can be used, but only for long distance transmission.

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[4] Information from Statnett through personal communication. E-mail correspondence 02.02.11

- 450 kV HVDC cable planned to be used for long distance power transmission. The cable is a mass impregnated single-core cable with cobber conductor and steel armoring.

Material requirements for the 33 kV and 132 kV cables are from product sheets from Nexans and ABB (Nexans n.d.) and (ABB 2010b). Amounts of materials required are calculated from the given cross-section sizes of the materials used in these cables. The material requirement for the 450 kV cable is gotten from data on the NorNed cable used between the Netherlands and Norway. As it has not been possible to obtain a detailed list of the materials required in the NorNed cable from the producer, data for the NorNed cable were obtained by doing physical measurements on a part of the NorNed cable which NTNU has got in-house. These measurements are assumed to give a good approximation. Because of lack in data on the manufacturing phase of cables, a part of the inventory is in monetary terms using the European IO data for the cable sector and the price of cables in basic prices. This means that inputs like electricity, heat and transport for the manufacturing phase, are included in the system through the IO system. The symmetric IO flow matrix (Z) for Europe is adjusted so that double counting of materials is avoided. The Z matrix is the IO flow matrix for Europe, including the countries given in appendix A.

Figure 4-1 shows an illustration of the foreground systems used in the LCA's of cables. It will be somewhat different for the 450 kV cable as this cable is not a XLPE cable, but a mass-impregnated paper insulated cable. For the entire offshore wind farm, the foreground system will be as in figure 4-2.

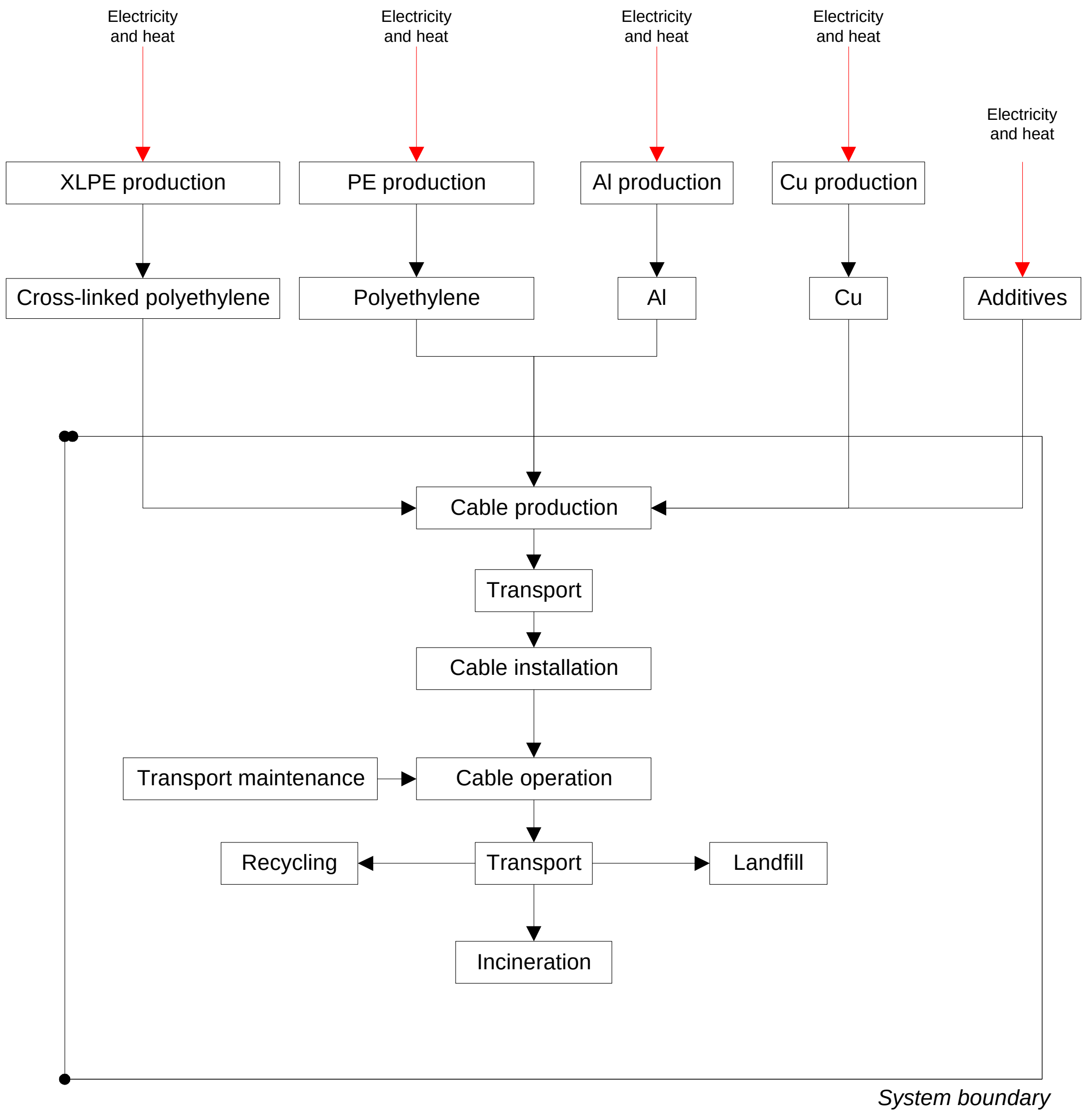


Figure 4-1. Illustration of foreground system in the analysis of the cables. The framed part is the foreground system's system boundary.

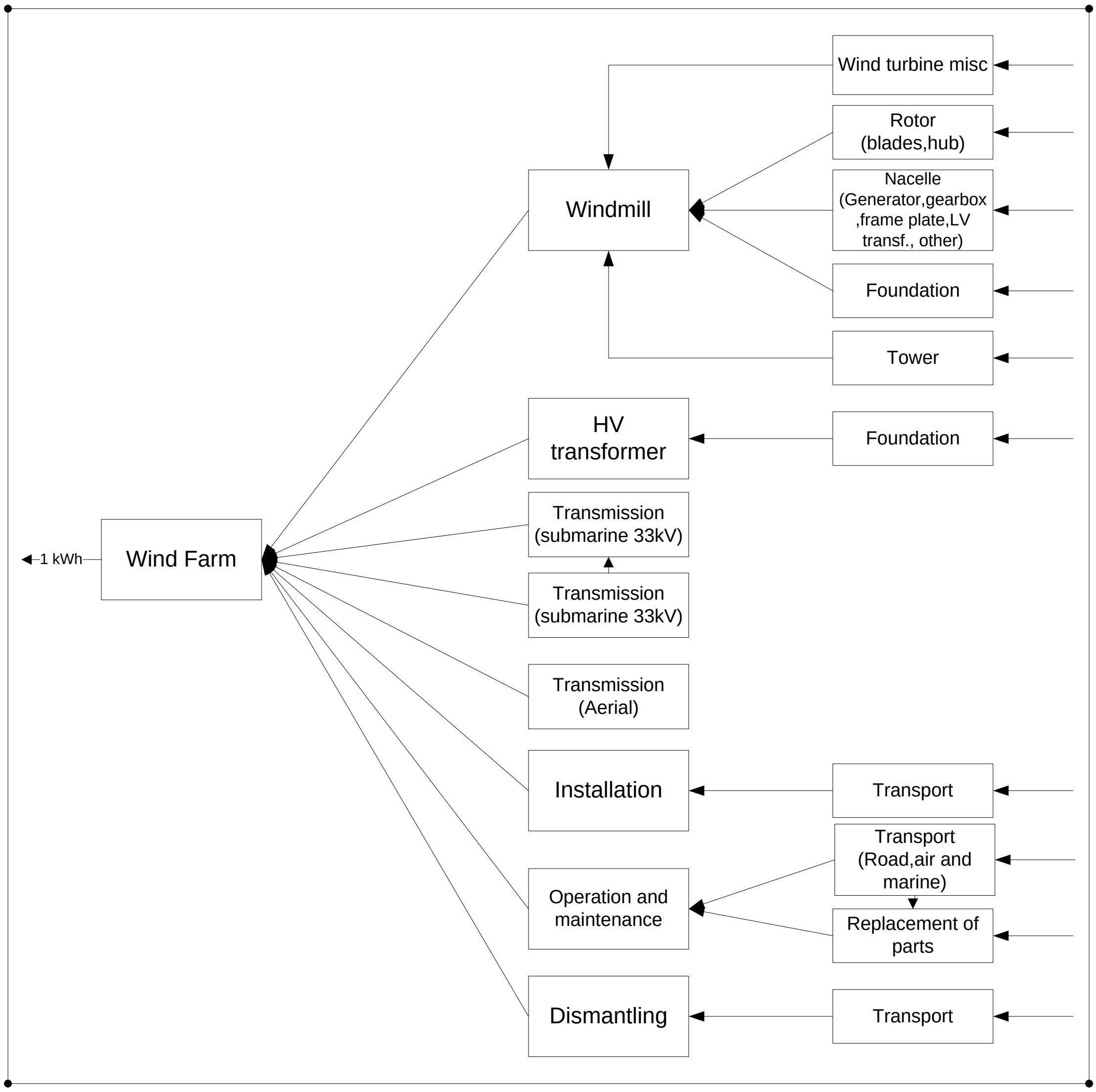


Figure 4-2. Illustration of foreground system in the wind farm.

4.1.1 LCI of Collection and transmission system

The cables in both the collection system and the transmission system of an offshore wind farm are typical HVAC submarine cables. For the transmission system also HVDC cables can be used, but this is only the case if the wind farm is located far offshore. This is explained previously in chapter 3.3. The 33 kV and 132 kV HVAC cables in this study, are XLPE insulated and with three-core copper conductors. Copper has been chosen as conductor material as these are submarine cables. It is assumed that one layer of galvanized steel is required to armor the cables, as the water depths in this case are shallow and not deeper than 30m [5]. The collection system in this study is composited of 63.3 km of 33 kV cables with different cross-sections in conductors. Table 4-2 later in this chapter, views what dimensions of 33 kV cables are required in the offshore wind farm Havsul 1 (Havsul 1 AS 2006). The transmission system consists of about 30 km of 132 kV cables. It is not specified in the licensing report of Havsul 1 what the size the cross-section of the conductor should be. As this wind farm is quite large, 390 MW, it is assumed that a cross section of 630 mm^2 will be a realistic assumption. The offshore wind farm Sheringham Shoal, located outside the coast of United Kingdom, has a production capacity of 315 MW and uses mostly cables in the transmission system with a voltage level of 145 kV. These cables have cross-section sizes of 3 *1*630 mm^2 and 3*1*1000 mm^2 (Angoulevant 2010). In this analysis, a cross section of 630 mm^2 is chosen for the analysis. The cables are of the type illustrated in figure 3-4.

Transport needed during installation, operation, maintenance and dismantling of cables in the wind farm must also be included in the studies. There will be transport both by land and by sea. All cables need transportation from production site to the harbor, where they will be transported out to the wind farm. The transportation distance of cables between production site and harbor is assumed to be 100 km by lorry. Assuming that the dismantling phase is modeled as an inverse installation phase, the total transport by lorry will be approximately 183 000 tkm for each of the cable types. In total there will be about 365 000 tkm of transport by lorry for both the 33 kV and 132 kV cables in total.

Amount of sea transport during installation, operation and dismantling of cables is based on a study of the Anholt offshore wind farm, undertaken a company named Rambøll (Rambøll 2009). This is a study regarding how much transport is needed in an offshore wind farm during installation, operation, maintenance and dismantling. In Rambøll's study, transportation regarding cabling in an offshore wind farm is looked on gathered. This includes transport required for cables both in the collection and transmission system. Amount of transportation required for installation of the cables investigated in this study, is based on Rambøll's study.

To study the collection and transmission systems individually, the amount of transport associated with cabling in Rambøll's study is split in two. Half of the transportation is

[5] Assumption based on personal communication with a specialist in high voltage cable technology at Sintef. Dated 17.03.11.

demanded by the collection system and half is demanded by the transmission system. This is a quite crude assumption made in order to perform to separate LCA's. It is assumed that the heavier weight of the transmission system will compensate for the collection system being longer and hence require longer transport distances. It is assumed that this will result in approximately the same amount of fuel consumed by the boats, for both cable types.

Cables, both in the internal cable grid and for the transmission cables, require a cable laying vessel with plough for installation. In order to protect submarine cables, all cables are buried about one meter down into the seabed (E.ON Sverige AB 2007). Chapter 4.1.1 will give an account of the inventories for 33 kV and 132 kV cables.

LCI of a 33 kV HVAC cable

This chapter presents the inventory of the 33 kV HVAC submarine cables, with XLPE insulation and cobber conductor. This cable system is meant to be used in the collection system of an offshore wind farm. Full inventory list can be found in appendix C.

Table 4-1. Technical data of the 33 kV cables used in the collection system.

Technical cable data		
Cable type	HVAC	
Voltage	± 33 kV	
Insulation	Cross- linked polyethylene (XLPE)	
Conductor	Three-core copper conductor	
Life time expectancy	40 years	(NEEDS 2008)

Table 4-2.Conductor dimensions of the 33 kV cables (Havsul 1 AS 2006).

Cable dimension	**Calculated length [km]**
3 x 95 mm^2 Cu	26,2
3 x 150 mm^2 Cu	5,9
3 x 240 mm^2 Cu	13,1
3 x 400 mm^2 Cu	11,0
3 x 630 mm^2 Cu	7,1
Total	**63,3**

Table 4-3. Life cycle inventory of the 33 kV cables. Material requirements are based on numbers from (Nexans n.d.)) and (Nexans 2008). Which data that are used for calculating the amounts of materials used, are found in appendix x.

Materials	Total amount [kg]	Amount [t/km]
Lead, at regional storage	495142	8
Copper, at regional storage	387852	6
XLPE insulation (Polyethylene)	115153	2
Steel, galvanized	751086	12
Polypropylene	77363	1
Total	**1827000**	**29**
Total weight from data sheet	**1637000**	

Table 4-4. Life cycle inventory of 33 kV cables. Transport requirements.

Transportation vessel	Amount	Unit
Cable lay vessel with plough (installation cables)	7	Shipdays
Inspection of cables during operation (20 years) (O&M)	156	Shipdays
Cable lay vessel with plough (EOL)	6,8	Shipdays
Transport, lorry >32t, EURO5 (from prod. site to port, 100 km)	182660	tkm
Transport, lorry >32t, EURO5 (from port to treatment, 100 km))	182660	tkm

Table 4-5. Different prices of 33 kV cables used in the collection system. (All in year 2000 prices).

Price of cable	Unit	Reference
3.06	EUR/kg	(Eurostat 2011)
5 589 382	EUR	*Calculated by using the Eurostat price and total cable weight*
12 389 644	EUR	(Green & Schellstede 2007)
19 555 190	EUR	(Arvesen & E. Hertwich 2011)

The inventory over is for the collection system of an offshore wind farm which consists of 33 kV cables. Total material requirements are found in column two in

Table 4-3. These amounts are calculated by multiplying the material requirements in [kg/km], for the different cross section sizes of 33 kV cables, with the length of the respective type of cable. This total amount of materials are then divided on the total length of the 33 kV cable grid in the collection system, which is 63.3 km. Column three in

Table 4-3 thus shows the average amount of material required in [t/km]. The same table also shows that there is a difference in calculated weight and weight given in the data sheet for the cable. This is probably because of uncertainties in the calculation parameters used, such as the material densities. These densities are probably not fully correct as they are valid for pure metals at 20 degrees Celsius. In reality the material densities can be somewhat higher or lower than the theoretically value, and therefore the weight does not add up absolutely correct. There can also be other uncertainties in the calculations. These uncertainties are assumed to be acceptable in this study. Lifetime of the cables is assumed to be 40 years.

The price used is from statistics by Eurostat (Eurostat 2011a). These numbers are in year 2000 basic prices, as the prices in the symmetric input output tables from EXIOPOL are (EXIOPOL 2011). Basic prices means the amount receivable by the producer from the purchaser for a unit of good or service produced as output, minus any tax payable and plus any subsidy receivable on that unit, as a consequence of its production or sale (United Nations 1999). Green and Schellstede study from 2007 operated with prices of 12 million Euros and 24 million Euros for the collection system (Green & Schellstede 2007). The prices were obtained from two different anonymous companies. These prices are much higher, but it is reasonable to assume that these prices include taxes and hence are not basic prices. In the light of this, the prices are not so different in size. The price used by Arvesen et al. is also much higher. In general, the Eurostat price seems very low. Eurostat does not distinguish between offshore and onshore power cables, which will probably have a great effect and not give a very realistic price. Submarine cables are expected to be more expensive than onshore cables. The prices for different materials will differ a lot. Therefore it is difficult to decide which price is more realistic than another. There are huge uncertainties in these prices, as they are not gotten first-hand from the relevant industry. Therefore the price based on the Eurostat price is used in this study, as this is known to be in basic prices.

LCI of a 132 kV HVAC cable

This chapter presents the inventory of a 132 kV HVAC submarine cable, with XLPE insulation and cobber conductor. The cable is meant to be used in the transmission system of an offshore wind farm. Full inventory list can be found in appendix C.

Table 4-6. Technical data of the 132 kV cables used in the transmission system.

Technical cable data		
Cable type	HVAC	
Voltage	± 132 kV	
Power	390 MW	
Insulation	Cross- linked polyethylene (XLPE)	
Conductor	Three-core, 630mm^2 Cu	
Life time expectancy	40 years	(NEEDS 2008)

Table 4-7. Life cycle inventory of the 132 kV cable. Material requirement based on numbers from (Nexans n.d.)) and (Nexans 2008). Which data that are used for calculating the amounts of materials required, are found in appendix x.

Materials	**Total amount [kg]**	**Amount [t/km]**
Lead, at regional storage	517114	22
Copper, at regional storage	514729	28
XLPE insulation (Polyethylene)	183004	7
Steel, galvanized	735951	28
Polypropylene	102394	4
Total	**2053000**	**88**
Total weight from data sheet	**1956000**	

Table 4-8. Life cycle inventory of 132 kV cables. Transport requirement.

Transportation vessel	Amount	Unit
Cable lay vessel with plough (installation cables)	7	Shipdays
Inspection of cables during operation (40 years) (O&M)	156	Shipdays
Cable lay vessel with plough (EOL)	6,8	Shipdays
Transport, lorry >32t, EURO5 (from prod. site to port, 100 km)	205319	tkm
Transport, lorry >32t, EURO5 (from port to treatment, 100 km))	205319	tkm

Table 4-9.Different prices of 132 kV cables used in the transmission system. (All in year 2000 prices).

Price of cable	Unit	Reference
3.06	EUR/kg	(Eurostat 2011a)
6 282 767	EUR	*Calculated by using the Eurostat price and total cable weight*
16 238 913	EUR	(Green & Schellstede 2007)
52 437 376	EUR	(Arvesen & E. Hertwich 2011)

The material requirements for the 132 kV cables in

Table 4-7 are calculated based on data found in technical data sheets from ABB (ABB 2010b). It is not specified in the licensing report of Havsul 1 what the cross section of the conductor should be for the 132 kV cable. As this wind farm is quite large, 390 MW, it is assumed that a cross section of 630 mm^2 will be a realistic choice as explained earlier. It can be seen from

Table 4-7 that also for 132kV cables there is a difference in calculated weight and weight given in the data sheet of the cable. This again is probably because of the calculation uncertainties mentioned previously.

For transport and prices it is the same as for the 33 kV cables. Transport is assumed to be the same amount as for 33 kV cables. Prices will be different from 33 kV cables due to different weight of the cables.

4.1.2 LCI of long distance transmission with HVDC cable

Long distance power transmission by submarine cables will call for use of HVDC technology. A direct linked power cable between for instance the south west coast of Norway and the east coast of Great Britain will be approximately 730 km long and with a high transmission capacity of about 2 x 700 MW. This is a link now being studied by the transmission system operator (TSO) in Norway, Statnett, and a National grid subsidiary in Great Britain, National Grid International Limited (Statnett 2009). A power cable like this must be a HVDC cable due to the long distance.

The NorNed transmission cable between Norway and the Netherlands will be used to assess the environmental impacts caused throughout the lifetime of a long distance HVDC submarine power cable. This cable is a 450 kV mass-impregnated paper insulated HVDC cable with a transmission capacity of 700 MW (ABB 2010a). It consists of two types of cables; a flat cable and a single-core cable. Through personal communication with experts in Statnett[6], it is known that this is the kind of cable that can be expected to be built between European countries as the United Kingdom, Germany, Netherlands, Norway and Denmark in the future. That is why this is used to assess the environmental impacts.

LCI of a 450 kV HVDC cable

This chapter presents the inventory of a 450 kV mass-impregnated paper insulated HVDC submarine cable. Full inventory list can be found in appendix C.

Table 4-10.Technical data for the NorNed cable (ABB 2010a).

Technical cable data	
Voltage	± 450 kV
Power	700 MW
Insulation	Paper insulated, Mass impregnated (MI)
Conductor	270 km 2 x 790 mm^2 Cu (flat cable) 2 x 150 km 700 mm^2 Cu (single-core cable)
Weight	84 kg/m (flat cable) 37 kg/m (single-core cable)

[6] Personal communication with Statnett. Dated 02.02.11 and 03.02.11.

Table 4-11.Technical data used in this study's cable.

Technical cable data	
Voltage	± 450 kV
Power	2 x 700 MW
Insulation	Paper insulated, Mass impregnated (MI)
Conductor	730 km 2 x 790 mm^2 Cu (flat cable)
Weight	112455 tonnes

Table 4-12. The life cycle inventory of the 450 kV cable. Material requirement based on numbers measured from the flat-cable part of the NorNed cable. All amounts are multiplied with two, as there will be laid two cables in parallel for transmission both ways when

Materials	**Total amount [kg]**	**Amount [t/km]**
Lead, at regional storage	2 x 16685919	2 x 23
Copper, at regional storage	2 x 9508474	2 x 13
Impregnated paper (insulation)	2 x 3885158	2 x 5.5
Steel, galvanized	2 x 24006863	2 x 33
Polypropylene	2 x 2140911	2 x 3
Total	**2 x 56227500**	**2 x 77**
Total weight from data sheet (ABB 2010a)		**84**

Table 4-13. The life cycle inventory of 132 kV cables. Transport requirement.

Transportation vessel	**Amount**	**Unit**
Cable lay vessel with plough (installation cables)	270	Shipdays
Inspection of cables during operation (40 years)	280	Shipdays
Cable lay vessel with plough (EOL)	270	Shipdays
Transport, lorry >32t, EURO5 (from prod. site to port, 100 km)	11245465	tkm
Transport, lorry >32t, EURO5 (from port to treatment, 100 km))	11245465	tkm

Table 4-14. Different prices of 450 kV cables used in the transmission system (in year 2000 prices).

Price of cable	Unit	Reference
3.06	EUR/kg	(Eurostat 2011a)
344 111 234	EUR	*Calculated by using the Eurostat price and total cable weight*

The NorNed cable is 580 km long. In this study the cable length was increased to 730 km which is around the length of a direct link between the south west coast of Norway and the east coast of Great Britain.

It has not been possible to obtain the material requirements of the NorNed cable from manufacturers, but the NTNU has got a part of the NorNed cable in-house (the flat cable part). This made it possible to physically measure the dimensions of this cable. As for the collection system and transmission system of the offshore wind farm, the IO system is used to cover manufacturing of the cable. This approximation of material requirements is assumed to be fairly good. The weight of the measured cable became 77 t/km (per cable), while the actual weight is 84 t/km for the flat-cable part. This is about 8 % weight difference, which is considered a low enough uncertainty.

For transport used during lifetime for these cables, crude assumptions had to be made based on a time schedule made for the NorNed project (J. E. Skog & Jendal 2006). No other transport specifications have been obtained. From this time schedule, an assumption is made that a total of nine months are used for installation. Dismantling of cables, which includes removing of cables and transport to shore, is modeled as an inverse installation. Hence, this requires the same amount of transport as installation. For inspection, an average of one week every year is assumed to be used.

4.1.3 LCI of an offshore wind farm

The Havsul 1 concession report is used as a basis for the wind farm examined in this study. Havsul 1 is a project owned by Vestavind Offshore AS, a company founded by the energy companies in Vestlandsalliansen (Vestavind Offshore AS 2010). Localization of the wind farm is outside the coast of Møre og Romsdal in Norway.

The life cycle study of this offshore wind farm includes the life cycle stages; manufacturing, assembling, transport to erection site, installation, operation and maintenance, dismantling and transport to waste handling site of components and cables required for the whole wind farm. Manufacturing and assembling of windmill, substructures, HV transformers and cables are included. For the windmill, this means tower, nacelle and rotor (including rotor blades). Inventory for the cables are from the inventories described in chapter 4.1.1.

Transportation to erection site includes transportation of components by lorry from the production and assembling site, to the harbor. It also includes transportation of components by marine vessels, from port to wind farm location. Required vessels and equipment for installation of HV transformers, cables, foundations and erection of windmill are included in detail in the assessment. Installation, operation and maintenance of the whole wind farm are also included in detail, both by including vessels required, and by including maintenance strategies for replacement of parts during lifetime. Appendix I gives an account of all material requirements in the wind farm. This concern windmills, HV transformers and cables.

The wind farm has a total installed effect of 390 MW, distributed on 78 windmills each with a nominal effect of 5 MW. All windmills are fixed to the seabed. Vestas' wind turbines V80-2.0 MW and a V90-3.0 MW, are used as a basis for defining the mass distribution and material required for the wind turbines in this study. Data regarding manufacturing of components to the wind farm and arrangement of the windmills, have been derived from the Havsul 1 concession report. Windmill foundations chosen for the assessment are Gravity based (concrete) substructures, which are developed by Vici Ventus Technology AS. Material use and mass intensities for the foundations are provided directly by Vici Ventus (Vici Ventus Technology AS 2010). Two HV transformer stations are required in a wind farm of this size. Material use and mass distribution for HV transformers are derived from ABB's product sheet for a 250 MVA HV transformer (ABB 2003). Material requirements for submarine cables, both 33 kV and 132 kV, are derived from ABB's and Nexans data sheets (Nexans 2008), (ABB 2010b), (Nexans n.d.) as explained in chapter 4.1.1. Inventories for the cables are as in chapter 4.1.1. For the high- voltage transmission cable on land, the appropriate process from the Ecoinvent 2.2 database is used.

By having total capacity of 390 MW, 3.1 % transmissions losses in grid and 3000 full load hours for the wind turbines, the annual production of this wind farm becomes 1134 GWh. An expected lifetime of 20 years for the wind farm gives a total production throughout lifetime of 22.7 TWh. With 3000 hours of full load production every year, the capacity factor for this wind farm becomes 34 %. The capacity factor of wind power is the ratio of average delivered power to theoretical maximum power. This can either be calculated by using the total power production from a wind turbine by full load through a year, or by using number of full load hours through a year, as;

$$CF = \frac{3000h}{8760h} = 0,343 \simeq 34\% \qquad 4.1$$

A capacity factor of 34 % is a relatively conservative estimate for an offshore wind farm. Nevertheless, this is most likely a more realistic estimate compared to those often presented for large offshore wind farms (Boccard 2009). An LCA study done by Vestas of offshore wind turbines with a nominal power of 3 MW operates with a capacity factor of 54 % (Vestas 2006). In the DOWEC baseline a capacity factor of 48 % is achieved (Rademakers et al. 2003), while more conservative statements will be around 30- 40 % (University of Massachusetts at Amherst n.d.). As the wind farm in this study is located not too far from shore, the great benefits of high wind intensities are not achieved, but it will still have benefit of more stable wind conditions compared to onshore power plants.

In the assessment of the entire wind farm, the functional unit is selected as 1 kWh of electricity generated from the offshore wind power plant, delivered to the grid on land. Full inventory list of the wind farm can be found in appendix I. Table 4-15 presents the main data for the wind farm in this study. Notice that the lifetime expectancy of the cables and the wind farm differ. The wind farm has a lifetime expectancy of 20 years, while the cables within the wind farm have a lifetime of 40 years. It is assumed that after 20 years of operation, the old wind farm will be replaced with a new similar wind farm. So the cables won't have to be substituted until after 40 years. It is very difficult to predict whether or not a new wind farm of the same type and size will be used in 20 years, but this assumption has been used in this study.

Table 4-15. Main data for the offshore wind farm.

Number of windmills	78 Units	(Havsul 1 AS 2006)
Number of HV transformers	2 Units	"
Nominal effect per wind turbine	5 MW	"
Total installed effect	390 MW	"
Lifetime wind farm	20 years	"
Lifetime cables	40 years	(Ecoinvent 2010)
Lifetime HV transformers	35 years	(ABB 2003)
Capacity of HV transformers	2 x 195 MW, 2 x 244 MVa	Calculated
Full load hours	3000 h	(Havsul 1 AS 2006)
Capacity factor	34 %	(Havsul 1 AS 2006)
Losses in transmission	3,10 %	(Havsul 1 AS 2006)
Annual production (excl.losses)	1170 GWh	Calculated
Annual production (incl.losses)	1134 GWh	Calculated
Production over lifetime (incl.losses)	22675 GWh	Calculated
Hub height	95 m	
Rotor diameter	120 m	
Length 33 kV submarine cable grid	63,3 km	
Length 132 kV submarine cable grid	30 km	
Transmission of electricity onshore	10 km	
Distance from shore	2,9 – 11 km	
Water depth	4 – 30 m	
Foundation type	Gravity based foundation (concrete)	(Vici Ventus Technology AS 2010)

Installation

For installation of foundations, wind turbines and HV transformers, special crane vessels are required. Mostly jack-up vessels are used. These vessels have support legs, which makes it possible for the whole vessel to be raised and lowered during operation. This makes the vessel fixed to sea bottom, and the installation therefore becomes steadier.

Cables, both internal cables and cables for transmission onshore, require a cable laying vessel with plough for installation. Included in cable laying is also tie-in of cables through J- tubes which are installed inside the windmill foundations (depending on foundation type). This will be connected with the wind turbine. In order to protect the submarine cables, all cables are buried about one meter down into the seabed (E.ON Sverige AB 2007). Eighteen vessels, and thus eighteen foreground processes, were used to cover construction and installation of the wind farm. Also, transportation from manufacturing factory of components to the harbor was included. Dismantling of the wind farm was modeled as a reverse installation process. The same amounts of vessels were assumed to be required.

Effective time for installation of foundation is estimated to 24-36 hours (Rambøll 2009).
Effective time for installation of wind turbines is estimated to 24-36 hours (E.ON Sverige AB 2007).
Effective time for installation of one HV transformer is estimated to 48- 72 hours.
Effective time for installation of cables is estimated to about two weeks for the whole wind farm (Rambøll 2009).

Transportation and installation of substructures
The concrete Gravity foundations are transported 100 km from production site to harbor, which gives approximately 28 700 000 tkm of transport by lorry.

The concrete substructures are, because of their weight and size, made on land before they are transported out on site. Before installing the structures, the seabed has to be prepared by smoothing it out and adding a base of gravel. Preparation of seabed calls for several vessels. Vessels needed for transportation and installation of Gravity based substructures are excavators, barges for transport of excavators, barges for transport of rock for stone bed, tugboats and jack- up vessels (Rambøll 2009).

An excavator is used for the actual preparation, and barges and transport vessels are used for transport and dumping of seabed material and rocks. When the foundation is finally in position, a jack-up vessel is needed to put the structure in place. Because of the size and weight of the foundations, they are towed with tugs from harbor to wind farm. Then they are filled with 5000 tonnes of gravel as ballast.

Transport and erection of HV transformer stations and windmills
HV transformer stations are split in two parts in this study; foundation and topside. As for the windmills, the foundations are studied separately under the same process as for windmill foundations. Transportation of the topside of HV transformer stations from production site to harbor is done together with the wind turbines and towers. Transformer stations' foundations are transported with the windmill foundations. This demands 4 600 000 tkm of transport by lorry.

Marine transportation of wind turbine, tower and topside of the HV transformers will be done by a jack-up vessel. Four turbines and towers can be transported in one trip by the jack-up vessel, which equals to approximately 22 trips in total. Tugs are used for towing the jack-up vessel out on site. The actual erection of one windmill will be performed in 4-5 lifts by using the crane on the jack-up vessel (Havsul 1 AS 2006).

Transport and installation of cables
Transport of cables from production site to harbor is also assumed to be 100 km, which gives approximately 390 000 tkm transport by lorry.

A cable laying ship is used for installation of the submarine cables. For the internal cable grid, 1 meter of cable alignment is assumed in the licensing report. This means that the internal cable grid occupies 63.3 decare of area, which is 0.13 % of the total area of the wind farm (Havsul 1 AS 2006). Also the 132 kV submarine cables are expected to have a certain cable alignment. A synopsis of all transport can be found in appendix C.

Operation and maintenance

For operation and maintenance of the offshore wind farm, vessels and equipment will be required for inspections, repair work and replacement of parts. For inspections, mainly service boats are used. In emergency situations, a helicopter is used if the weather allows it. During repair work and replacement of parts, larger vessels with cranes are needed, and longer downtime on the windmill can be expected.

Operation of this wind farm is mainly done by remote control from a control center onshore (Havsul 1 AS 2006). Preventive maintenance of 78 wind turbines through 20 years is estimated, based on a study undertaken by Rambøll, to be about 3900 days in total (Rambøll 2009). This gives 2.5 days per wind turbine per year of preventive maintenance. Preventive maintenance for HV transformer stations is assumed to be somewhat higher than for the windmills, 7.5 days per substation per year. For details on how many ship days are used for maintenance work, see appendix H. Inspection of cables is also included in this study and is assumed to take two weeks per year in average, an assumption taken from Rambøll's study (Rambøll 2009). It is assumed than the vessels will work 24 hours a day during work time. Transport of personnel to wind turbines and substations will normally take place by boat. Only for emergencies are helicopter used. In this study it is assumed that a helicopter is needed for emergencies once a year per turbine. The helicopter is then assumed to transport personnel out on site, and then return. It is not supposed to be on standby out on the production site.

There is not much information about maintenance strategies available for offshore wind farms, especially not for corrective maintenance work. For this study a maintenance strategy for corrective maintenance has been designed. A failure rate of 1.55 failures per wind turbine per year is used as a starting point of designing a maintenance strategy (Rademakers & H Braam 2003). Distribution of this failure rate can be seen in table 4-6.

Table 4-16. Occurence of failures distributed on four failure categories, for the wind farm. Based on (Rademakers et al. 2003) and (Salzmann 2009).

Failure Category	Required Action[1]	Equipment[1]	Occurrence[1]	Failures (per turbine)	# of failures for 78 turbines per year
1	Replacement of heavy component	Vessel + Jack-up	1 %	0,0155	1,2
2	Replacement of large part	Vessel + Build up Internal Crane	7 %	0,1085	8,5
3	Replacement of small part (<1t)	Vessel + Permanent Internal crane	23 %	0,3565	27,8
4	Replacement of small part (man carried) or no part (inspection)	Vessel or Helicopter	69 %	1,0695	83,4

These four maintenance/failure categories have been used, presented by Rademakers et al. (Rademakers et al. 2003). The table shows the occurrence of failures distributed on these four failure categories. It also describes the different types of maintenance vessels required and how many parts are needed to be replaced for the different failures. In appendix G there is an explanation on how the calculations and distribution of failures are done in this table, and the assumptions that are taken.

Dismantling

Dismantling of the wind farm is included in rough terms in the study. For dismantling of the wind farm, vessels needed for dismantling and transport from wind farm to final disposal, is included. Treatment of materials, incineration and recycling of materials are not included in this assessment. This partly because of the difficulty and uncertainty of knowing how this will be done, what will be recycled and what can be reused. Dismantling of an offshore wind farm has not been done yet. Use of recycled materials for metals is instead included in input for production of components. Processes used for material inputs are from Ecoinvent 2.2 where the European production mix already consists of both primary and secondary materials, especially for metals. This means that the model will be credited for using secondary materials, by avoided production, but it is not credited for the material in dismantling which can be recycled and thus reduce environmental impacts. Hence, the model is in one way neutral when it comes to being credited for recycling.

A synopsis of all transport can be found in appendix H.

4.2 Life Cycle Impact Assessment (LCIA)

4.2.1 LCIA of collection system (33 kV cable)

From the environmental impact assessment done of the 33 kV HVAC cables, the results are as presented in figure 4-3. These are impacts caused by 1 MW*km of cable. Contribution to the climate change category is 229 kg CO_2 -eq/MW /km, for marine eutrophication it is 0.3 kg N -eq/MW /km, for marine eco-toxicity the contribution is 11.8 kg 1,4-DCB -eq/MW /km and for human toxicity the contribution is 991 kg 1,4-DCB -eq/MW /km. For fossil and metal depletion the contributions are respectively 58.5 kg oil -eq/MW /km and 31 kg Fe –eq/MW /km. Contribution to smog is of 2.1 kg NMVOC/MW /km, while contribution to particulate formation is 1 kg PM10 -eq/MW /km.

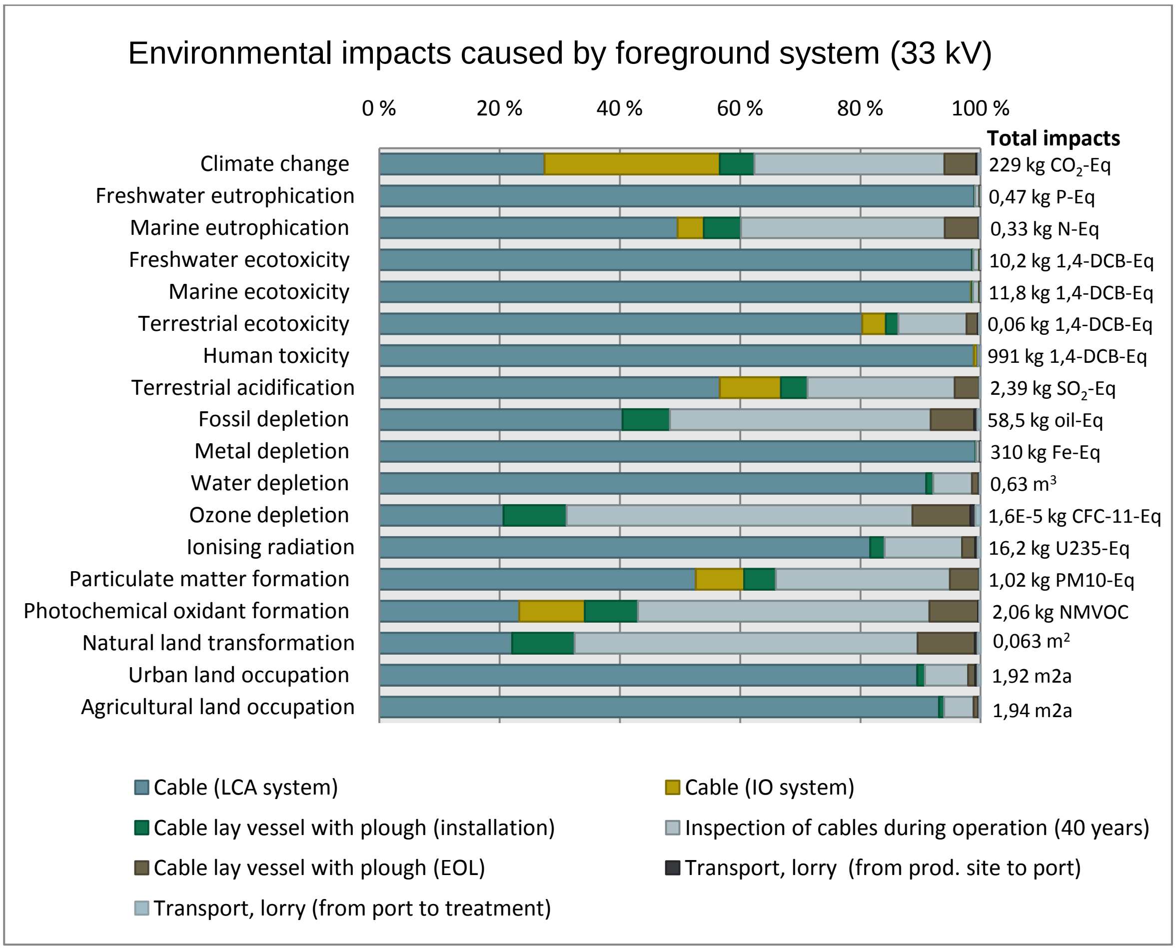


Figure 4-3. Distribution of environmental impacts caused by 1 MW*km of 33 kV HVAC cable. The impacts are distributed on the foreground processes.

Results from the basic contribution analysis are presented graphically in figure 4-3. The processes called "*Cable (LCA system)"* and *"Cable (IO system)"* define manufacturing of the cables. The "LCA part" covers direct material inputs required to manufacture this type of cable, such as copper, steel and polyethylene. The “IO part” covers inputs to the manufacturing process which are not covered by the direct material requirements. These are inputs such as electricity to manufacturing.

It can be seen that the LCA part of the system, hence the materials required, dominates the contribution in almost every impact category. To climate change it can be observed that materials covered by the LCA system contribute with 27.5 % of the total impacts in this category, while manufacturing of cables covered by the IO system constitute 29 % and the vessel used for inspection of cables throughout lifetime contributes with 31.5 %. For those categories where the use of materials does not dominate, either the IO part of the system (manufacturing) or the vessels used for inspection of cables during operation dominates. In freshwater eutrophication, freshwater eco-toxicity, human toxicity, marine eco-toxicity and metal depletion, the materials required for the cable constitute almost 100% of the impacts. This might not be the case in reality, as uncertainties associated with the impact categories in Ecoinvent and the IO and LCA methods are high. This is discussed in chapter 2.1 and chapter 4.4. Transport required during installation, operation and dismantling of cables, constitutes huge parts of the impacts in climate change, fossil depletion, marine eutrophication, ozone depletion, particulate matter formation and photochemical oxidant formation. The cable laying vessel used both during installation and end-of-life phases, constitute a minor part of the impacts in several categories. Manufacturing of cables (denoted the “Cable (IO system)”) contributes mainly in climate change, particulate matter formation, photochemical oxidant formation and terrestrial acidification. In appendix D climate change, particulate matter formation and photochemical oxidant formation are more explicitly presented.

4.2.2 LCIA of transmission system (132 kV cable)

The distribution of environmental impacts caused by the foreground processes of a 132 kV cable is not very different from the distribution found for 33 kV cables, but levels of impact in the different categories are higher. The results are as presented in figure 4-4. These are impacts caused by 1 MW*km of the 132 kV cable defined in this study. Contribution to the climate change category is 520 kg CO_2 -eq/MW /km, for marine eutrophication it is 0.8 kg N -eq/MW /km, for marine eco-toxicity the contribution is 32.1 kg 1,4-DCB -eq/MW /km and for human toxicity the contribution is 2720 kg 1,4-DCB -eq/MW /km. For fossil and metal depletion the contributions are respectively 134 kg oil -eq/MW /km and 835 kg Fe -eq/MW /km. Contribution to smog is 4.64 kg NMVOC/MW /km, while contribution to particulate formation is 2.44 kg PM10 -eq/MW /km.

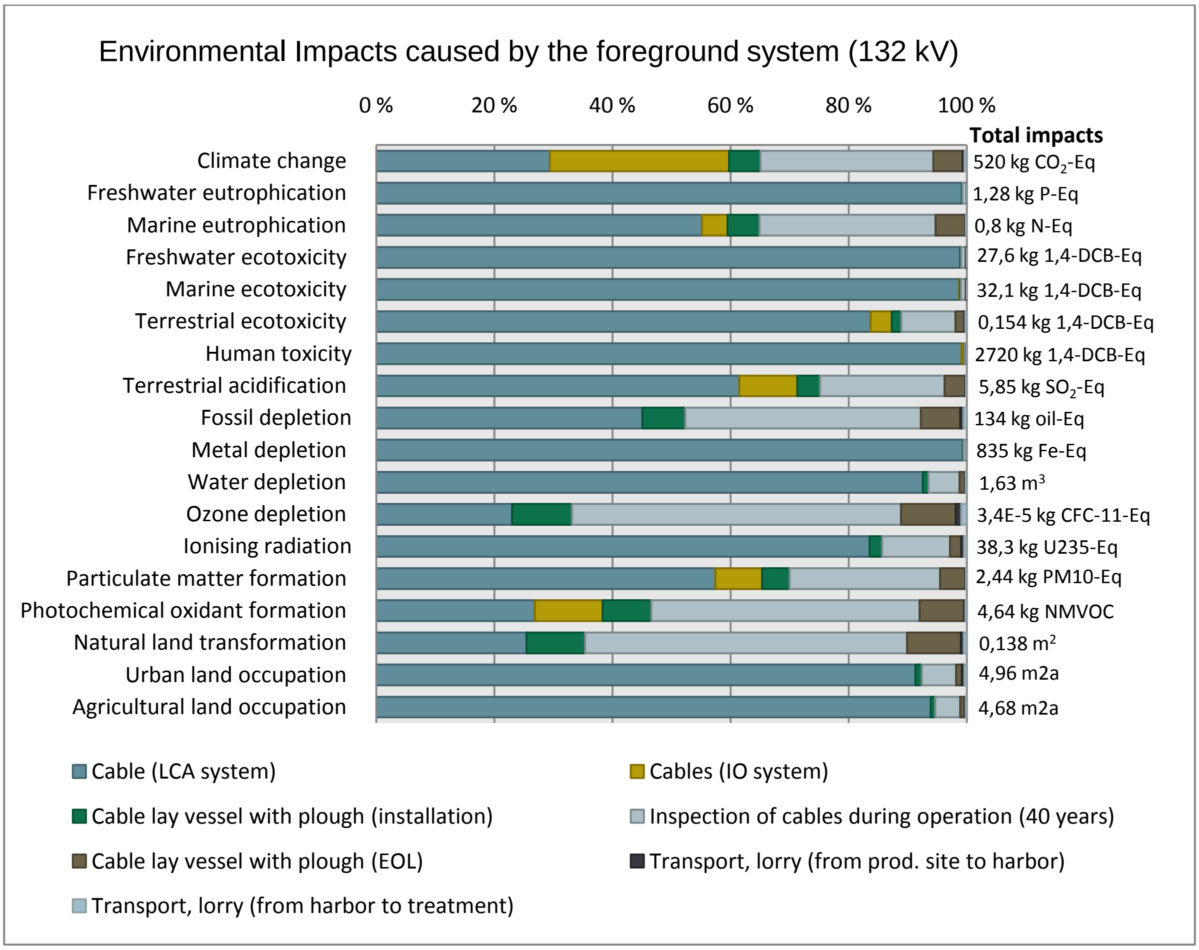


Figure 4-4. Distribution of environmental impacts caused by 1 MW*km of 132 kV HVAC cable. The impacts are distributed on the foreground processes.

As for the 33 kV cable, the part called "Cable (LCA system)" represents material inputs for the cables and the part called "Cable (IO system)" represents other inputs to manufacturing of cables such as electricity. The same distribution of foreground processes on the different impact categories is seen for the 132 kV cables as for the 33 kV cables. In the climate change category the materials required, other manufacturing inputs and the vessel used for inspection of cables during lifetime contributes with respectively ~ 29 %, ~ 30 % and ~ 29 % of total impacts in this category. It is not surprising that the shares of impacts in the different categories are the same in percentage both for 33 kV and 132 kV cables. The 33 kV and the 132 kV cables are of the same type, just with different material requirements. Same amount of transportation is also assumed to be required for these two types of cable systems. In appendix D climate change, particulate matter formation and photochemical oxidant formation are more explicitly presented.

4.2.3 LCIA of long distance power transmission (450 kV HVDC cable)

The distribution of environmental impacts caused by the foreground processes of a 450 kV cable used in long distance transmission is given in figure 4-5. These are impacts caused by 1 MW*km of the 450 kV cable defined in this study. Contribution to the climate change category is 215 kg CO_2 -eq/MW /km, for marine eutrophication it is 0.28 kg N -eq/MW /km, for marine eco-toxicity the contribution is 14.2 kg 1,4-DCB -eq/MW /km and for human toxicity the contribution is 1200 kg 1,4-DCB -eq/MW /km. For fossil and metal depletion the contributions are respectively 39.2 kg oil -eq/MW /km and 382 kg Fe -eq/MW /km. Contribution to smog is 1.34 kg NMVOC/MW /km, while contribution to particulate formation is 0.93 kg PM10 -eq/MW /km.

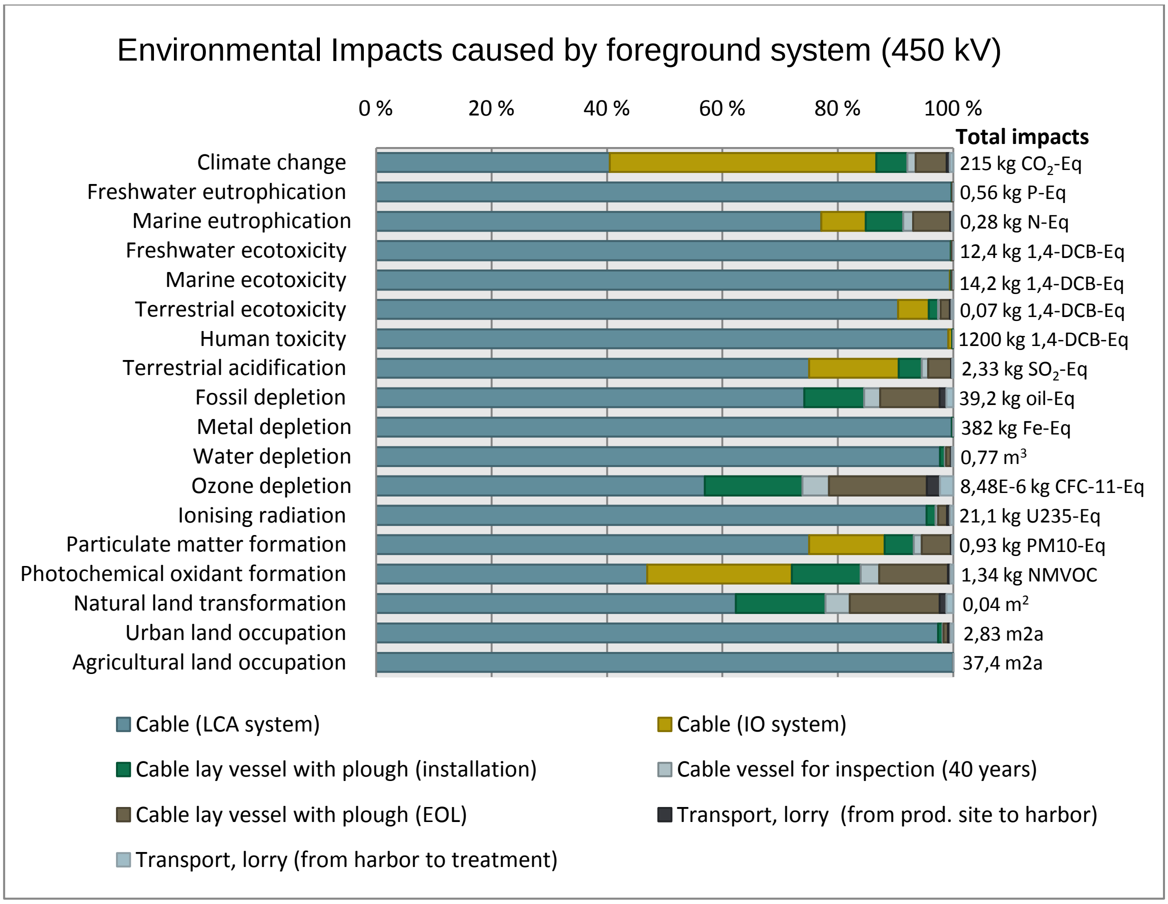


Figure 4-5. Distribution of environmental impacts caused by 1 MW*km of 450 kV HVDC cable. The impacts are distributed on the foreground processes.

As for the analyses of 33 kV and 132 kV cable systems, the part called "Cable (LCA system)" represents material inputs for the cables and the part called "Cable (IO system)" represents other inputs to manufacturing of cables. The LCIA of a long distance cable transmission shows that it is the material used in manufacturing of cables which constitute the greatest amount of environmental impacts in almost every category. For agricultural land occupation, freshwater eco-toxicity, freshwater eutrophication, human toxicity, marine eco-toxicity and metal depletion, materials used in the cable constitute nearly 100 % of the impacts.

How the IO system contribute is not so easy to investigate. By calculating the E matrix, it is possible to see which sectors that contributes to the different impact categories. It is found that for all the cable types, the two biggest contributing sectors from the IO system are "Manufacture of basic iron and steel and of ferro-alloys and first products there" and "Production of electricity by coal". These contribute with respectively 68.6 g CO_2/ EUR and 56.5 g CO_2 /EUR. The total emissions of CO_2 from the IO system are 238 g CO_2/EUR. This indicates that use of fossil fuels and also indirect use of materials are important contributors to the environmental impacts caused by the cables. By mathematically diagonalize the second tier in the demand vector, y, the emissions associated with the cable sector's purchases are found. By the term second tier, it is meant the term A*y in the geometric series expansion in chapter 2.2.1. In doing this it is found that the emissions of CO_2 are highest from the purchases the cable sector does from the sectors "Manufacture of basic iron and steel and of ferro-alloys and first products there" and "Production of electricity by coal". The emissions of CO_2 associated with purchases the cable sector does from these sectors, are respectively 53.7 g CO_2/EUR and 28.1 g CO_2/EUR.

In some categories, also other inputs to manufacturing have a remarkable contribution. To climate change, materials used in the cable contribute with 40 % of total impacts, while manufacturing of cables (covered by the IO system) contributes with 46 %. The remaining 14 % are mainly due to use of cable laying vessel during installation and end-of-life phases. In marine eutrophication, particulate matter formation, photochemical oxidant formation (smog), terrestrial acidification and terrestrial eco-toxicity it is also observed that inputs to manufacturing of cables have some contribution. In the smog formation, particulate matter formation and terrestrial acidification categories, the manufacturing (the IO system) covers respectively 25 %, 13 % and 16 % of total impacts.

Transportation contributes remarkably in some impact categories. To fossil depletion and ozone depletion, transportation covers respectively 26 % and 43 % of total impacts. It is mainly the cable laying vessel used during installation and end-of-life phases that causes these environmental impacts. The stressors causing impacts to fossil depletion are mainly crude oil required for fuel in the vessels, hard coal used in steel for the cables and natural gas used in metal production. In appendix D climate change, particulate matter formation and photochemical oxidant formation are more explicitly presented.

4.2.4 LCIA of an offshore wind farm

Table J-1 in appendix J gives an account of the environmental impacts caused by the offshore wind farm. This table shows the distribution of contribution to total impacts from the different parts of the system, per kWh of electricity delivered to the grid onshore. The results are presented graphically here in figure 4-6. Delivery of 1 kWh of electricity from the wind farm to grid on land causes 20.6 g CO_2 -eq to climate change, 0.022 g P-eq to marine eutrophication, 0.55 g 1.4-DCB -eq to marine eco- toxicity, 0.11 g SO_2 -eq to terrestrial acidification, 16.3 g Fe -eq to metal depletion and 6.94 g oil-eq to fossil depletion. By disaggregating the total impacts for each impact category, onto the main processes in the foreground system, the distribution will be as in figure 4-6.

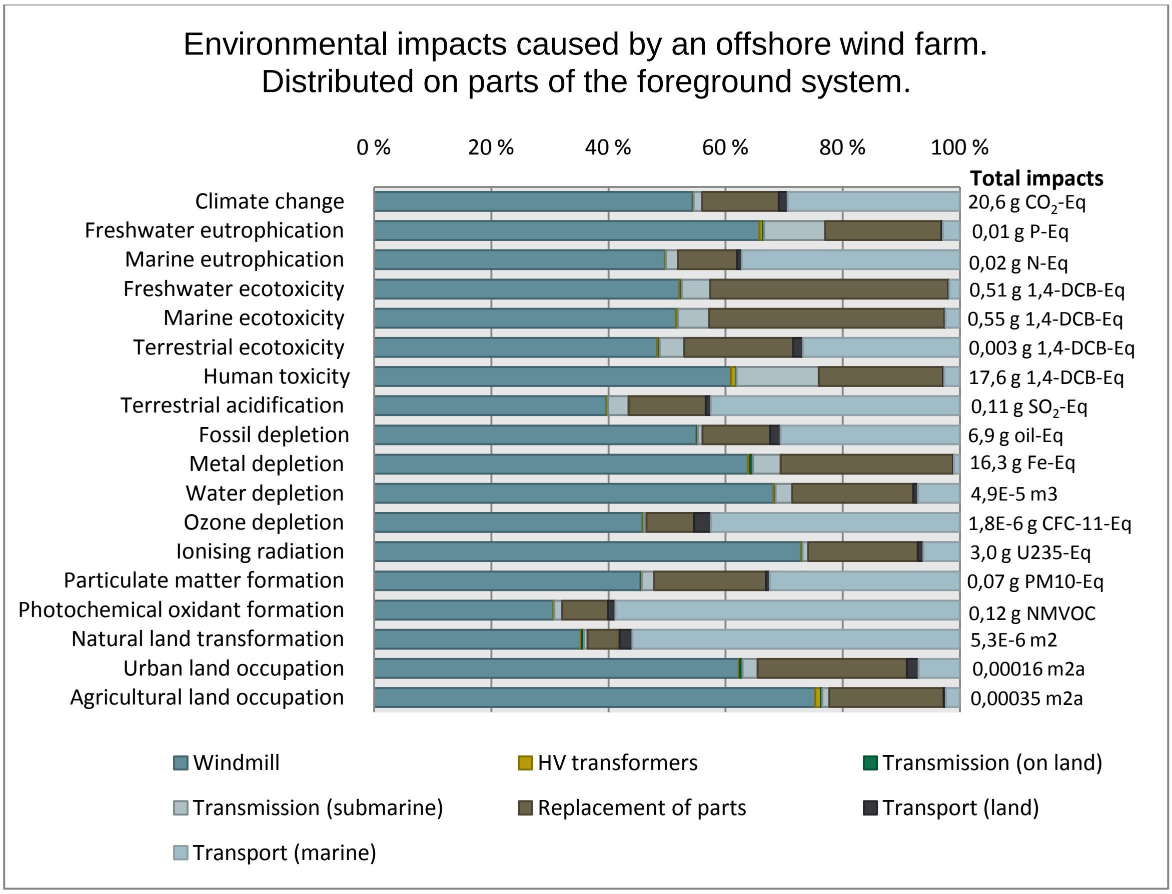


Figure 4-6. Contribution to different impact categories. Impacts are distributed on the various parts of the foreground system.

The windmill constitutes the largest impacts in nearly every impact category, contributing between 30 – 70 % in all categories. The windmill contributes with 54 % of the total impact to climate change, 50 – 60 % in all eutrophication and eco- toxicity categories, 40 % to terrestrial acidification and 64 % to metal depletion.

Impacts caused by replacement of parts and use of marine vessels are also substantial. This is shown by the brown and light blue colored bars in figure 4-6. On terrestrial acidification, marine vessels have about the same contribution as the windmill of 40 %. In climate change, terrestrial eco-toxicity and fossil depletion the contribution from marine vessels make up around 30 % of total impacts. Replacement of parts contributes most to freshwater and marine eco- toxicity with 40 % of total impacts in these categories, and in metal depletion it contributes with 30 % of total impacts. To climate change, replacement of parts contributes with 13 % of total impacts to this impact category. Contribution from the submarine transmission system is largest in impact categories for freshwater eco-toxicity, freshwater eutrophication, human toxicity, marine eco-toxicity and metal depletion. It does however not dominate in any category. To climate change the submarine transmission system contribute with about 1.5 % of the total impacts, to freshwater eutrophication the contribution is 10 % of total impacts to this category and in human toxicity the contribution is 14 %. For a closer look at the distribution of contributions in the different environmental impact categories, see table J-1 in appendix J.

A further disaggregation of the foreground parts of the offshore wind farm will reveal which processes that mainly causes the contributions to the environmental impacts. Figure 4-7, figure 4-8 and figure 4-9 show graphically a further disaggregation of the distribution of environmental impacts caused by the different parts of the foreground system.

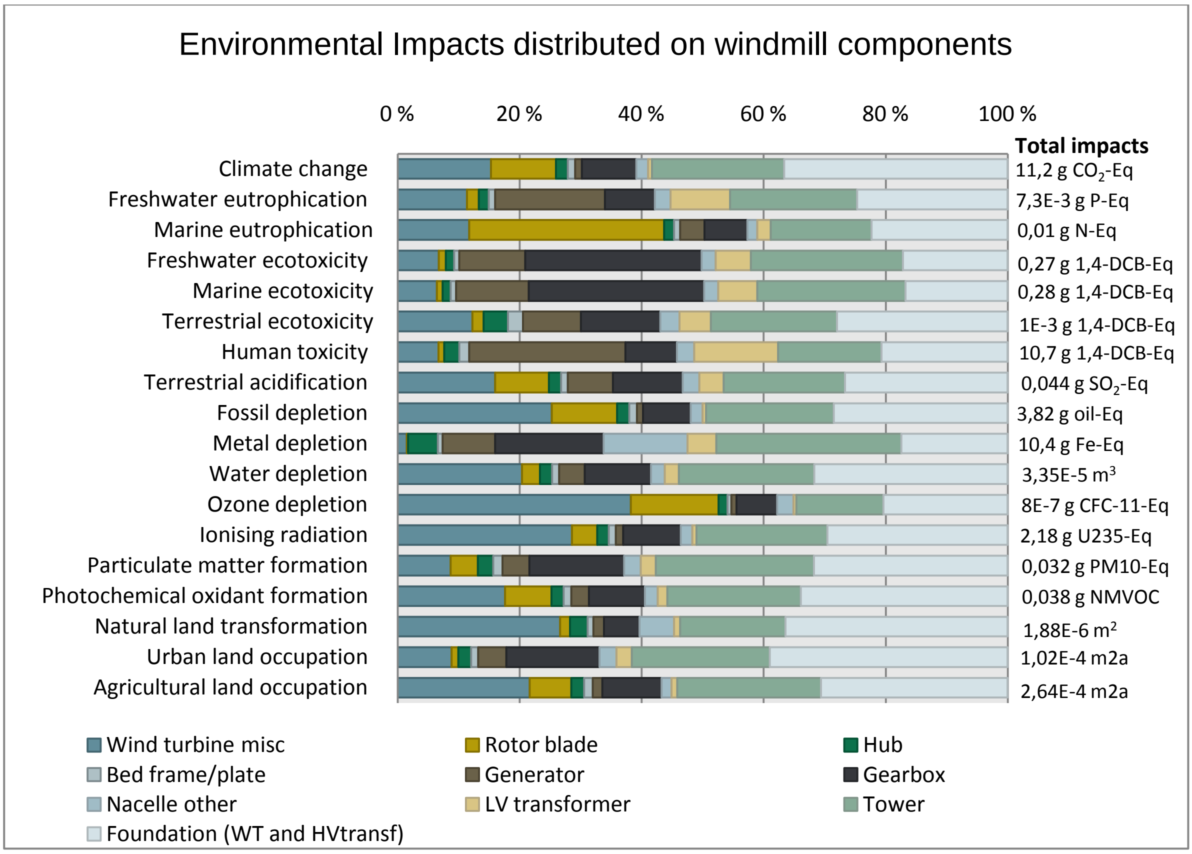


Figure 4-7. This graph shows the distribution of contribution to the different impact categories, from the different windmill components.

In figure 4-7 the windmill is further disaggregated into the different components. The tower and the foundation are huge contributors in almost all impact categories. In some categories also the process “wind turbine miscellaneous” contributes much. From the graph it can be seen that the foundation contributes with between 15- 40 % of the impacts caused by the windmill in every impact category, with an average around 30 %. The tower contributes with between 15- 30 %, with an average around 20 %. This indicates that both tower and the foundation are substantial contributors to the overall impacts from the wind farm as well, since the windmill is such an important contributor. We know that total impacts to climate change from the wind farm are 20.6 g CO_2-eq/ kWh_{el}. From the contribution analysis it is found that foundations contribute with 4.1 g CO_2-eq/ kWh_{el} which equals to 20 % of the total impacts from the wind farm, and about 35 % of the impacts to climate change caused by the windmill. The tower contribute somewhat less with 2.4 g CO_2-eq/ kWh_{el}, which equals to 12 % of total impacts to climate change and about 20 % of the impacts caused by the windmill.

The figure showing the environmental impacts distributed on the entire foreground system, figure 4-6, shows that the contributions from marine vessels are remarkable in almost every impact category. To climate change, the figure shows that marine vessels constitute 30 % of the overall impacts. For that reason it is of interest to disaggregate transport further and look into the share of emissions caused by the vessels used for the various phases of the life cycle; installation, operation, maintenance and dismantling. The life cycle phases installation, operation and maintenance includes use of marine boats and lorries, as well as necessary replacement of parts throughout lifetime.

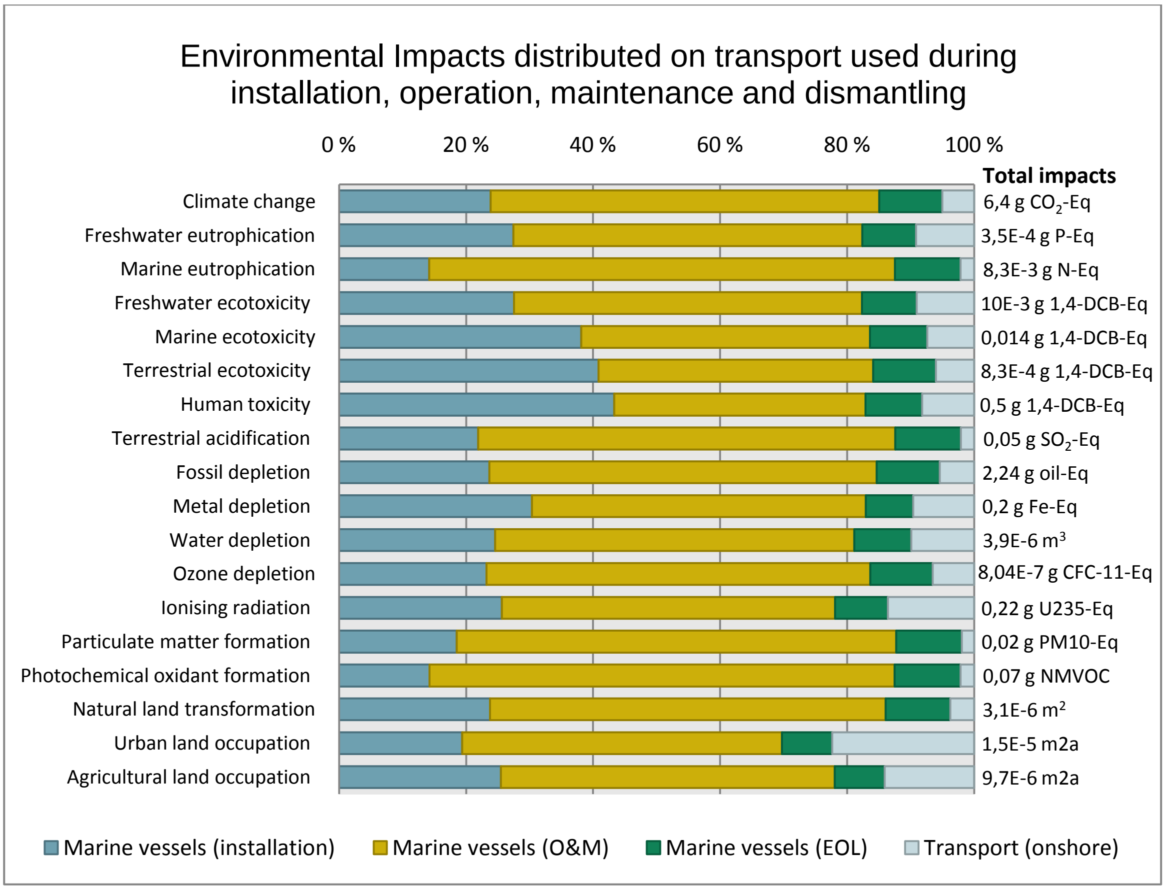


Figure 4-8. Distribution of contribution to the different impact categories, from the transportation needed during installation, operation and dismantling.

Figure 4-8 shows the distribution of total impacts caused by vessels used, disaggregated on whether the vessels are used for transportation by road or marine installation, operation, maintenance or dismantling.

Of vessels used for installation, operation, maintenance and dismantling, marine vessels used for operation and maintenance are the greatest contributors in almost all impact categories as shown in figure 4-8. Vessels for operation and maintenance constitute between 20 – 70 % of the overall impacts caused by transport in all impact categories. In marine, terrestrial and human eco- toxicity, the marine vessels used for installation constitute about the same share as marine vessels for operation and maintenance, with 40 % of the overall impacts caused by transport. Marine vessels used during the end-of-life (EOL) phase, and lorries used for transport onshore, have a minor contribution between 10- 30 % in every category.

The contribution to climate change from equipment and vessels used for installation is about 7.4 % of the *overall impacts* to climate change from the wind farm, which equals to 1.5 g CO_2 -eq/ kWh_{el}. Use of vessels for operation and maintenance work contributes with about 18.9 % of the *overall total impacts* from the wind farm (3.9 g CO_2 -eq/ kWh_{el}) and vessels for dismantling contributes with about 3 % (0.6 g CO_2 -eq/ kWh_{el}) of total impacts to climate change from the wind farm. Transport by lorry contributes with 0.37 g CO_2 -eq/ kWh_{el} to climate change (~1.5 %). Total contribution from transportation both onshore and offshore is found in table J-1 in appendix J, and is 6.37 g CO_2 -eq/ kWh_{el}. Vessels used for operation and maintenance are hence the main responsible for the total impacts caused by vessels from the production system.

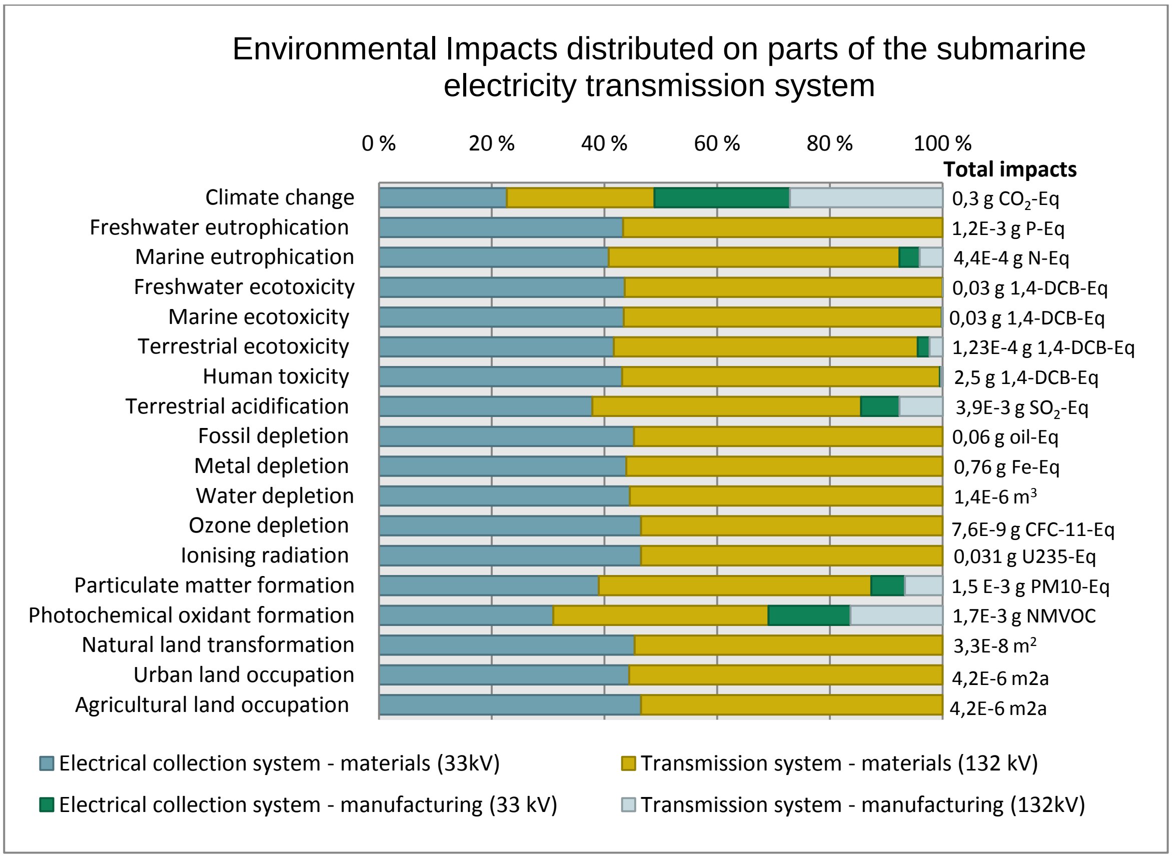


Figure 4-9. Distribution of contribution to the different impact categories, from the submarine electrical transmission system.

A further disaggregation of the submarine electricity transmission system is given in figure 4-9. The distribution of impacts between the collection and transmission system is nearly 50/50. In some categories the transmission system contributes with a little more. It is mainly the materials used in the cables that constitute the environmental impacts caused, shown with the darker blue and orange bars. Contributions from inputs from manufacturing processes (IO system) are rather small compared to the impacts due to materials used. Only for climate change, marine eutrophication, particulate matter formation, photochemical oxidant formation, terrestrial acidification and terrestrial eco-toxicity, there are contribution from manufacturing. To climate change and photochemical oxidant formation, the shares of impacts are more equally divided between the four parts of the system. To climate change, manufacturing and materials cause about the same share of the total impacts with 23 % caused by materials in the collection system, 26 % caused by materials in the transmission system, 24 % caused by manufacturing of the collection system and 27 % caused by manufacturing of the transmission system.

4.3 Analysis and discussion

The life cycle assessments performed of power transmission associated with offshore wind power generation, are of three cable types. The 33 kV cables are cables used in the collection system of an offshore wind farm. The 132 kV cables are cables used for transmission from the offshore wind farm and onshore, while the 450 kV cable is a cable used for long distance transmission for instance between Norway and Great Britain. The assumed use of cables, has determined the design of the cables and requirements of transportation during installation, operation and dismantling. After having accomplished these life cycle assessments, the inventories of the 33 kV and 132 kV cables were included in the full inventory of an offshore wind farm. The objective of conducting a LCA of the offshore wind farm was to assess the environmental impacts associated with offshore wind power generation. Later, in chapter 5, the environmental impacts associated with power transmission in the North Sea will be investigated and discussed further.

In the analyses of cables, data input for material requirements and requirements of vessels for installation, operation and dismantling were included in detail. Data input for the manufacturing processes was included by using the EXIOPOL IO tables (Tukker et al. 2009). By using the symmetric input-output tables provided by the EXIOPOL project, an analysis of the economical sector covering cable manufacturing was carried out. This was to detect the emission intensities associated with a demand of 1 Euro put upon this sector. The sector including manufacturing of electrical power cables in EXIOPOL is called “Manufacture of electrical machinery and apparatus n.e.c. (31)”. The emission intensities calculated from the IO system, were then included in the stressor matrix in the life cycle inventory analysis. A “dummy process” denoted “Cables manufacturing (IO)” was made in the life cycle inventories for the cables, to represent the environmental impacts caused by the manufacturing processes covered by the IO framework. This procedure was made for all the different analyses of cables.

The results from the basic contribution analyses show that for all three cable sizes, the materials used in manufacturing of the cables (called the “Cable (LCA system)”) have the highest influence in almost every impact category. Materials required in production of submarine cables are mainly metals and plastic. These materials demand processing and preparation which calls for energy demanding and emitting processes. The raw materials are not renewable, which can lead to material depletion in a long-term perspective. Impacts to climate change from the materials required in cables are mainly due to the use of materials such as polypropylene, polyethylene, pig iron and sinter in steel, lead and copper. Use of metals will also have disposal of different by-products, which will especially contribute in the toxicity categories. Disposal of waste products from metals is the main reason why the process denoted “Cable (LCA system)” is remarkable in categories as for instance freshwater eco-toxicity, freshwater eutrophication, human toxicity and marine eco-toxicity (see figure 4-3, figure 4-4 and figure 4-5). The materials used in manufacturing of 33 kV cables, constitute 98 % of impacts to marine eco-toxicity. For 132 kV cables the share is 98.7 % and for the 450 kV cable the share is 99.7 % to marine eco-toxicity. These shares are mainly due to disposal of waste products and slag in processing of metals. The same tendency can be found for impact categories such as freshwater eutrophication, freshwater eco-toxicity, marine eutrophication and human toxicity.

To climate change, the contribution from cable manufacturing processes (denoted the "Cable (IO system)") is also remarkable with almost the same share of impacts as from the materials. By using matrix manipulations and calculating the E vectors for different tiers in the production system, the stressors form the IO system are studied more closely. It is found that for all the cable types, the two biggest contributing sectors to CO_2 emissions, from the IO system, are "Manufacture of basic iron and steel and of ferro-alloys and first products there" and "Production of electricity by coal". These are the sectors causing the highest individual emissions of CO_2 from the IO system, with emissions of 68.6 g CO_2/ EUR and 56.5 g CO_2 /EUR. The emissions of CO_2 are also highest from the purchases the cable sector does from these two sectors, with emissions of respectively 53.7 g CO_2/EUR and 28.1 g CO_2/EUR.

For the 450 kV cable, transportation required has low impacts in every impact category, due to less usage of transportation during lifetime. For the 33 kV and the 132 kV cables on the other hand, transportation used for inspection of cables during lifetime has a remarkable high share in several impact categories. To climate change, transportation contributes with ~ 45 % for 33 kV cables, ~ 40 % for 132 kV cables and ~ 15 % for 450 kV cables.

Structural path analyses (SPA) of environmental impacts have been performed for the different cables. Only the results for the SPA for climate change will be presented here. The objective with this analysis is to systematically extract important supply chains, structural paths, which contribute to environmental impacts (Manfred Lenzen 2006). The resulting structural path analysis will reveal which processes in the production system are having the main responsibility for the environmental impacts to climate change, associated with a foreground process. It will also reveal which processes are causing a demand on whom. Figure 4-10 and figure 4-11 will give the results of the SPA of climate change for the three cables. These figures show the "paths" of the emissions contributing to climate change in the product system. The "curly" arrows are the emissions, in percentage of overall CO_2-eq/MW /km, caused by the respective process used in the given path. The percentages given in the first tier are numbers from the contribution analysis, showing how much of the overall impacts are caused by the respective foreground processes.

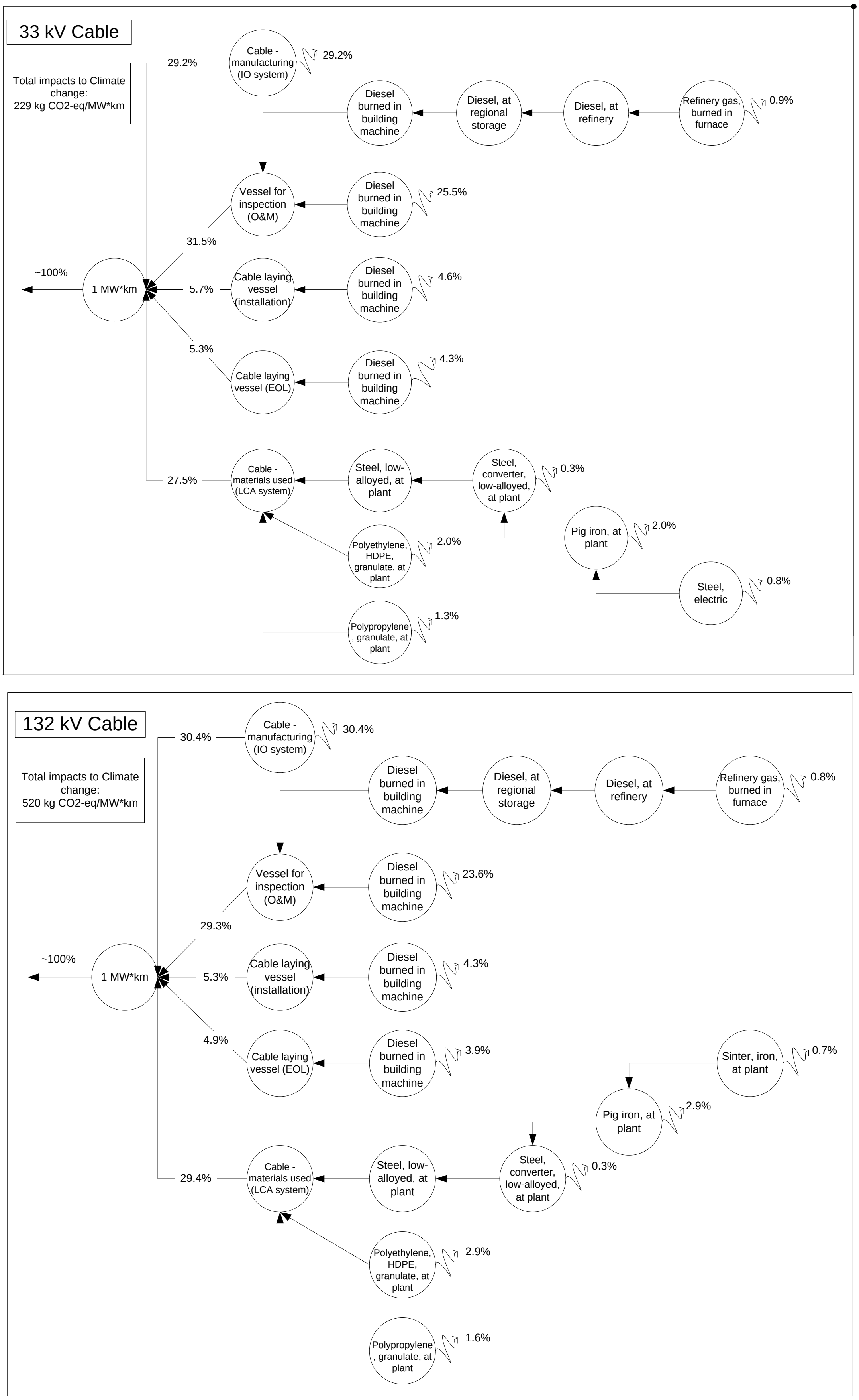


Figure 4-10. Structural path analysis of impacts to climate change made by the 33 kV cable system and the 132 kV cable system.

For the 33 kV cables the total impacts to climate change are 229 kg CO_2 -eq/MW /km. Of this, ~ 32 % are caused by the use of vessels for inspection during 40 years lifetime, 29 % is caused by other manufacturing processes covered by the IO system and 27.5 % of the impacts are caused by materials required for manufacturing of the cables. The 29 % contribution made by manufacturing (the IO system) is mainly due to the cable sector's requirement of purchases from production of electricity by coal and manufacturing basic iron and steel products. The 27.5 % caused by materials used, are contribution from many processes and mainly processes associated with plastics and metals used. In figure 4-10 the "paths" of emissions are illustrated, in order to show which of the processes required for the foreground process covering manufacturing of materials, are causing impacts to climate change. For instance it can be seen that "Pig iron, at plant" needed in low-alloyed steel in the cables, and "Polyethylene,HDPE, granulate, at plant", both contribute with 2 % each of the overall impacts to climate change from the cable. 32 % of the total impacts to climate change are due to the use of vessel for inspection. About 26 % of these impacts are due to the fossil fuel consumption required by the vessel during operation.

In figure 4-10 also the results of a SPA done on climate change for the 132 kV cable are shown. The total impacts to climate change are 520 kg CO_2 -eq/MW /km. Of this, ~ 30 % are due to manufacturing processes excluding materials used ("IO system"), ~ 29 % are due to materials required in the cables and ~ 29 % are due to use of vessels for inspection through 40 years. Which background processes that are responsible for the contribution to climate change from the different foreground processes are the same as for the 33 kV cable and can be studied in the figure 4-10.

The similarities between the 33 kV and 132 kV cable in distribution of environmental impacts from foreground processes, are because the cable types are the same. The cable types are; HVAC XLPE insulated cables with three-core copper conductors. The type of materials required for both cables are the same, only with different quantity. The emission intensities included in the stressor matrix from the IO framework, are also the same for both cable types. These emission intensities are given in a per Euro unit, which implies that it is the variation in price of the 33 kV and 132 kV cables that determine the contribution to environmental impacts from the IO system. The price is calculated by using the Eurostat price of 3.06 EUR/kg for cables (Eurostat 2011b). Hence, the price and the environmental impacts depend on the weight of the cable and therefore also the material distribution of the cable. This is valid for all impact categories, and not only for climate change. Amount of transportation required during installation, operation and dismantling of the 33 kV and 132 kV cables are assumed to be the same. Similarity in the LCI of these two cable types makes the results from their contribution analyses very similar in percentage distribution. Total impacts caused by the 132 kV cable are basically just scaled up due to higher material intensities in the system.

For the 450 kV cable, it will be somewhat different because it is a different type of cable requiring other material types and less transportation during lifetime. The results from a structural path analysis for climate change are shown in figure 4-11.

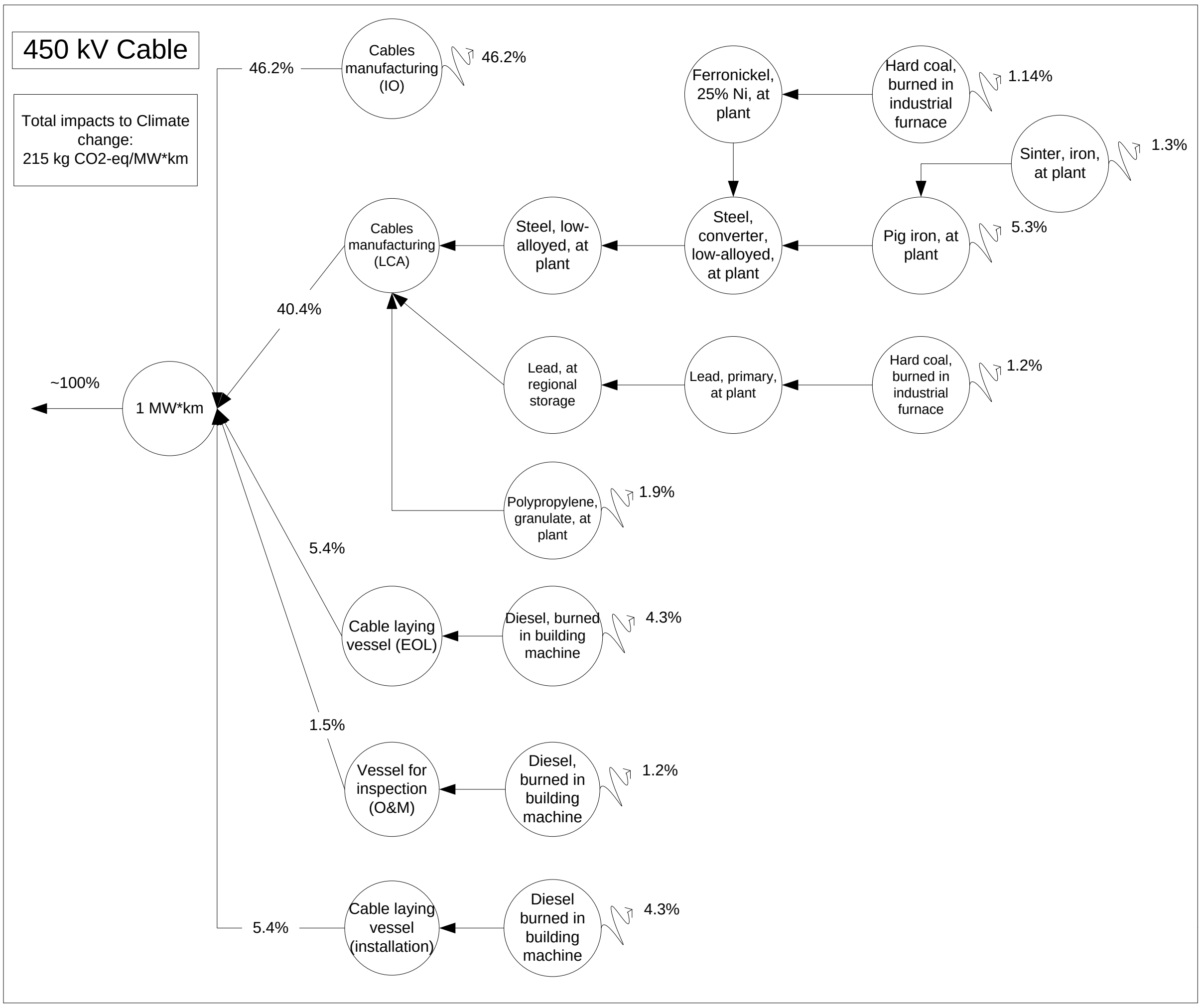


Figure 4-11. Structural path analysis of impacts to climate change made by the 450 kV cable system.

The 450 kV cable has a total contribution to climate change of 215 kg CO_2 -eq/MW /km. In figure 4-11 it can be observed that manufacturing of the cables constitute in total 87 % of the total impacts to climate change, whereof 40.4 % are due to materials used in the cable and 46.2 % are due to other inputs than material inputs in manufacturing of the cable. The contribution from the IO framework is the same as for the 33 kV and the 132 kV cables. These are not included in the SPA figure as these contributions are given in per Euro. The process “Cables – materials (LCA)” can be further disaggregated and is included in the SPA figure. The foreground process covering material requirements of the cable have several background processes that constitute the impacts to climate change. For instance “Pig iron, at plant” constitutes 5.3 % of the overall impacts to climate change from this cable. The remaining shares of impacts to climate change are mostly due to the use of marine vessels during installation, operation and dismantling of the cable. The use of fossil fuels in these vessels contributes to climate change with a share of between 1.2- 4.3 % of the total impacts to climate change from this cable type. This 450 kV cable has quite low total impacts to climate change compared to what the cables used within an offshore wind farm have. This is due to the length and amount of transfer capacity of this cable compared to the amount of materials and transport required. The LCA of the 450 kV cable system consists of two cables each having a transfer capacity of 700 MW, while the transfer capacity of cables *within* the wind farm is 390 MW. The length is 730 km for each of the 450 kV cables (they lay in parallel), compared to 63.3 km for the 33 kV cable grid and 30 km for the 132 kV transmission cable. Even though the requirements for materials are much higher for the 450 kV cables, the high transfer capacity and long distance will make the amount of material per MW*km quite low.

After carrying out these individual life cycle assessments of the cables, the inventories for the 33 kV and 132 kV cables were included in the total inventory of an offshore wind farm. Then a LCA was performed for the offshore wind farm. The results show that delivery of 1 kWh of electricity from the wind farm to grid on shore causes 20.6 g CO_2 -equivalents to climate change, 0.022 g P -equivalents to marine eutrophication, 0.55 g 1.4-DCB -equivalents to marine eco-toxicity, 0.11 g SO_2-equivalents to terrestrial acidification, 16.3 g Fe-equivalents to metal depletion and 6.94 g oil-equivalents to fossil depletion. Of the 20.6 g CO_2-equivalents to climate change, ~55 % are due to the windmill, ~30 % are because of use of vessels and 13 % are due to the need for replacement of parts throughout a lifetime of 20 years. These are the three largest contributors to climate change. Only 1.5 % of the total impacts to climate change are due to submarine power transmission associated with the offshore wind farm (the 33 kV collection system and the 132 kV transmission system).

The results from the structural path analysis on the impacts to climate change caused by the offshore wind farm are shown in figure 4-12.

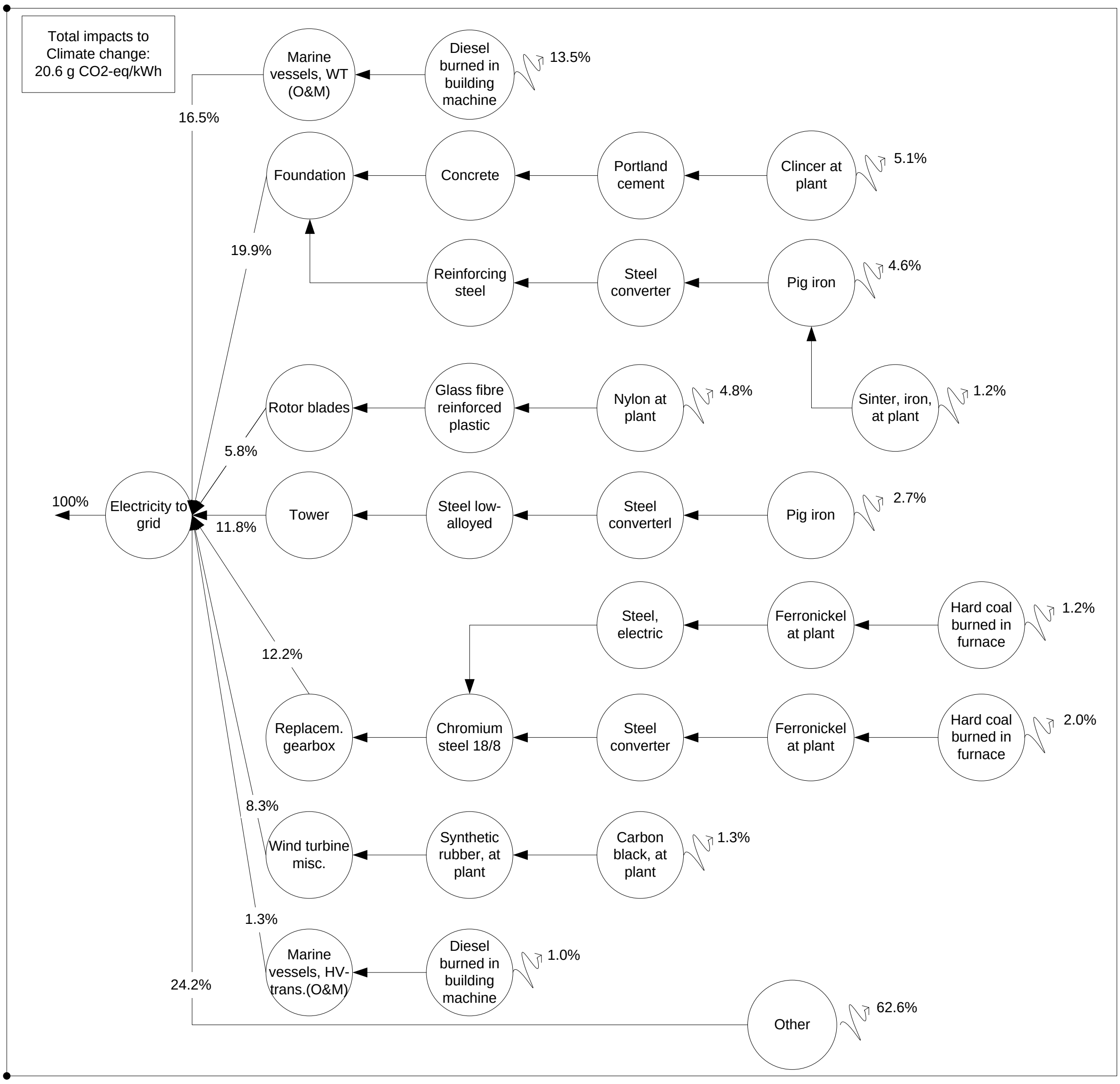


Figure 4-12. A structural path analysis performed for the offshore wind farm in this study.

In the life cycle impact assessment of this offshore wind farm, it is found that the foundation and tower constitute the greater part of impacts caused by the windmill. The foundation constitutes 37 % (4.1 g CO_2 -eq/kWh$_{el}$) of the impacts to climate change caused by the whole *windmill*, which equals to ~20 % of the total contribution to climate change from the entire *wind farm*. For the tower, the contribution is 2.4 g CO_2 -eq/kWh$_{el}$ which equals to 21 % of impacts caused by the whole *windmill* and ~12 % of total impacts to climate change from the entire *wind farm*. For comparison, Martínez et al. found that for concrete foundations used onshore, emissions of CO_2 -equivalents per kWh of electricity was 1.6 g. For the tower it was 1.4 g (Martínez et al. 2009). The much higher material intensity of offshore windmills will result in higher environmental impacts.

The windmills in this study are bottom-fixed concrete substructures. To make the foundations, huge amounts of concrete and steel are required as these foundations are the whole substructure of the windmill and thus need to be heavy enough to withstand the rough environmental conditions offshore. Impacts caused by the substructures therefore become high. From the structural path analysis for climate change in the figure above, it is shown that the most important contributors to climate change from the windmills are; clinker used for concrete, sintered iron used for reinforcing steel in foundation and pig iron used both for low-alloyed steel in the tower and in the foundations.

The share from foundation and tower are remarkable also in the toxicity and eutrophication impact categories. Structural path analysis for eutrophication shows that metals used in producing electrical collection systems, generators, foundations and cables, are among the processes causing the demand which leads to contribution of impacts on both freshwater and marine eutrophication. The contribution comes mainly from disposal of sulfidic tailings and electricity/heat production from hard coal. In the eco- toxicity categories it is also the use of metals in components that leads to environmental impacts. The contribution comes mainly from disposal of sulfidic tailings and nickel slag. Stressors making the environmental impacts on eutrophication are phosphate, nitrates and nitrogen oxides while stressors causing eco-toxicity are for instance nickel, copper, manganese and zinc. These stressors are present mainly due to the requirement of fossil fuels to produce materials, and because of some spoil from different raw material mining activities. In metal depletion, the use of steel in the tower will have a great impact and constitute about 30 % of the total impacts on metal depletion caused by the windmill. Manganese concentrate used in low-alloy steel, tin in the nacelle and use of ferronickel in chromium steel for gearboxes are some of the processes contributing most to metal depletion. The stressors causing impacts are mainly raw materials in ore, such as nickel, iron, tin, manganese and copper. These findings emphasize what has been stated earlier about metals being an important reason for the environmental impacts caused by a windmill, and thus the overall system (e.g. (Weinzettel et al. 2009)).

The second largest contributor to climate change is the use of vessels for the installation, operation/maintenance and dismantling phase. Especially the use of marine vessels and equipment will contribute much. None previous LCA studies of offshore wind farms, where transport is included in great detail, have been found. Transport for installation is normally included, and some transport for operation and preventive maintenance is normally included (Weinzettel et al. 2009), (Vestas 2006), (Martínez et al. 2009). The assumptions of transportation distances and use of these vessels are normally very simplified, therefore it is assumed that the impacts from installation, operation and maintenance generally become underestimated in LCA's since these phases requires quite a lot of transport and thus fossil fuels. In this study, the processes covering installation, operation and maintenance of the offshore wind farm, are found responsible for approximately 8.1 g CO_2 -equivalents per kWh_{el}, which equals ~ 39 % of total impacts on climate change. This included replacement of parts throughout lifetime and vessels used in these phases. From the structural path analyses, it is evident that fossil fuels needed for marine vessels are the main reason for the large contribution from marine vessels in all environmental impact categories. This study has included the use of marine vessels and transportation required on shore in a much greater detail than previous studies. This is in order to investigate the impacts caused by operation and maintenance of the wind farm throughout lifetime. Doing this, is probably one of the reasons why the environmental load from vessels have a higher share in this study than in previous studies.

Figure 4-6 shows that the contribution from use of transport is significant, with 30 % of total emissions to climate change. Hence transportation should not be excluded or be given a lower priority in a LCA study of an offshore wind farm. It can be seen in figure 4-8 that it is mainly the impacts caused by marine vessels used for operation and maintenance that constitutes this share. 60 % of the contribution to climate change from the marine vessels is caused by the vessels used for operation and maintenance. This equals to about 3.9 g CO_2- eq/ kWh_{el}, which is ~19 % of total climate change impacts. Also, 40 % of the contribution to marine and freshwater eco- toxicity from the marine vessels, and more than 60 % of contribution to terrestrial acidification, are caused by marine vessels used in operation and maintenance work. From the structural path analyses for climate change in figure 4-10, it is evident that fossil fuel needed for marine vessels is the main reason for the large contribution of marine vessels on environmental impacts. From the structural path analysis it can be found that diesel used in marine vessels for operation and maintenance work on wind turbines, make up 13.5 % of the total impacts to climate change. Diesel used in marine vessels for operation and maintenance of HV transformers only makes up a share of 1 % of total impacts to climate change. It should be noticed that vessels for operation and maintenance of windmills are the vessels used definitely most throughout lifetime. It is thus not very surprising that these are the vessels contributing most to the environmental load.

The third large contributing part to environmental impacts from the system is the replacement of parts. It is replacement of gearboxes that constitutes the largest contribution to environmental impacts in all categories. This is due to the assumptions made on which parts that represent replacement of parts in the various failure categories given in table 4-16. Gearboxes are the components assumed needed to be replaced most frequently, which results in allocation of the highest impacts. Contribution to climate change impacts caused by replacing gearboxes equals to 2.5 g CO_2 -eq/kWh_{el}. From the structural path analysis of climate change it can be seen that the demand of energy from hard coal, for producing chromium steel used in gearboxes, is one of the paths causing a significant share of total impacts to climate change. For the toxicity categories it is use of ferronickel in chromium steel and disposal of nickel slag from making ferronickel, which contribute significantly to the total environmental impacts from replacement of gearboxes. The only two impact categories where replacement of gearboxes does not dominate, in proportion to total impacts caused by changing parts, are human toxicity and freshwater eutrophication. In these categories, replacement of generators has a higher contribution due to a much higher amount of copper used in generators than in gearboxes and another type of disposal. Use of different types of alloyed steel is a central element of uncertainty in the analyses. In practice it is for instance less nickel in the gearbox than in the chromium steel process in Ecoinvent.

Power transmission associated with the offshore wind farm does not constitute a great share of the environmental impacts caused by the wind farm. The contribution to climate change from submarine power transmission is of 1.5 % of the total impacts. This equals to 0.3 g CO_2-eq/kWh_{el}. In general, the contribution from the submarine power transmission system is higher in the toxicity and eutrophication categories due to the use of noble metals. In freshwater eco-toxicity the contribution is of 0.03 g 1,4-DCB -equivalents (4.9 %), in freshwater eutrophication the contribution is 0.001 g P -equivalents (10.5 %), in marine eco-toxicity the contribution is 0.03 g 1,4-DCB -equivalents (5.3 %) and in metal depletion the contribution is 0.8 g Fe -equivalents (4.7 %). The largest contribution from the submarine power transmission system is found in human toxicity where the contribution is 14 % of the total impacts from the wind farm, which equals 2.5 g 1,4-DCB -equivalents. In all these categories it is the use of copper which has the greatest effect on impacts. This results in disposal of sulfidic tailings, which has great impact on human toxicity, marine eutrophication and freshwater eutrophication. In the freshwater eco-toxicity and marine eco- toxicity categories it is mainly the need for primary copper which causes the environmental impacts. These results are derived from the respective structural path analyses, but it should be remembered that the uncertainty associated with especially the toxicity categories are high.

By studying the environmental impacts caused by the wind farm, it has been found that operation and maintenance of offshore wind farms are very important to consider in detail when assessing environmental impacts from such a power plant. Use of vessels for operation, maintenance and replacement of parts, together contribute with nearly 40 % of total contribution to climate change from the system. Also the tower and foundations will contribute with great impacts, for instance to climate change were they contribute with respectively 12 % and 19 % of the total impacts caused by the wind farm. The submarine power transmission in the wind farm is not having a large contribution to the total environmental impacts from an offshore wind farm. It will mostly cause impacts in toxicity and eutrophication categories, due to the use of noble metals.

4.4 Data quality and uncertainty

The uncertainty in a process based (bottom-up) life cycle assessment is in general considered to be fairly high. Normally it is distinguished between two types of uncertainties (ISO 14042 2003); data uncertainty and uncertainty about the appropriateness and accuracy of the model. In this study, both types of uncertainty are present. There will be uncertainties in the data collected. It has not been possible to collect all the wanted data either, and assumptions have been made on how some parts of the system are built up. Arvesen notes that the cut-off errors of process based LCA studies of renewable energy systems can be higher than 50 % (Arvesen & E. Hertwich 2011). So there is a high uncertainty associated with the system boundary in LCA. Data uncertainty is probably giving some of the highest uncertainties in this system. This is because the inventories for all processes are not complete due to lack of information on processes, and because of assumptions that have been necessary to propose in order to carry out the assessment. Strategies, for instance for maintenance of an offshore wind farm, are in this study determined based on other studies and information found in different sources. This introduces a high uncertainty in the assessment, as the information is not first-hand. It can affect the results, and might allocate a too high share of total impacts to the wrong process. Nevertheless, the results in this study are considered to be adequate.

There is also a high degree of uncertainty in using the IO framework to cover the missing inputs in the inventories. By including the IO system for manufacturing of cables, some adjustments have to be done to the A matrix in the IO framework. To avoid double counting, the material amounts included in the LCI must be excluded in the IO system. This must be done by either subtracting the material amounts from the respective IO sectors, or by putting the respective sectors to zero. Either two of these methods have their advantages and disadvantages. In reality some of these materials, for instance steel, will also be used for other processes than directly as inputs to manufacturing of the cable. Putting the respective sector to zero will hence underestimate the amounts of materials used. By subtracting the amounts of materials used in manufacturing of cables directly from the respective sectors, new challenges and uncertainties occur. To do this, a price must be found for the different materials. This might be difficult as there are big price variations on these types of materials. This uncertainty may at worst result in having to subtract more materials than available in the A matrix, leaving negative numbers in the A matrix. The A matrix cannot hold negative numbers, so this has to be handled. Whether to put the respective sectors to zero or to subtract the given amount of material required, both cause uncertainties. Thus are the respective sectors set to zero here, to avoid negative numbering in the A matrix. Another important uncertainty regarding the IO framework used in this study is associated with the stressors. The IO data covers fewer stressors than the LCA system does. This results in an underestimation, and in worst case absence of, the environmental impacts caused by the IO system in several impact categories. In the LCIA, the LCA part of the system will hence be attributed a larger share of the total environmental impacts in some categories, as data from the IO system is missing. This is not necessarily how the distribution of environmental stress would be in reality. More about uncertainty in IOA can be found in for instance (Roy 2004).

Uncertainties associated to characterization factors used in ReCiPe method are also important to beware of. The different impact categories, especially the toxicity categories, include high uncertainties. It is difficult to decide precisely how surroundings and environment will react to different toxic substances, as this cannot be tested. This means that the toxicity categories might be emphasized too much or too little in an impact assessment. In this study, contribution to the toxicity impact categories has been emphasized to a large extent. More about the uncertainties can be read in (Althaus et al. 2010). Uncertainties associated with whether midpoint or endpoint indicators are used, are to some extent included in the ReCiPe method already. Choosing between an individualist, hierarchist or egalitarian perspective will also automatically include a decision about uncertainty level, as ReCiPe has defined these perspectives with different uncertainties (Goedkoop et al. 2009). There are also uncertainties associated with the processes in Ecoinvent. Some processes have higher uncertainties than others, due to bad inputs or just old data inputs. For instance, there are two processes used in the life cycle assessment of the offshore wind farm that point out and are assumed having overestimated impacts; the use of nylon 66 in rotor blades and the natural gas furnace used for combustion of natural gas. According to the LCA software *SimaPro* these processes have high uncertainties associated, but are still used due to lack of other better processes to apply in the model (Ecoinvent 2010), (SimaPro 2007).

Except from the uncertainties in the methods of LCA and IOA, the uncertainties associated with analyses of cables are mainly due to data uncertainty. For all three cable types there is an uncertainty in the data inputs for materials. For the 33 kV and 132 kV cables, these data are gotten form datasheets given by producers. These data sheets provide the cross-section sizes of the different material types used in the cable. From this, material amounts have been calculated based on material densities. This gives an uncertainty, as density should ideally be measured for each material to get it exact. In addition, the data sheets only provide data for the main materials used. Materials like for instance binder tape is excluded from the data sheets. This means that some materials are left out of the analysis. For the 450 kV cable it is somewhat different. The cross-section sizes for this cable were not provided by the cable producer. As Sintef Energiforskning has got a physical part of the NorNed cable in-house, measurements were made directly on this cable. Then, the amounts of materials were calculated by using material densities. This gives an uncertainty in the material data. For all these three cable types, these approximations of material distributions are assumed not to have a great impact on the results, as metals are assumed to have the greatest environmental impacts and are thus the most important materials to include. These are included satisfactory. By using the weight given in the data sheet for the 33 kV cable, the total weight should be 1637 tonnes. In this analysis the weight becomes 1827 tonnes. For the 132 kV cable the weight in data sheet is 1956 tonnes, while the weight calculated and used in the analysis is 2053 tonnes. For the 450 kV the weight for this part of the NorNed cable is 84 ton/km (ABB 2010a), while the weight found in this study is 77 ton/km. The differences are between 5 – 10 % and assumed to be acceptable.

Another uncertainty is associated with the prices used for the cables. This uncertainty will then be connected to the use of the IO framework in the analysis. The prices used are got from the statistics on the production of manufactured goods in Eurostat. The price is 3.06 Euro per kg of cable, and apply to the sector called “Insulated electric conductors for voltage >1;000V excl. winding wire; coaxial cable & other coaxial electric conductors; ignition & other wiring sets used in vehicles; aircraft; ships” in the Eurostat table (Eurostat 2011b). Hence, the price depends on the total weight of the cable, which again depends on the material requirement calculated. The price from Eurostat is in basic price, without any taxes included, and in year 2000 pricing. In table 4-5, table 4-9 and table 4-14, the respective prices are presented together with some other prices for submarine cables. The price presented by Green et al for the collection system in a wind farm (33kV cables) is about 10 million Euros (Green & Schellstede 2007), while the price from Arvesen et al is about 19 million Euros (Arvesen & E. Hertwich 2011). These prices are about 2-3 times higher than the price from Eurostat. The same tendencies are observed for the 132 kV cables and 450 kV cables. Since the calculation of environmental impacts from the IO part of the system depends on the price of the cable, the price will affect the results. The price by Green et al is expected not to be in basic price, and therefore it would be lower if taxes were excluded from the price. The difference between prices from Arvesen et al. and Eurostat is also high. There are huge uncertainties in these prices, and the price from Eurostat might be too low. The price by Eurostat is used in this analysis since it is known to be in basic prices, and the correct basic prices were not possible to obtain directly from any cable producers. The contribution in impact assessment might be lower than it would be if the correct prices were obtained.

As for the analysis of the cables, uncertainties are associated with the data inputs to the different processes in the offshore wind farm as well. There are many processes to describe the system, which all claim solid data inputs. Some of the larger uncertainties of data in the system are for the vessels used. For marine vessels, only fuel consumption is included in the assessment and the emissions associated with burning of this fuel. The vessel itself, production, operation, maintenance and dismantling of the vessel, is not included. This is because use of marine vessels is given, and calculated, in unit “ship days”. In Ecoinvent, the processes for operation of marine vessels have units ”tkm”. To use the Ecoinvent processes, all data for use of marine vessels in this study have to be transferred from “ship days” to “tkm”. This is not an intuitive conversion unless you have the distances of transport and the weight transported. This could be done, but it would still require crude assumptions on especially distance. Applying new, crude assumptions to numbers already being based on assumptions about travel distance etc, would also give high uncertainties. In addition to this; the processes which had to be used for operation of marine vessels, if Ecoinvent processes were to be used, do not fit to all the different kind of vessel processes in this study. Ecoinvent only has processes for “operation barge”, “operation transoceanic tanker” and ”operation transoceanic freight ship” which would only give crude assumptions for many of the vessels used. Based on this, it can be said that the uncertainty with use of vessels is high. Still, the emissions from consumption and burning of fossil fuel in boats are included, which gives the contribution of emissions from operation of the vessel. These are the emissions coming from actually using these vessels. Transportation by lorry, of windmill components and cables, will also have a data uncertainty attached as the transportation distance is crudely assumed to be

100 km only by lorry. Most likely there will be used several types of transportation vessels together with the actual lorry, as escort cars, for transporting the components.

Uncertainties around the failure rate and replacement of parts are also quite high. Crude assumptions are made on which components are replaced, and how often this has to be done. The failure rates and how failure rates are designed vary a lot in different studies, because different assumptions and approaches are taken. In this study, number of replaced parts is based directly on the failure rate and a percentage distribution of failures into four failure categories. This will lead to results being not fully correct, but giving a reasonable estimate.

For both the analyses of cables and the full analysis of the offshore wind farm, covering of recycling gives a huge uncertainty in the analysis. A large missing gap in accuracy and information in the model is to a great extent related to the poor information on recycling of materials. Recycling of materials is not included properly in the models and discussion and assessment of the importance of recycling is not accomplished properly. To cover for missing recycling, use of recycled materials in inputs to production processes is included. Recycling is quite important for the total environmental impacts caused by the wind farm, and hence including a complete recycling process of the wind farm and of all waste is expected to improve the environmental profile for the wind farm further. This is recommended for further work.

Even though there are uncertainties connected to system boundary, processes and data used in the analyses, the results are considered to be adequate. The assessments are thoroughgoing and the results give good indications of what are the distribution and order of magnitude of environmental impacts from the different cables and the offshore wind farm.

Chapter 5

5 Power generation and power transmission in the North Sea

This chapter will focus on giving an answer of the following questions; what are the environmental costs and benefits associated with large-scale expansion of power generation and power transmission in the North Sea? What can be concluded with respect to system designs and strategies for maximizing net environmental benefits? What is the role of sea cables on smoothing intermittent wind power? What are the challenges associated with power scheduling and standby requirement? The term “environmental costs and benefits” is understood as positive and negative environmental consequences.

These questions are very complex, and caution has been made in presenting firm conclusions as all relevant analyses have not been possible to perform in this study. The following discussions have aimed at including the most important topics in answering the problem description, and reflected around these.

5.1 Discussion on environmental costs and benefits

Offshore wind power is a new and relatively mature technology that gets more attention and interest as the energy demand and the challenges of climate change increases. North Europe is in a leading position regarding offshore wind power, with the United Kingdom, Denmark, Germany and the Netherlands in the lead. Interest for offshore wind power is also growing in Norway (Volden et al. 2009). The ambitious targets and plans for offshore wind power development in the North Sea have raised questions regarding how to integrate the wind power in the existing power systems of Europe. This has to be done in an efficient and secure way. In the context of this, it is assessed whether it’s beneficial to develop an offshore power grid in North Europe in order to connect the offshore wind farms and the different power markets in Europe. Several barriers – technical, market, legal, regulatory – hinder the development of this grid. Two major projects undertaken are the *Trade Wind* project and the *OffshoreGrid* project, both exploring the benefits a European grid can have on the integration of large amounts of wind power. For further reading about these projects, see (Hulle 2009), (Trade Wind 2009), (Decker et al. 2009), (Intelligent Energy Europe 2011).

Impacts on the environment due to development of offshore wind power plants and power transmission cables, are not only caused by direct emissions to air, soil and water. Effects on competing maritime uses and marine environment must also be taken into account when assessing environmental impacts. There are also environmental impacts caused by for instance visual impairments of the seabed topography, noise and smell. These factors can affect benthic flora and fauna, birds, marine mammals, fish and other, and are considered as serious environmental impacts in development of offshore wind farms and cable laying of submarine cables. Placement of windmill foundations, towers, rotors and transformer stations require space both on seabed, in the air and in water. This can lead to habitat loss for benthos, birds, marine mammals and fish, which can be very difficult and critical for some species. Building an offshore wind farm will also create a change in the seabed’s landscape as foundations and submarine cables require interference with, and preparing of, the seabed. Dependent on what type of foundation is used, this will include digging in the seabed and use of artificial hard substrates to make the foundations steady. As a result, this can demolish the seabed for benthos and fish in the respective areas and might result in extermination of benthic communities or species. Transformation of the seabed will also have an effect on cultural assets as the seabed has an archive function of soil (Köller, J. Köppel, et al. 2006).

Changes in water flows in the area around the wind farm, due to the windmills interfering with water flows, can be critical for instance for the benthos and benthic flora. The sections of the windmill raised above sea level can cause noise pollution because of noise and humming from the rotors. This is not expected to seriously injure marine mammals, but can lead to displacement of animals. The effects of noise from the construction phase can on the other hand cause lethal damage on marine mammals. Artificial illumination will also be used on the windmills as safety for navigations of ships and similar. This can cause collisions between birds and windmills, because sea birds get confused of the light (Köller, J. Köppel, et al. 2006). Especially sea birds are in a vulnerable position when it comes to colliding accidents with windmills, but this problem might not be as common in offshore wind farms as it is for onshore wind farms. These consequences might lead to some bird species being forced to change habitat. All these environmental costs are important when discussing environmental impacts caused by submarine power transmission and development of offshore wind farms. It should be mentioned that the impacts on for instance benthic fauna and flora will be greater for bottom-fixed windmills than it probably would be from floating windmills, as they interfere considerably less with the seabed. At present it is nevertheless most likely to install bottom-fixed substructures, as floating windmills are not commercialized yet. For extended knowledge of the consequences wind farms have on flora and fauna, see the status report of the environmental monitoring program of Horns Rev offshore wind farm (Vattenfall A/S 2005) or the book *Offshore Wind Energy. Research on Environmental Impacts* (Köller, W. Peters, et al. 2006). This report will focus upon environmental consequences and extended effects from emissions to soil, air and water.

To discuss the environmental consequences and extended effects from emissions to soil, air and water caused by expansion of power generation in the North Sea, development of wind power has been focused upon as this is the most realistic alternative. The great environmental benefits from large-scale expansion of power generation from offshore wind power plants in the North Sea, are due to the power being generated from a renewable resource. This allows us to produce electricity without having any direct emissions from the power production itself. Offshore wind power production will in general be one of the environmentally best alternatives for electricity production available, in order to meet the emission targets and at the same time cover the increasing demand for power. The greatest environmental gain will be achieved if development of wind power leads to a phase out of already existing electricity production from fossil resources, and stimulate to further development of power production from renewable energies. If wind power replaces electricity from fossil resources, a reduction in CO_2 emissions will be achieved. If, however, increase in demand for electricity is covered by wind power instead of power from fossil sources, then the emissions will be kept at the present level and in that way contribute with an environmental gain. A higher electricity production is then achieved without new emissions from power generation.

A wind power plant is nevertheless a material intensive system that requires a particularly great share of metals, which leads to environmental impacts such as depletion of resources and eco- toxicity. A power plant situated far offshore will also require inspections which imply use of fossil fuels in vessels. In the analysis of this study, it has been found that delivery of 1 kWh of electricity from an offshore wind farm with bottom-fixed windmills, causes 20.6 g CO_2 -equivalents to climate change. All results are found in table J-1 in appendix J and graphically in figure 4-6 in chapter 4.2.4. The results show that environmental impacts caused by an offshore wind farm are not only related to emissions to air, but also to impacts such as depletion of resources and toxicity in marine and fresh waters. The emission of 20.6 g CO_2 -equivalents per kWh of electricity produced, are related to the whole life cycle of the wind farm and will not occur as direct emissions from generating electricity in the wind farm. Emission of CO_2- equivalents are related to production of windmill components, cable production, production of HV transformers and vessels used during installation, operation, maintenance and dismantling work of an offshore wind farm. From this analysis we understand that assessment of how environmentally damaging a power plant is, must be carried out in a life cycle context. Offshore wind farms have associated emissions, but these are caused by installation work, maintenance and operational work and dismantling of the wind farm. By installing an offshore wind farm instead of power generating plants using for instance coal, there will nevertheless be a high amount of avoided emissions.

It is interesting to compare the environmental impacts caused by an offshore wind power system to impacts from other electricity sources. This is interesting in order to understand the differences and similarities in environmental impacts from different electricity productions, and to see the changes by shifting from for instance coal power to wind power production. To investigate this, environmental impacts associated with production of 1 kWh of electricity from an offshore wind power plant, were compared to the environmental impacts from electricity production from hard coal, natural gas and the European electricity mix. The assessments were carried out by using the LCA software tool *SimaPro* (SimaPro 2007). Processes from the Ecoinvent 2.2 database were used for the impact assessments of these electricity production systems (Ecoinvent 2010). The Nordel mix was used both for the hard coal and natural gas processes. Nordel was until 1.july 2009 the body for co-operation between the transmission system operators in Denmark, Finland, Iceland, Norway and Sweden. Now it is a part of the European network of transmission system operators for electricity (ENTSO-E) (ENTSO-E 2011a). The results from comparing environmental impacts from the different electricity sources are presented in figure 5-1.

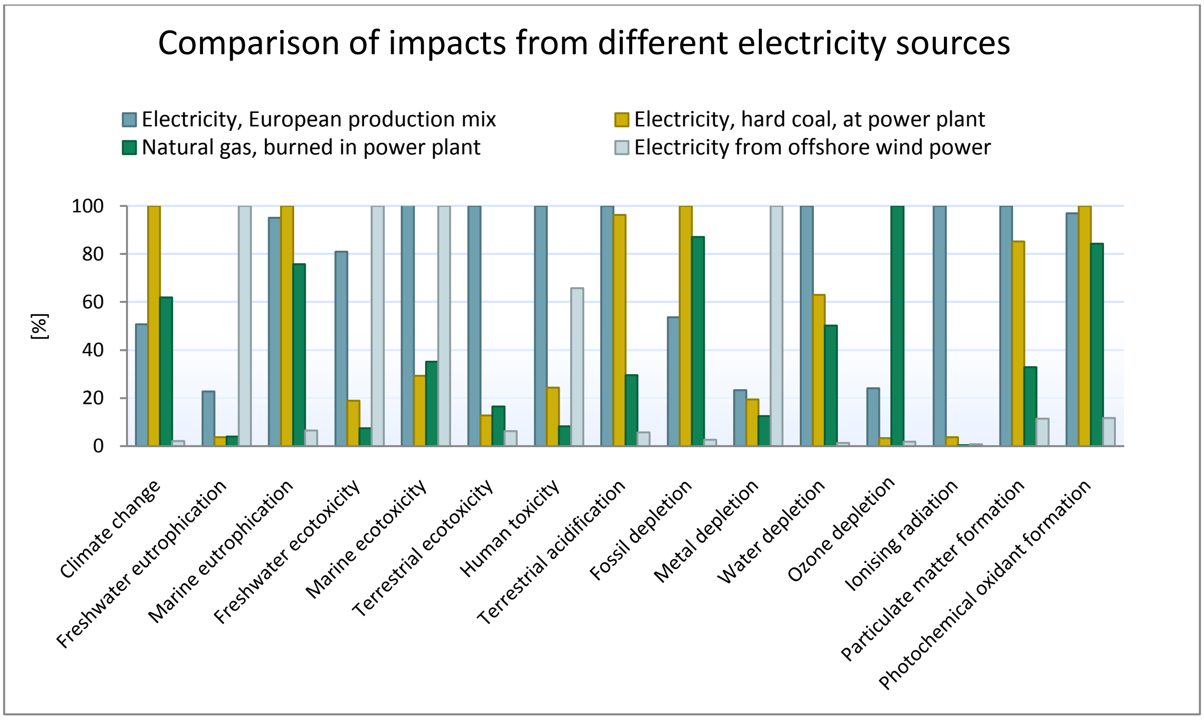


Figure 5-1. Environmental impacts from different electricity sources per kWh of electricity delivered to the grid.

Figure 5-1 shows the results from comparing the environmental impacts caused by producing 1 kWh of electricity from the different electricity sources. In each impact category, the results are referred to the electricity source with the highest absolute contribution in the respective impact category. In general hard coal and the European production mix will have the absolute largest contributions in several categories. To climate change, the assessments found that offshore wind power production contributes with 20.6 g CO_2 -eq/ kWh_{el}, while hard coal contributes with 965 g CO_2 -eq/ kWh_{el}, natural gas with 589 g CO_2 -eq/ kWh_{el} and the European production mix contributes with 489 g CO_2 -eq/ kWh_{el}. These three sources all emit more than 20 times more CO_2 -equivalents per kWh_{el} throughout lifetime, than the offshore wind power system does. Nevertheless, it can be seen that offshore wind power is responsible for the highest absolute impacts in the following three categories; freshwater eutrophication, freshwater eco-toxicity and metal depletion. In marine eco-toxicity, the electricity mix for Europe is slightly higher than offshore wind power. In these four impact categories, metals are the main contributors. It is mainly use of toxic metals such as copper and chromium steel that constitute these environmental impacts. From the contribution analysis (see e.g chapter 4.2.4) it was found that contribution to both freshwater and marine eco-toxicity mainly is due to the disposal of typically nickel smelter slag and sulfidic tailings from production of components such as gearboxes. In almost all remaining impact categories, the impacts from wind power are very small compared to impacts caused by the other electricity sources. In for instance climate change, marine eutrophication and fossil depletion, electricity from the wind farm has significantly lower impacts than the other alternatives. In some categories, as for instance water depletion and ionizing radiation, the impacts are near to zero. An offshore wind power plant will not use fossil resources directly to produce electricity, and does therefore not emit CO_2 -equivalents during power generation. This results in low impacts to climate change and fossil depletion. The other three electricity sources all produce electricity from fossil sources and therefore have emissions to air from the electricity production itself, in addition to emissions associated with construction of the power plant. This is why these alternatives will have higher contribution in climate change, terrestrial acidification, particulate matter formation and photochemical oxidant formation. Since they depend on fossil resources, the environmental impacts on fossil depletion will be high for these alternatives. Building power production sites for hard coal, natural gas, nuclear power plants etc. will also affect the use of land and natural transformation. This is not considered in detail in this study as it does not have the same relevance for offshore wind farms.

The European electricity mix differ some from the other alternatives in that it includes several types of electricity production, and is thus more complicated to analyze. Disposal of waste and spill of substances to aquatic systems from electricity production sites can be some of the reasons for contribution to for instance marine and freshwater eutrophication. The European electricity mix has the highest contribution to impacts on acidification, ionizing radiation, particulate matter formation and natural land transformation. This is because the production mix consists of power production from several types of electricity producing entities such as coal, natural gas, nuclear and wind power. The results from comparing offshore wind power production to other relevant and realistic alternatives indicates that it can be environmentally rational to have a large-scale expansion of offshore wind power in the North Sea, if the alternative is to develop more high polluting power generation on land. This conclusion is independent from socio-economic considerations, policy assessments and studies of grid capacity and consumption patterns.

With large-scale development of offshore wind power in the North Sea, the necessity of large-scale power transmission arises. The idea of a transnational offshore grid in the North Sea and Baltic Sea has in the recent years been proposed several times by different market participants, as stakeholders and TSO's (Hulle 2009). Several studies have been, and are now, undertaken examining technical, economic and political aspects of different alternative offshore grids. A study called *OffshoreGrid* is at present undertaken within the Intelligent Energy Europe program. The study develops a scientifically based view on an offshore grid in Northern Europe, and will formulate a suited regulatory framework considering technical, economic, policy and regulatory aspects (Intelligent Energy Europe 2011).

Development of a power cable is dependent on differences in the power system and the prices in both ends of the cable. In this study, focus is on the environmental costs and benefits from developing a transnational offshore grid in the North Sea. The environmental costs and benefits associated with an offshore power grid should be included in the assessment of whether or not to build a power grid in the North Sea. New transmission capacity, both onshore and offshore, is essential if developing large-scale offshore power generation. When Europe's power system gets considerable contribution from wind and solar power, the demand for balancing services in the power system appears in order to handle the standby requirements and make power scheduling easier. Connection of several power markets, with different price structures, will increase the possibility of balancing the intermittent wind power and secure power supply. New technology for HVDC transmission provides new possibilities for making regulating power available, on each side of the power transmission cable. Hydropower generation is expected to be the best and most environmentally friendly alternative to use for producing balancing power. Hydropower production in the Nordic regions could be utilized for this, as Norway and Sweden hold most of the large hydropower reserves in the world. If this is to be utilized, a higher power transmission capacity has to be installed between the Nordic regions and Europe. Thermal power can also (and will most likely in reality) be used in the European power system as standby power reserves. However, to achieve as high environmental benefits as possible, renewable energy sources should be made use of. In this study, Norway's possibility to deliver balancing power to Europe has been emphasized.

New installation of power capacity in Norwegian hydropower plants, combined with further establishment of transmission capacity in the North Sea and expanded capacity onshore, can consequently be important actions for EU to reach its emission targets. The Sinclair Knight Merz states in the report *Offshore Grid development for a secure renewable future – a UK perspective,* that; "As a general rule, the EU Renewable Energy Directive allows imported renewable generation from non-EU countries to count towards a Member State's target only if the electricity is produced by a new installation, or by the increased capacity of an installation refurbished after the Directive came into force (June 2009)" (Sinclair Knight Merz 2010). This implies that Norway can contribute with balancing power, but that it will only help EU to meet its emission targets *if* the power comes from new installation of hydropower capacity. Norway is anticipating the development of an additional 11 TWh of hydropower by 2025, and 11 TWh of wind power (Sinclair Knight Merz 2010).

There are two main reasons why hydropower is the most suitable energy source to use for regulating services in balancing the power system; It is a renewable energy source that can easily be stored in reservoirs for future demand, and the power plants can easily be switched on and off on very short notice. Hydropower also correlates well with wind power, because they complement each other. Figure 5-2 below shows how offshore wind power production in the North Sea can work well together with a hydropower dominated system as the Norwegian system.

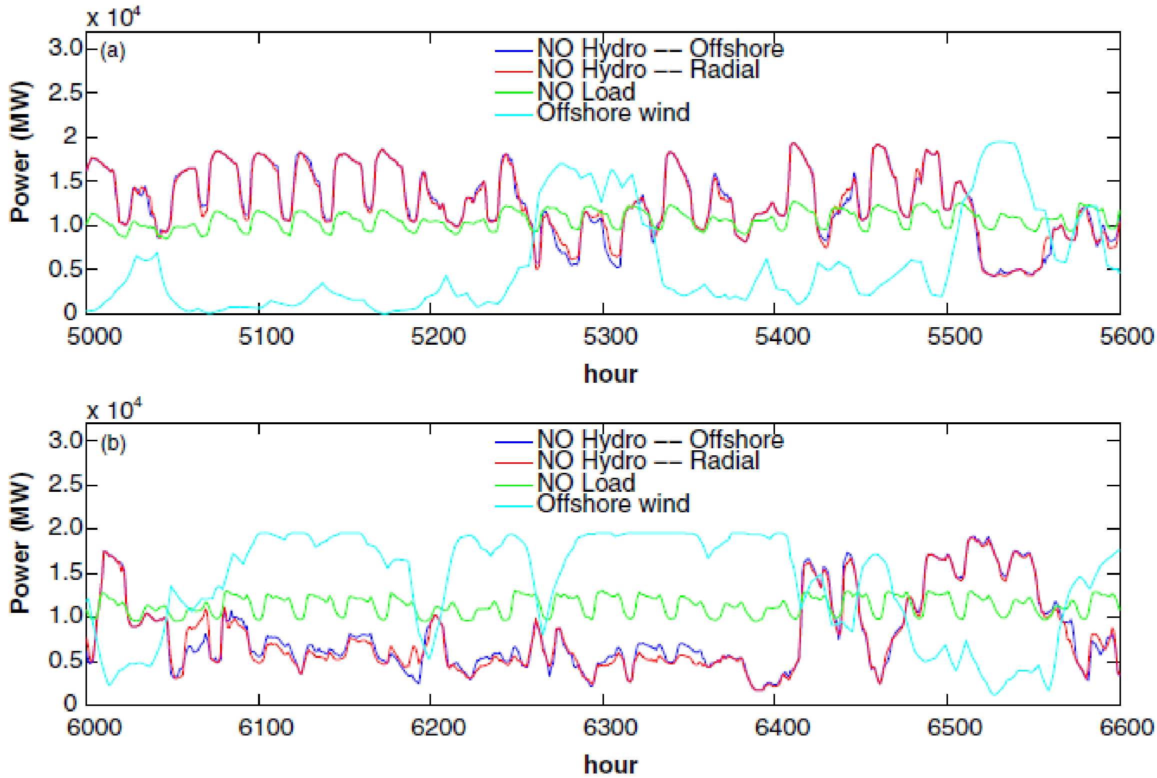


Figure 5-2. The Norwegian hydro and load profiles versus the North Sea's offshore wind profile (Huertas-hernando et al. 2010).

Figure 5-2 is presented in the article *Analysis of grid alternatives for North Sea offshore wind farms using a flow-based market model,* and shows the relationship between the Norwegian hydropower production in Norway (NO) and the total offshore wind power production in the North Sea (Huertas-hernando et al. 2010). A scenario for how much offshore wind power will be installed by 2030 is made by Huertas-hernando et al., based on the *TradeWind* project. It is assumed a total of 302 GW of installed wind power, whereof ~90 GW is offshore wind power. This is in accordance with EWEA's wind targets for wind power, which are 300 GW total installed wind power (~180 GW onshore, ~120 GW offshore) (Huertas-hernando et al. 2010), (Zervos & Kjaer 2008), (Trade Wind 2009). In the hours 5000-5600 (July/August) it can be observed that the total North Sea offshore wind production is low. Europe may have a shortage in supply for power. In these hours the hydropower production in Norway is chosen to be higher than the demand, and there is hence a surplus in production which can be exported to the Continent through HVDC cables. Around hours 5300 and 5500, the situation is turned and hydropower production is low while wind power production is high. As long as it is windy the water is stored in the reservoirs until more power is required again. It is very advantageous that hydropower production in Norway follows the Norwegian demand profile very closely. Then standard load balancing schedules can guarantee for supply and efficient balancing reserve allocation in this situation. Between hours 6000-6600 (August/September) the total offshore wind power production in the North Sea is higher than the Norwegian demand, and hence hydropower production is kept low and water is stored for future power production.

Another example scenario made by the EU project *TradeWind,* shows a situation where the EU will require regulating power. The *TradeWind* project has investigated how the large share of wind power, that is presumed having to be installed within 2020-2030, will contribute to the power production in the EU-27 countries (the 27 member countries of the EU plus Norway and Switzerland). The project also investigates wind power's maximal and reliable integration in the Trans-European power markets (Trade Wind 2009). The project has investigated several scenarios, and one of them assumes that a total of 206 GW wind power is installed in Europe within year 2020. The total power production capacity in Europe is estimated to be about 1100 GW in year 2020, which makes wind power constitute ~19 % of total capacity. Simulations based on wind data from year 2000- 2006 are made. These simulations are used to investigate what smoothing effect it has that the wind is irregular in Europe. It is not windy everywhere in Europe at the same time, and when the wind is gone in one area, it will blow in another or several other areas. The simulation based on wind data from December year 2000 shows that the total maximum contribution from wind power would constitute ~54 % of the total installed capacity, which equals about 111 GW. The total minimum contribution of wind power would constitute ~9 %, corresponding to 19 GW. The difference between these extremes are over 90 GW, and minimum and maximum would occur within a time span of four days (Trade Wind 2009), (Bysveen et al. 2007). This example shows how intermittent wind power can be, and why it is difficult to carry out production scheduling when the production system includes huge amounts of wind power. A gap of 90 GW in production needs to be covered, and this has to be done by a production system which can supply power when it is needed. In Europe this gap in production will most likely be covered by using power production based on fossil resources as coal and gas, if not other alternatives are made available. If coal and gas power plants are not using Carbon Capture and Storage (CCS) technology, there will be an increase in greenhouse gas emissions and the gain of producing electricity from renewable resources can be considerably smaller. Therefore, as far as it's possible, these production gaps should be covered by hydropower, preferably from the Nordic regions, since hydropower correlates very well with wind power and the power plants can be switched on/off on short notice.

If all power markets in Europe are connected to each other, and a great share of power comes from wind power, some problems might occur due to all power markets having a demand for regulating power. When installing new power production from renewable energy sources, it is preferred that the regulating power should also come from renewable energy sources. In that way, the environmental benefit will not be reduced. The wind power potential in the North Sea, outside the coast of Norway, is of a size which makes it able to cover a substantial part of EU's requirement for renewable energy. Norway has long experience and established knowledge about offshore installations, which can contribute to Norway having a great opportunity of developing the electricity sector into a future export industry. This opens up for the technology and contractor industry in Norway. If Norway chooses to go all in for development of offshore wind power, then the Norwegian power system and Norwegian market participants will also demand more regulating power. It is conceivable that Europe must compete with Norway for access to the regulating services. As long as Norway has enough capacity to deliver balancing power both for covering the wind power in the Norwegian system, and for covering the demand for regulating power in Europe, everything is all right. The capacity of Norwegian hydropower is on the contrary not unlimited, even though capacity can be increased some. Pushed to the extreme you could say that Norway in this case would have to choose between selling Norwegian wind power or selling regulating power to European markets (Bysveen et al. 2007).

An alternative can be to invest in pumped-storage hydropower plants in Norway. These are hydropower plants having pump turbines that transfer water to a high storage reservoir during off-peak hours, by using surplus power (Alstom 2011). Then, this power can be used to cover temporary peaks in demand, or to cover demand for regulating services both in Norway and in Europe. In the same way as for regular hydropower plants, a pumped-storage hydropower plant will function as storage capacity for days with surplus power because of strong wind and low demand. Pumped-storage hydropower plants can be switched on very quickly, making it a very useful tool for regulating power due to peaks in consumption or unplanned outages of other power plants. There is no purpose in pumping water back in the reservoir if there is already sufficient water to cover the capacity required. A regulated power reserve like this can be one alternative solution on how to meet a demand for regulating power which exceed the given hydropower capacity available. Pumped-storage hydropower does not increase the share of renewable energy and must have its own economical foundation based on periods of higher prices on the power pumped back into the reservoirs (Adapt Consulting AS 2010). Electricity is required to operate the pumps. This electricity should also preferably come from renewable energy sources to avoid emission of greenhouse gases. The environmental benefits from pumped-storage hydropower are gained from not having to build polluting coal and/or gas power plants for covering the peak load. Hence, the environmental benefits are found in avoided emissions from alternative fossil fueled power plants. If enough pumped-storage hydropower is available, and thus enough regulating power exists, it is conceivable that this can stimulate to further development of power generation from renewable energy sources such as wind power and solar power.

By developing new, stronger power transmission links between the Nordic regions and Europe, the Norwegian hydropower will be made accessible for the European thermal power systems as well. If the hydropower deals with not controllable variations in consumption and wind power production, the thermal power plants using fossil fuels can be utilized better during operation. Smoother production from thermal power plants can be achieved due to better production scheduling, which improves the efficiency of the power plants. This result in the power plants being operated in a more CO_2 effective way, emitting less CO_2 -equivalents per kWh of electricity produced. If, however, thermal power plants are used to deal with not controllable variations in consumption (producing regulating power), then higher pollution can be expected from these power plants as the thermal power plants have to be operated on part-load and will be switched on/off more often. This lowers the efficiency of power production, pollutes more and increases the production costs.

New transnational power exchange will also lead to several other environmental benefits which are not emphasized in this study, mainly due to time limitations. The environmental benefits associated with developing an offshore power grid in the North Sea, are to a great extent achieved indirectly as a result of installing new transmission capacities. Some of the most important environmental benefits have been discussed above. Next, the environmental costs associated with developing an offshore grid in the North Sea will be discussed.

The power cables themselves will cause environmental costs as these have environmental impacts associated with the production, installation, maintenance and dismantling phases. From the life cycle impact assessment of a 450 kV HVDC power transmission cable carried out in chapter 4.2.3, it was found that contribution to some of the impacts caused by 1 MW*km of this type of cable are; 215 kg CO_2 -eq/MW /km to climate change, to marine eco-toxicity the contribution is 14.2 kg 1,4-DCB -eq/MW /km and for human toxicity the contribution is 1200 kg 1,4-DCB -eq/MW /km. Results of all environmental impacts are found in appendix D. Hence, installing a submarine offshore grid of transnational cables will have a substantial environmental load associated with it. Manufacturing of cables will require huge amounts of metals and plastics, which are energy intensive materials and will lead to depletion of resources. Installation, operation, possible maintenance work (reparations and/or inspections) and dismantling work will all demand use of marine vessels which requires use of fossil fuels, oil for lubrication and more. This will cause emission of CO_2 -equivalents as well as causing impacts on the marine environment (such as eco-toxicity and eutrophication). An interconnection between Norway and Great Britain is considered to be a very useful link in order to interconnect two different power markets. A direct link will be around 750 km long with a transmission capacity of 1400 MW, distributed on two cables, using HVDC submarine cables similar to the NorNed cable. Using the LCA results give that a link between these two countries will emit around 0.2 million tonnes of CO_2 –equivalents throughout the lifetime. This equals to about 0.4 % of the total domestic emissions from Norway in 2009 (Statistics Norway 2011). Compared to the annual production of electricity from one coal power plant (80 % availability, 800 MW) which emits (0.965 kg CO_2-eq/ kWh_{el}) * 0.8 * 8760 h/year * (800 MW*10^3 kW/MW) = 5.4 million tonnes CO_2-equivalents per year, the emissions are small. Still, the emissions of 0.2 million tonnes of CO_2-equivalents throughout the lifetime are associated only with this power link, and not with the entire system which have to be upgraded and strengthened if transmission between these power markets shall be realized. Then, new capacity on shore must also be installed. So, the sizes of emissions depend on how much of the system is included when doing the assessment. The actual total emissions are most likely much higher.

Another interesting factor that causes negative environmental impacts from cables is transmission losses in the cable. These will affect the emissions. If the transmission losses are high, then more power has to be produced and transmitted in order to meet the demand for power in the receiving end of the cable. An increased transmission of power means that some electricity is produced, and causing emissions, without it being utilized as useful energy. With an increasing length of the power cable the transmission losses also increases, which call for a higher electricity production. A power link between Great Britain and the offshore wind farm Doggerbank can be used as an example. On Doggerbank, a large offshore wind farm of 9000 MW is being planned. This wind farm will have an estimated annual electricity production excluding losses of around 27 000 GWh. The transmission losses for the 580 km and 700 MW *NorNed* cable between the Netherlands and Norway, are ~3.7 % (J.-E. Skog et al. n.d.). If the same transmission losses are assumed for the cable between Doggerbank and Great Britain, then 999 GWh/year will be energy lost. For comparison; the electricity consumption per household in Norway 2009 was 16 858 kWh. 999 GWh/year equal to the annual amount of electricity required by 59 000 Norwegian households. Hence, if the losses were reduced by using new more efficient technology, this energy could be utilized. The power plants did not have to produce more electricity to cover for losses, and therefore an environmental gain would be achieved. Transferring power one way when prices are high in that price area and low in the other price area, and the other way when the price ratio is reversed, could potentially be economically profitable without being appropriate from an environmental standpoint. If these two price areas are two different countries, then it is conceivable that one of these countries have a more polluting electricity production than the other. Hence will it be most environmentally beneficial to produce the electricity in one price area and transmit it to the other area in order to avoid electricity production from a more polluting source.

These are just some of the environmental impacts attached to development of an offshore power grid in the North Sea. There can also be environmental consequences on benthic fauna and flora as cable laying requires digging the cables into the seabed. A large power grid will interfere with quite large areas of the seabed. In the next chapter, a discussion is provided on what system design and strategies for an offshore power grid will maximize net environmental benefits.

5.2 System design and strategies for maximizing net environmental benefits

It is a huge task and major challenge to conclude on what system design and strategies that will maximize net environmental benefits associated with large-scale expansion of power generation and power transmission in the North Sea. To do this, economical and policy studies should also be performed to investigate for instance what the transmission alternatives are and which interconnections are actually feasible to build. The different policies, including environmental policies, in affected countries will have an impact on which electrical power cables that are necessary, wanted and will give an environmental gain. The kind of power generation the respective countries will and can have in the future, and countries' tendencies in power consumption patterns, will be important to investigate. An offshore grid must connect both generation and demand, and comply with regulations and standards as well as being technologically feasible. This calls for comprehensive load flow analyses, and analyses of generation and demand, of the different power systems affected by a transmission grid in the North Sea. All these factors will influence in discussing what realistic system design and strategies that will maximize net environmental benefits. Another important element that will influence the results majorly is the discussion and decision-making of what type of cable technology shall be utilized. Whether it is chosen to utilize HVAC or HVDC technology, with either Voltage Source Converter technology (VSC) or Current Source Converters technology (CSC) if DC is used, the environmental impacts will differ. Use of different types of technologies, requires different types and amounts of materials. To develop a power link only because it will be environmentally beneficial is not realistic to anticipate. There must also be socio-economic benefits. It is therefore understood that investigation of these questions call for deep analyses in many fields. In order to do a full analysis and give a robust and complete answer to this question, all the factors mentioned above should preferably be investigated in order to conclude on which system design and strategies for expansion of power generation and transmission in the North Sea that will maximize net environmental benefits. It is not achievable to conclude with one alternative in a study with this restricted timescale.

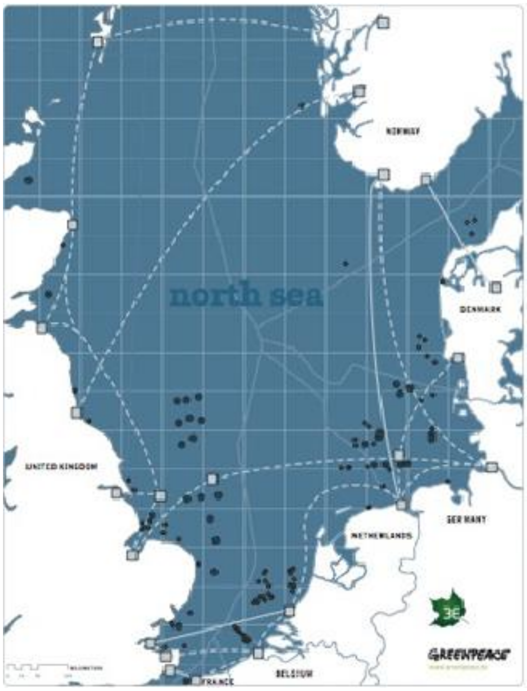


Figure 5-3. One of the alternatives for an offshore power grid in the North Sea (Offshore.no 2008).

Figure 5-3 shows one of the suggested designs of an offshore power grid in the North Sea. The black spots plotted in the figure are different offshore wind farms and installations under planning or development. The purpose is to link the United Kingdom and Scandinavia (here Norway and Denmark) with the continental Europe, in order to make the power market more open, the electrical supply stable and the power system more flexible. A grid like this also opens up for increased electricity production from large offshore wind power plants located far offshore. It will be difficult to study all combinations of possible transmission links, so in this study emphasis is put on the transmission links that are crossing the North Sea and are expected to have highest transmission capacities. Especially a power link between Great Britain and Norway will be discussed, as this is recognized as one of the main links in an offshore power grid like this.

There are often discussed two types of offshore power grids in the North Sea. These are radial grids and meshed offshore grids. Radial connection means that for instance wind farms are connected directly to the onshore grid, and that there are point-to-point HVDC cable connections between countries across the North Sea. A meshed grid is based on the use of offshore nodes to build a meshed HVDC offshore grid. Wind farms and/or oil platforms are linked with interconnectors between each other, before they are linked to the onshore transmission grid. In this study mostly radial grid alternatives are investigated with direct connections between for example Norway and the UK, or connections via one offshore installation. These are the type of power links that are expected to be installed to begin with. The power connections between different North European countries today are radial cable connections. Examples of radial connections in operation are the *BritNed* cable between Great

Britain and the Netherlands, and the *NorNed* cable between Norway and the Netherlands. Having a connection via for instance an oil platform is also a possibility, and is discussed widely. There are, however, some difficulties associated with doing this. A connection between two countries requires a high power transmission level and thus high DC voltages. HVDC transmission means that an AC/DC converter is required on the platform, which is equipment requiring much space due to a requirement of air insulation. Space is expensive and difficult to achieve on an oil platform. In addition, if there are not circuit breakers on the cable, the oil platform risks having to close down production. This is very expensive, and these circuit breakers are not fully developed yet. These difficulties are mainly due to technology development and economics, and will be very important in decision-making. The environmental benefits from a power connection via an oil platform will be discussed later. A meshed grid is assumed to be the most likely alternative in a distant future if developing a huge offshore super grid including large offshore wind farms, but a meshed grid is a very complex system to investigate. There are many alternative ways of building a meshed grid and still none alternatives to this type of grid have been published from the ENTSO-E or from other relevant stakeholders or studies undertaken. Hence, radial connections will be in focus in the present study.

In this discussion some alternatives of transnational power connection across the North Sea are chosen to be investigated in the context of environmental costs and benefits. Environmental impacts from four alternative connections between Great Britain and Norway are investigated in this study, as well as the environmental impacts from the BritNed link (Great Britain – the Netherlands), Skagerrak 4 link (Norway – Denmark) and the NorNed link (Norway – the Netherlands). All these links are assumed to transmit power in both directions. Power cables between Norway and Great Britain are assumed to be very useful and central in an offshore grid across the North Sea, which is why extra emphasis is put on this. Norwegian power generation is dominated by hydropower, while Great Britain has a large share of thermal power generation and is already in the lead regarding offshore wind power. Norway can have problems covering the load in dry-years, while Great Britain will have their challenge during peak load hours due to how thermal power plants are operated and the intermittences in wind. Combining these two types of power generation in one system can reduce these drawbacks considerably, as discussed in previous chapters. Regarding the economic side, the structural difference between the hydro dominated market and the thermal dominated market will cause price-differences. This is expected to give high trading income on new links.

The alternatives of transmission between Great Britain and Norway are; a direct power connection, connection via the Shetland Islands, a link via the Sleipner oil field and a link via an offshore wind power plant at Doggerbank. Transmission capacities are between 1000-1500 MW. The link via the Shetland Islands is interesting for the United Kingdom as it will secure the electrical power supply to the islands. It is also planned a 600 MW wind farm on the Shetland Islands, which makes the connection with Norway interesting as well (The Crown Estate 2008). Unfortunately it has is not been possible to obtain numbers on the transmission capacity of this type of link between Norway and the Shetland Islands. Therefore an estimate of the total environmental impacts caused by this link has only been done for contribution to climate changes, with simple assumptions. The other power cables studied and used as examples are either already in operation (NorNed and BritNed), or under planning and expected to be finished within year 2014 (Skagerrak 4) (Statnett 2009a). The transmission capacities for these cables are between 700 – 1300 MW. All the submarine power cables discussed here are mass-impregnated HVDC cables with copper conductor.

Data and information about the different power links are presented in table 5-1 and the different links are numbered from one to seven. The same power cables and numbering are found illustrated in figure 5-4. To investigate the scale of environmental impacts caused by these transmission alternatives, the LCA performed of a 450 kV HVDC cable in chapter 4.2.3, was made use of and adjusted to fit the analyses of the new cables investigated. By adjusting the LCI's of the 450 kV HVDC cable and using the information given in table 5-1 below, the environmental impacts throughout the life cycle of different submarine cables were estimated. These results are not exact, as there in reality are differences in cable types and voltage levels of cables used for the different transmission alternatives. The results will nevertheless be interesting, in order to examine the order of magnitude in environmental impacts for this kind of power transmission.

Table 5-1. Alternatives for which the environmental impacts associated are studied.

Connection points **(All connections have transmission both ways)**	**Length** **(in sea)**	**Transmission capacity**
1. Direct connection between Norway and UK	730 km	1400 MW
2. Connection between Norway and UK via the Shetland Islands	850 km	Unknown
3. Connection between Norway and UK via the Sleipner oil field	400 km	1000 MW [7]
4. Connection between Norway and UK via Doggerbank	630 km	1500 MW
5. Connection between UK and the Netherlands, "BritNed"	250 km	1320 MW
6. Connection between Norway and Denmark, "Skagerrak 4"	140 km	700 MW
7. Connection between Norway and the Netherlands, "NorNed"	580 km	700 MW

[7] Assumption based on personal communication with a specialist in Statoil. Dated 09.05.11.

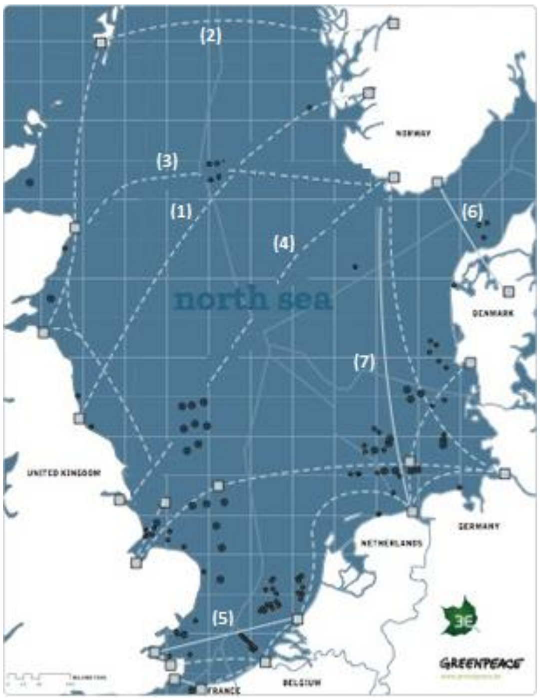
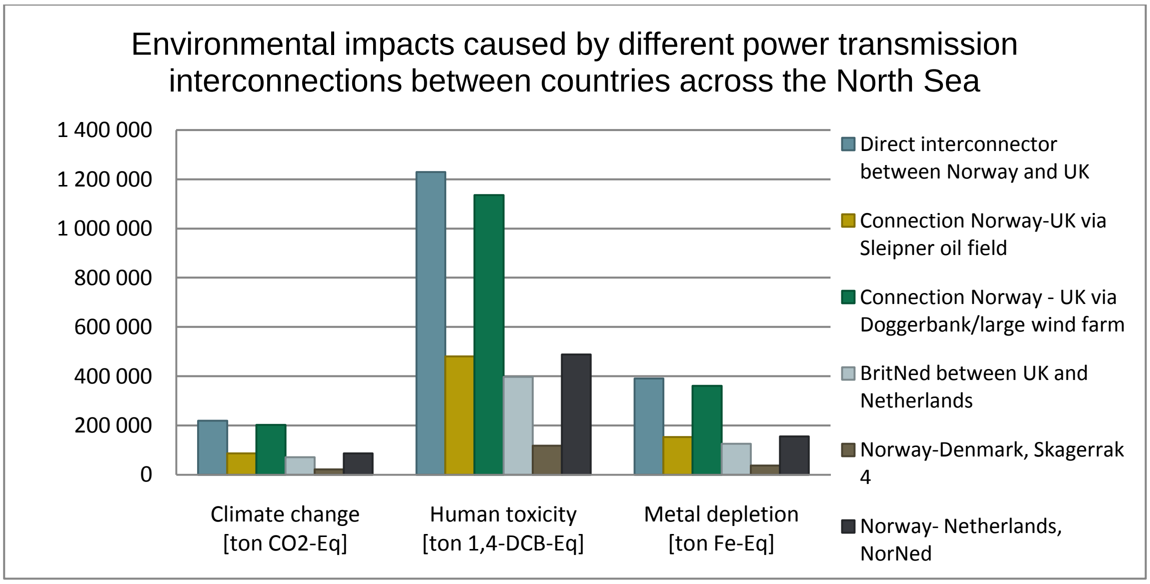
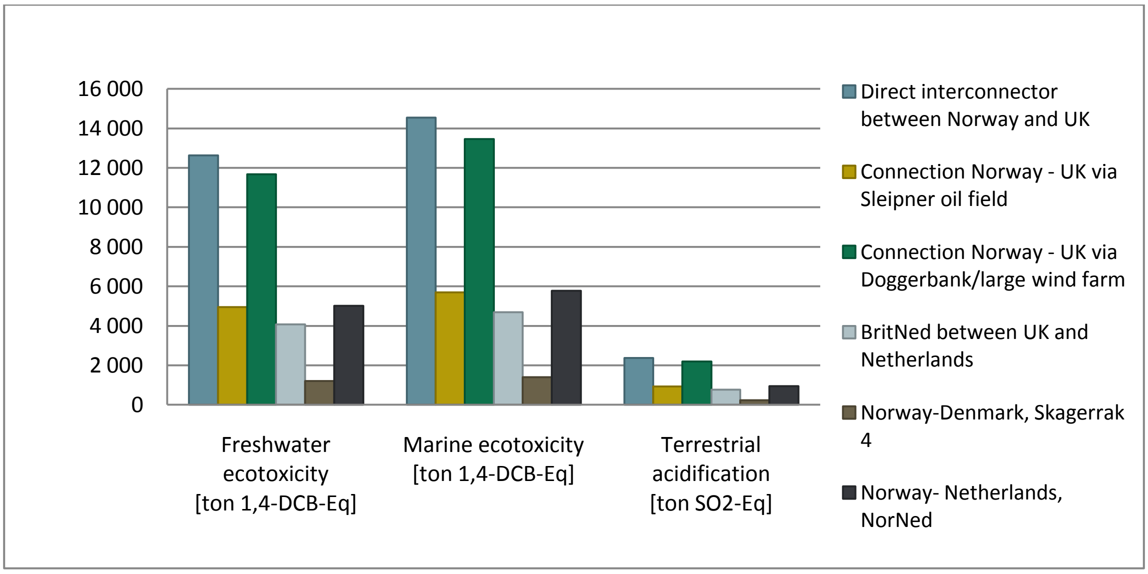


Figure 5-4. Illustration of alternative power transmission cables in the North Sea (Offshore.no 2008). The illustration has been modified to include all the alternatives investigated in this study. The numbering is the same as in table 5-1.

The results give that the different transmission alternatives will contribute with between 21 000 tonnes and 219 000 tonnes CO_2-equivalents to environmental impacts causing climate changes, throughout the lifetime of the cables. A cable like the Skagerrak 4 cable (link 6) can from these calculations be expected to contribute with around 21000 tonnes CO_2 -equivalents, the BritNed cable (link 5) contributes with 70 800 tonnes CO_2-equivalents, the connection via Sleipner (link 3) contributes with 86 000 tonnes CO_2 -equivalents and the NorNed (link 7) contributes with 87 100 tonnes CO_2 -equivalents. For the four different links between Great Briatin and Norway, it is the direct power connection that causes the highest contribution to climate change with 219 000 tonnes CO_2 -equivalents throughout lifetime. Thereafter follows the link via Doggerbank that will have a contribution of around 203 000 tonnes CO_2 -equivalents to climate change and the link via Sleipner of 86 000 tonnes CO_2 -equivalents throughout lifetime. These results are calculated from crude assumptions and will therefore just give indications on the magnitude of emissions that could be expected from these types of cables. It should be noticed that the transmission capacity for instance of the link via Sleipner, is an assumption that might be too low and therefore give too low environmental impacts. Figure 5-5 presents the resulting environmental impacts for some selected impact categories, caused by the different power connections.





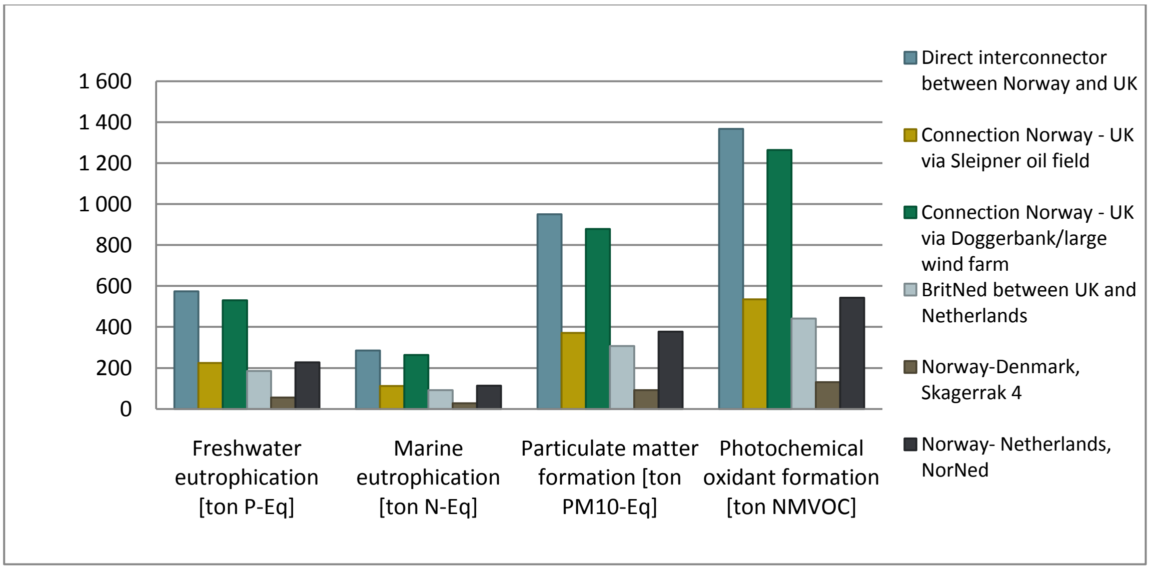


Figure 5-5. Figure 1, 2 and 3 (from top) show which transmission cable that causes the highest absolute impacts in selected impact categories.

In every impact category it is the longest cables, with the highest transmission capacities, that have the largest associated environmental impacts. This is the case because higher transmission capacity in a cable normally involves a greater use of materials, which will lead to higher environmental stress. Mathematically in this study, this will be the case because the functional unit in the LCA of the cable is 1 MW*km, whereof numbers of MW refer to the cable's transmission capacity and km to the length of the cable. This means that to find the total environmental impacts throughout lifetime, the environmental impacts per functional unit are multiplied with the transmission capacity and length of the respective cable. Hence the longest and most powerful cables will cause greatest environmental impacts. It can be observed that the proportions between the environmental impacts for the different options are equal for each impact category.

Until now, only environmental impacts associated with the transmission cables themselves are discussed. Several of these links are interconnections via offshore installations. On Doggerbank, for instance, a large offshore wind farm of 9000 MW is being planned. The potential for the whole area is 13 GW, which equals to 10 % of the total electricity requirements in the UK (Statoil 2010). By modifying the life cycle inventory of the wind farm (the LCA performed in chapter 4.2.4), a LCA is performed of an offshore wind farm with 9000 MW of installed capacity. The results show that environmental impacts to climate change will be 19.8 g CO_2-eq/ kWh_{el} for the large wind farm, and a total of 523 260 GWh of electricity are produced throughout lifetime. This results in a total of 103.4 million tonnes of CO_2 -equivalents throughout the entire lifetime. If a coal power plant which emits 0.965 kg CO_2 -eq/kWh_{el} is used to produce the same amount of electricity, the contribution to climate changes would become about 505 million tonnes CO_2 -equivalents. This is almost five times higher emissions than from the offshore wind power plant. Still, the coal power plant has the benefit of being implemented in an electricity grid which can handle this type of electricity production well. And it does not require particular development of new infrastructure or grid capacity. A coal power plant will also be easier to operate in the grid as it can have a production plan based on expected electricity demand. Not having to build out new capacity or infrastructure, means that new environmental stress will be avoided.

Development of new infrastructure and power capacity is on the contrary required if large offshore wind farms are developed. The wind power production will be very difficult to plan and control directly. Since wind power plants produces electricity when the wind blows, the electricity is delivered to the grid independent of when and where there is a demand for electricity. This means that the electricity grid must have large enough capacity to transport the electricity to where it is required at all times. For Europe and Scandinavia, large-scale expansion of wind power in the grid will require investments in new grid capacities both onshore and offshore. Consequently there will be an addition in environmental costs if wind power in the North Sea is developed, caused by having to expand the grid onshore et cetera. This should be included when discussing what system design and strategy that will maximize net environmental benefits. When estimating the environmental impacts caused by a power link between Great Britain and Norway, via an offshore wind farm at Doggerbank, the environmental impacts from the offshore wind farm should be included in the environmental accounts. Adding the impacts to climate change from the wind farm at Doggerbank, to the total impacts caused by the power cable, gives a total of 103.6 million tonnes CO_2 -equivalents for this alternative which is 0.3 million tonnes CO_2 –equivalents higher. The total environmental impacts to climate change for the link via Doggerbank, hence become tremendously much higher than the other alternatives. The same applies to the power links via the Sleipner oil field or the Shetland Islands. These links also require development of wind farms, platform installations and more, which will give a great addition in environmental impacts. By including the environmental impacts for these offshore installations as well, the order of which alternative that have the highest associated impacts changes. Then, a direct link between Great Britain and Norway becomes the alternative causing the lowest environmental impacts. Concluding on what system design and strategies that will maximize net environmental benefits from an offshore grid, will be affected by several factors. How much upgrading of capacity is required in the already existing power system, and what is required of new infrastructure and power capacity, will affect the results much. The whole power system of Europe and Scandinavia will be affected if there is a large-scale expansion of wind power and transmission in the North Sea.

What is then the magnitude of the environmental impacts associated with an entire offshore power grid in the North Sea? To study this, the suggested grid in figure 5-3 is used as a basis. It is assumed that the link between Great Britain and Norway via the Shetland Islands has a transmission capacity of 1500 MW. The environmental impacts of four alternative grids are examined. Focus in the discussion will be on impacts causing climate changes. The link between Norway and Great Britain is the one modified in each alternative studied. In all four alternatives listed below, the following links are included in addition to the ones listed explicitly in each alternative; link between Great Britain and Norway via the Shetland Islands, the BritNed link, the NorNed link and the Skagerrak 4 link (excluding the old Skagerrak 1, 2 and 3 links). A future offshore power grid will probably be larger than this, but it is difficult to predict how the design will be. Hence focus is put on power links that are assumed to be developed in the near future and that have high transmission capacities. The four alternative grids examined here are given below. The total contributions to climate changes from the respective alternative offshore grids are presented beneath each alternative.

Alternative 1.
An offshore grid in the North Sea, having a direct linked power cable between Great Britain and Norway. Total environmental impacts to climate change from the entire offshore power grid in this alternative is: ~ 672 000 tonnes CO_2 -equivalents.

Alternative 2.
An offshore grid in the North Sea, having a link between Great Britain and Norway via an offshore wind farm at Doggerbank. Total environmental impacts to climate change from the entire offshore power grid in this alternative is: ~ 104 million tonnes CO_2 -equivalents.

Alternative 3.
An offshore grid in the North Sea, having a link between Great Britain and Norway via the relatively small offshore wind farm Havsul 1outside the coast of Norway and the offshore wind farm at Doggerbank. Total environmental impacts to climate change from the entire offshore power grid in this alternative is: ~ 109 million tonnes CO_2 -equivalents.

Alternative 4.
An offshore grid in the North Sea, having a link between Great Britain and Norway via the Sleipner oil field. Total environmental impacts to climate change from the entire offshore power grid in this alternative is: ~ 538 000 tonnes CO_2 -equivalents.

It is not surprising that the link with most offshore installations connected is the alternative having the highest environmental impacts. By linking two offshore wind farms together through a power link between Great Britain and Norway, the contributions to climate change will be 109 million tonnes CO_2-equivalents as seen in alternative 3. Second comes alternative 2, linking Great Britain and Norway via the Doggerbank wind farm. This causes 104 million tonnes CO_2 -equivalents. Alternative 1 and 4 contributes with respectively 672 000 tonnes CO_2 -equivalents and 538 000 tonnes CO_2 -equivalents to climate change. Alternative 3 with 109 million tonnes CO_2 -equivalents equals to about 2 % of the yearly contribution to climate change from a modern coal power plant. This is not very much. Still, the environmental impacts estimated here do not give the complete picture of what the environmental costs and benefits associated with an offshore power grid are. The uncertainties are very high, and the systems studied are incomplete.

Even though alternative 2 and 3 result in the highest contribution of CO_2 -equivalents, these alternatives will have production of electricity from renewable wind energy. This will give an environmental gain as discussed earlier. In a study carried out by Pehnt et al., some interesting results were found which can be interesting for alternative 2 and 3. Pehnt et al. estimated that there would be 18 – 70 g CO_2 -eq/kWh_{el} in additional emissions from thermal power plants as a direct consequence of wind power production in the North Sea (Pehnt et al. 2008). This was mainly due to thermal power plants having a higher fraction of part-load operation as they were used to regulate for the wind power in the system. These emissions and considerations were not included in the previous assessment of the 9000 MW Doggerbank wind farm or the offshore grid. Hypothetically, if it is assumed that the results from Pehnt et al. study are applicable to Doggerbank and Great Britain, and the additional emissions could be eliminated by installing a power cable between Great Britain and Norway so that hydropower is used as regulating power instead of thermal power, then a large share of emissions could be eliminated from alternative 2 and 3. Using additional emissions of 44 g CO_2 -eq/ kWh_{el} (the mean between 18 and 70), then the total eliminated emissions associated with building the power cable would be 44 g CO_2-eq/ kWh_{el} * 523 260 GWh * 10^6 kWh/GWh = 23 million tonnes CO_2 -equivalents. 523 260 GWh is the total electricity production throughout lifetime for Doggerbank. For the smaller wind farm Havsul 1 in alternative 3, the total eliminated emissions would be about 1 million tonnes CO_2 -equivalents. If these eliminated emissions of respectively 23 million tonnes CO_2-equivalents and 24 million tonnes CO_2-equivalents are subtracted from alternative 2 and 3, then the results of these alternatives will be respectively 81 million tonnes CO_2-equivalents and 85 million tonnes CO_2-equivalents. The environmental impacts are reduced considerably. These emissions are still substantial, and higher than the total domestic emissions for Norway in 2009 which were 51.3 million tonnes of CO_2 –equivalents (Statistics Norway 2011). Still, these emissions are relatively small when distributed on all countries affected. The European Environment Agency (EEA) states that the emissions emitted by the EU-27 countries in 2007 were about 5045 million tonnes CO_2-equivalents (European Environment Agency 2009b). 85 million tonnes of CO_2 -equivalents thus equals to about 1.7 % of the total emissions from the EU-27 countries, while 81 million tonnes CO_2-equivalents equals to about 1.6 %.

Alternative 4 includes electrification of for instance an oil platform at the Sleipner field, which can also give an environmental gain. Electrification of the continental shelf means to supply oil and gas installations on the Norwegian shelf with power from the grid onshore or from offshore wind power plants. Today, most offshore installations produce their own power by using gas turbines. This electricity production constitutes a quarter of Norway's total emissions of both NO_x and CO_2 (Volden et al. 2009). To maximize net environmental benefits in doing this, the electrification has to be done by using renewable resources to produce the electricity required. The electricity should be produced by for instance wind power. If an expansion of offshore wind power is carried out in the North Sea, then electrification of the shelf can be possible to achieve. Electricity produced at the oil platforms is expensive, and the gas turbines are heavy. The oil companies hence have a high willingness-to-pay for an alternative power supply. There are several arguments for and against electrification of the Norwegian shelf, which will not be discussed here. Still, this initiative can give an environmental gain. Alternative 3 is the option having the lowest environmental impacts associated, as this is only a direct link between Great Britain and Norway. Until now, this is also the mostly discussed and acknowledged alternative for power transmission between these two countries.

A large-scale expansion of offshore power generation and power transmission in the North Sea will, regardless of design, causes environmental stress on the environment. If large offshore wind power plants are developed in the North Sea, then increased interconnections between the European power markets are a necessary criterion, both onshore and offshore. The more wind power plants that are installed in the North Sea, the more stable production throughout the year can be expected. Including a larger geographic area means that it can be windy in one place, while it is windless another place in the system. This also contributes to a more stable production. In a utopian case, there could be a global grid of windmills which would make the electricity production very regular. A more stable wind power production would make it easier to carry out a reliable production scheduling of the onshore power production. This could cause a more optimal operation of for instance thermal power plants onshore, which could result in a higher efficiency factor. This would again result in lower emissions. In addition, a precise production plan could make it possible to avoid operation of the highest polluting power plants as long as possible. But since the power grid in Europe and Scandinavia today are not robust and strong enough for having a lot of wind power implemented, these environmental benefits cannot be obtained before the grid is strengthened. Common for all the alternative ways of designing a grid in the North Sea, is that there will be huge extended effects in the whole power system. This makes it very difficult at this point to conclude on what system design and strategy of an offshore grid that will maximize net environmental benefits. However, the grid itself is expected to open up for further investment and expansion of electricity production from wind power and other renewable energy sources. This will be essential in the future, as the electricity demand increases at the same time as we experience the increasing consequences caused by anthropogenic emissions and the environmental stress that society brings upon the surroundings.

Chapter 6

6 Conclusion and further work

Offshore wind power technology is a fairly new and evolving technology, which has been given continuously more attention in the recent years. By relocating wind farms from land areas and out to sea, higher and more stable wind conditions can be achieved that will give higher electricity production. At the same time, relocating wind farms out to sea will reduce the discussion and disagreements about having them onshore, close to where people live. North Europe is in a leading position regarding offshore wind power, with the United Kingdom, Denmark, Germany and the Netherlands in the lead. The ambitious targets and plans for offshore wind power development in the North Sea have raised questions regarding how to integrate the wind power in the existing power systems of Europe. This has to be done in an efficient and secure way. In context of this, it has been assessed whether it's environmentally beneficial to develop an offshore power grid between the countries around the North Sea in order to connect the offshore wind farms and the different power markets in Europe. In this study the primary objective has been to assess the life cycle environmental impacts of electricity transmission for offshore wind power development in the North Sea. The environmental costs and benefits associated with expansion of large-scale power generation and power transmission in the North Sea has been evaluated, and life cycle assessments have been used for quantification of the environmental impacts associated with submarine power cables and an offshore wind farm. Evaluation is also made of how cabling between different power markets (in this case countries) affect the various power systems, and what role a power link can have when it comes to smoothing intermittent wind power in a system where wind power becomes more dominant.

To carry out the LCA's, the requirement and stressor matrices (A and F) for the foreground system were made and a Matlab code was written to be able to upload the foreground system to the LCA GUI software used for the impact assessment. Basic contribution analyses and SPA's were carried out in the analyses of 33 kV HVAC cables, 132 kV HVAC cables, 450 kV HVDC cables and of an offshore wind farm of 390 MW with bottom-fixed windmills. These results gave a quantified answer to the magnitude of the environmental impacts associated with offshore power transmission and wind power generation in the North Sea. Then, these results from the LCA's were used in carrying out discussions about environmental costs and benefits associated with power transmission and power generation in the North Sea and what role submarine power cables have on smoothing intermittent wind power.

Common for the results of all the submarine power cables, was that the manufacturing of cables constituted most of the environmental impacts in almost all impact categories. Manufacturing of cables was split into two foreground processes; “Cable (LCA system)” and “Cable (IO system)”. These two processes covered respectively the materials used (denoted the LCA system) and other inputs to the manufacturing processes (denoted the IO system). Materials required in the cables caused about the largest shares of impacts in nearly every impact category. Required in production of submarine cables are mainly metals and plastic. These materials demand both processing and preparation which calls for energy demanding and emitting processes. The raw materials are not renewable, which can lead to material depletion in a long-term perspective. Impacts to climate change from the materials required (covered by the process denoted “LCA system”) were mainly due to the use of materials such as polypropylene, polyethylene, pig iron and sinter in steel, lead and copper. Use of metals had also disposal of different by-products, which especially contributed in the toxicity categories as for instance freshwater eco-toxicity, human toxicity and marine eco-toxicity. Due to how the IO system was included in this study, it has not been very easy to investigate in great detail which background processes that causes the contribution to environmental impacts. By studying which sectors that contributes most to the emissions caused by the cable sector in the IO system, an indication is given of what background processes that affect the impacts. It was found that for all the cable types, the two biggest contributing sectors from the IO system were “Manufacture of basic iron and steel and of ferro-alloys and first products there” and “Production of electricity by coal”. These contributed with respectively 28.8 % and 23.7 % of the total emissions of CO_2 (per Euro) from the IO system. It was also the purchases that the cable sector did from these two sectors that caused the highest emissions of CO_2/EUR as well. This indicates that it is purchases of energy and materials which affect the emissions associated with the IO system most.

Some of the most important findings when quantifying the environmental impacts caused by the power transmission cables are presented here. For 1 MW*km of the 33 kV HVAC cables, the contribution to climate changes were 229 kg CO_2 -eq/ MW/ km. Of this, about 31.5 % were caused by the use of vessels for inspection during 40 years lifetime, 29 % were caused by other manufacturing processes covered by the IO system and 27.5 % of the impacts were caused by materials required for manufacturing of the cables. For 1 MW*km of the 132 kV HVAC cables, the contribution to climate change were 520 kg CO_2 -eq/MW /km. Of this, about 30 % were due to manufacturing processes excluding materials used (“IO system”), 29 % were due to materials required in the cables and 29 % were due to the use of vessels for inspection through 40 years. Since the 33 kV and the 132 kV cables were of the same type, the distributions of impacts became very similar, even though the amounts of contributions differed. The 450 kV cables were HVDC cables, and therefore had a different construction. 1 MW*km of the 450 kV cable caused a contribution to climate change of 215 kg CO_2 -eq/MW /km. Of this, manufacturing of the cables constituted in total 87 % of the total impacts. About 40 % of these were due to materials used in the cable and 46 % were due to other inputs than material inputs in manufacturing of the cable. The remaining 14% of impacts to climate change were mainly due to the use of cable laying vessel during installation and end-of-life phases. In general, the LCIA of this cable type showed that it was the material used in manufacturing of cables which constituted the greatest amount of environmental impacts in most impact categories. For agricultural land occupation, freshwater eco-toxicity, freshwater eutrophication, human toxicity, marine eco-toxicity and metal depletion, materials used in the cable constituted nearly 100% of the impacts.

The offshore wind farm in this study was found to have a total production of 22.7 TWh of electricity delivered to the grid on land during a lifetime of 20 years. This covers the demand of roughly 60 000 Norwegian households over 20 years (Statistics Norway 2010). For comparison, the total consumption of electricity in Norway in 2008 was about 130 TWh, where approximately 3 TWh were imported power (Statistics Norway 2010a). The offshore wind farm in this study will be able to cover less than 1% of the yearly total Norwegian demand for electricity. In this study total impacts to climate change from the offshore wind farm were found to be 20.6 grams of CO_2 -equivalents per kWh of electricity delivered to grid on shore. This is somewhat higher than impacts found in previous studies. These impacts were primarily due to offshore wind farms being very material intensive systems to build, where processing of metals and manufacturing of materials are among the processes contributing greatly to total impacts. The windmill, replacement of parts and marine vessels were the parts of the foreground system having in general the greatest contributions to environmental impacts in all impact categories. To climate change the share of contribution was; windmill (~55 %), vessels (~30 %) and replacement of parts (~13 %).

The windmill contributed with between 30-70 % in all impact categories. These contributions were found to be mainly due to the great material use of clinker in concrete for foundations and use of pig iron both in steel for foundation and tower. The foundation constituted 35 % of the impacts to climate change caused by the windmill, which was equal to 20 % of the total contribution to climate change from the whole wind farm. The high contribution from foundations was mainly because it represented the whole substructure of the windmill, and therefore required huge amounts of concrete and steel. For the tower, the contribution was found to be 20 % of impacts caused by the windmill and 12 % of total impacts to climate change from the wind farm. This was due to the use of low-alloyed steel in towers. Marine vessels were also considerable contributors in all impact categories. It was mainly marine vessels used for installation, operation and maintenance work that constituted the impacts from marine vessels. From the structural path analyses, it was evident that fossil fuels needed for marine vessels were the main reason for the large contribution from marine vessels in all environmental impact categories. Contribution from replacement of parts to the different environmental impact categories was primarily due to the processing of chromium steel used in replaced gearboxes, and the use of fossil fuels in processing metals. From the structural path analysis of climate change it was seen that demand for energy from hard coal, for producing chromium steel used in gearboxes, was one of the paths causing a significant share of total impacts to climate change. For the toxicity categories it was use of ferronickel in chromium steel and disposal of nickel slag from making ferronickel, which contributed significantly to the total environmental impacts from replacement of gearboxes.

While the LCA's were used to give a quantitative response to the question about what were the environmental impacts associated with offshore wind power generation and power transmission in the North Sea, also a qualitative response were given to this question discussing environmental costs and benefits and how submarine cables can smooth out intermittent wind power. Developing offshore wind power generation and power transmission in the North Sea will have environmental costs and benefits associated both directly, due to production of components and use of vessels, and indirectly due to for instance changes in power generation mix in the different power markets and whether or not hydropower is used as balancing power. The indirect environmental costs and benefits from large-scale development of power generation and transmission in the North Sea are important to include in this discussion. Offshore wind power in the North Sea will generate renewable energy to Europe, which can contribute to Europe meeting their emission targets. Still, increased development of offshore wind power would demand an upgrading and installation of new capacity in the power grid onshore, which will give environmental costs. An increased share of wind power in the power system also demands more regulating power available. If not hydropower or other non-emitting energy sources are available, then it is natural to use the thermal power plants for providing balancing power. These thermal power plants will hence risk to be operated on part-load, which lower the efficiency and thus increases the level of pollution. Indirect consequences like this will lower the environmental benefits from utilizing wind power for electricity production drastically. A realistic alternative is to develop enough pumped-storage hydropower plants which make it possible to only utilize hydropower.

Development of an offshore power grid in the North Sea will also meet challenges when it comes to environmental loads from the system. The power grid will open up for more renewable electricity from wind power, which is good, but it will also lead to more intermittent wind power being able to flow between power systems. This gives an increased need for a strong power grid in all affected power systems, as well as a demand for more balancing power. This will give environmental costs which are not necessarily considered primarily, but which are very important when assessing all environmental costs and benefits associated with an offshore power grid. Developing a larger power grid in the North Sea will contribute to the need for regulating power being reduced. More power plants in the system give a steadier contribution of power into the system. If the wind is calm in one area, then it might be windy somewhere else. It has been studied what environmental costs and benefits that can be achieved if a power grid is developed in the North Sea. Several alternative offshore grids were investigated, with different levels of environmental costs attached. One of the alternatives studied an offshore grid in the North Sea, where two wind farms were implemented in the power transmission between Norway and Great Britain. These were; one large offshore wind farm outside Great Britain at Doggerbank and one smaller offshore wind farm outside the coast of Norway. This offshore grid was estimated to emit about 85 million tonnes of CO_2 -equivalents throughout the lifetime, if including the avoided emissions from using Norwegian hydropower as balancing power instead of thermal power. This equals to about 1.7 % of the total emissions from the EU-27 countries and indicates that the environmental impacts from the offshore grid are substantial, but not very high compared to the total emissions. Nevertheless, these results only give us indications on what the actual environmental impacts are, as the uncertainties are high. Many other aspects should also be investigated in addition to those studied here, in order to get a complete answer to these questions.

Some very important aspects regarding development of offshore wind power and power transmission in the North Sea have been presented and discussed in this report. Further investigation of environmental loads from offshore wind farms and submarine power cabling across the North Sea should be encouraged, as there are not many studies assessing this and more knowledge on this field is recommended. This present study is a wide study including many different aspects which all should be subject to more profound investigations. To improve this assessment, it is suggested to expand the life cycle assessments into full hybrid LCA's. This would cover the system boundaries better, and include missing inputs to a number of processes. There should also be made one assessment of an entire offshore power grid also including converters and transformers in greater detail. That would give a better quantification of the environmental impacts associated with the offshore grid. Common to all the life cycle analyses is that a closer collaboration with the industry and suppliers is essential to make realistic and updated data available for the processes that are studied. From experience, it has been quite difficult to obtain the desired data, because much of the essential information is confidential and kept within the companies and industry. To conduct robust analyses, with a high quality on input data, it is necessary to have a stronger cooperation with the industry. Then, less time has to be spent on collecting data from various sources, and more time could instead be used on making the analysis comprehensive, providing credibility to the analysis and lower in particular the data uncertainties.

To strengthen an analysis of the environmental costs and benefits from offshore wind power generation and power transmission in the North Sea, also comprehensive power flow analyses for the European power systems, and large-scale simulations of the power production in Europe, should be performed. Then, the expected transmission capacities between the power markets would be known, and a clearer expectation of what the transmission losses would exist. The results from a hybrid LCA of the entire system could then be evaluated in context with the results of the power flow analyses, and in context with economical analyses done of what the consequences are in the affected power markets from large-scale expansion of wind power and power transmission in these areas. An effort should also be put upon acquiring more knowledge about what is included in the different impact categories in ReCiPe. Marine environmental impacts are assumed not to be well enough covered by the impact categories. To improve the results from the life cycle analyses, an effort should also be put upon including all relevant impacts to the different categories.

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Appendix A - Mathematics in the input output system

The input-output system is made from the system input-output tables (SIOT) for the different European countries. The flow matrices, Z, are known for several countries. These are product-by-product matrices including 129 commodities, taxes, value added and imports. Prices are given in basic prices.

The output vector, x, for the different countries are known. The stressor matrices, F, for the different countries are known. This makes it possible to calculate the A matrix for Europe, and the total emissions for Europe, the e vector. We do not have the flow matrix for all European countries. The countries that are included in this input-output system are;

AT – Austria
BE - Belgium
BG - Bulgaria
CY - Cyprus
CZ - Czech Republic
DK - Denmark
EE - Estonia
FI - Finland
FR - France
DE - Germany
GR - Greece
HU - Hungary
IE - Ireland
IT - Italia
CH - Switzerland
LV - Latvia
LT - Lithuania
LU - Luxembourg
MT - Malta
NL - Netherlands
NO - Norway
PL - Poland
PT - Portugal
RO - Romania
SK - Slovakia
SI - Slovenia
ES - Spain
SE - Sweden
GB - United Kingdom
TR - Turkey

The A matrix and e vector for Europe are calculated in Matlab. Three Matlab scripts were made in order to read all matrices needed and calculate the relevant matrices. The code is presented below.

Script 1

```
% Script that makes the A matrix for Europe.
% Summing all Z matrices for European countries, into one.
% A = Z*diag(g)^-1.

clear all
clc
format compact


%Gets the different Z from the exel-files
Z_Austria = xlsread('SIOT_Austria.xlsx','ModelB','F15:ED143');
Z_Belgium = xlsread('SIOT_Belgium.xlsx','ModelB','F15:ED143');
Z_Bulgaria = xlsread('SIOT_Bulgaria.xlsx','ModelB','F15:ED143');
Z_Cyprus = xlsread('SIOT_Cyprus.xlsx','ModelB','F15:ED143');
Z_CzechRepublic = xlsread('SIOT_CzechRepublic.xlsx','ModelB','F15:ED143');
Z_Denmark = xlsread('SIOT_Denmark.xlsx','ModelB','F15:ED143');
Z_Espana = xlsread('SIOT_Espana.xlsx','ModelB','F15:ED143');
Z_Estonia = xlsread('SIOT_Estonia.xlsx','ModelB','F15:ED143');
Z_Finland = xlsread('SIOT_Finland.xlsx','ModelB','F15:ED143');
Z_France = xlsread('SIOT_France.xlsx','ModelB','F15:ED143');
Z_Germany = xlsread('SIOT_Germany.xlsx','ModelB','F15:ED143');
Z_Greece = xlsread('SIOT_Greece.xlsx','ModelB','F15:ED143');
Z_Hungary = xlsread('SIOT_Hungary.xlsx','ModelB','F15:ED143');
Z_Ireland = xlsread('SIOT_Ireland.xlsx','ModelB','F15:ED143');
Z_Italy = xlsread('SIOT_Italy.xlsx','ModelB','F15:ED143');
Z_Latvia = xlsread('SIOT_Latvia.xlsx','ModelB','F15:ED143');
Z_Lithuania = xlsread('SIOT_Lithuania.xlsx','ModelB','F15:ED143');
Z_Luxembourg = xlsread('SIOT_Luxembourg.xlsx','ModelB','F15:ED143');
Z_Malta = xlsread('SIOT_Malta.xlsx','ModelB','F15:ED143');
Z_Netherlands = xlsread('SIOT_Netherlands.xlsx','ModelB','F15:ED143');
Z_Norway = xlsread('SIOT_Norway.xlsx','ModelB','F15:ED143');
Z_Poland = xlsread('SIOT_Poland.xlsx','ModelB','F15:ED143');
Z_Portugal = xlsread('SIOT_Portugal.xlsx','ModelB','F15:ED143');
Z_Romania = xlsread('SIOT_Romania.xlsx','ModelB','F15:ED143');
Z_Slovakia = xlsread('SIOT_Slovakia.xlsx','ModelB','F15:ED143');
Z_Slovenia = xlsread('SIOT_Slovenia.xlsx','ModelB','F15:ED143');
Z_Sweden = xlsread('SIOT_Sweden.xlsx','ModelB','F15:ED143');
Z_Switzerland = xlsread('SIOT_Switzerland.xlsx','ModelB','F15:ED143');
Z_Turkey = xlsread('SIOT_Turkey.xlsx','ModelB','F15:ED143');
Z_UnitedKingdom = xlsread('SIOT_UnitedKingdom.xlsx','ModelB','F15:ED143');

%Reading in the respective x- vectors.

x_Austria = xlsread('SIOT_Austria.xlsx','ModelB','ER15:ER143');
x_Belgium = xlsread('SIOT_Belgium.xlsx','ModelB','ER15:ER143');
x_Bulgaria = xlsread('SIOT_Bulgaria.xlsx','ModelB','ER15:ER143');
x_Cyprus = xlsread('SIOT_Cyprus.xlsx','ModelB','ER15:ER143');
x_CzechRepublic = xlsread('SIOT_CzechRepublic.xlsx','ModelB','ER15:ER143');
x_Denmark = xlsread('SIOT_Denmark.xlsx','ModelB','ER15:ER143');
x_Espana = xlsread('SIOT_Espana.xlsx','ModelB','ER15:ER143');
x_Estonia = xlsread('SIOT_Estonia.xlsx','ModelB','ER15:ER143');
x_Finland = xlsread('SIOT_Finland.xlsx','ModelB','ER15:ER143');
x_France = xlsread('SIOT_France.xlsx','ModelB','ER15:ER143');
x_Germany = xlsread('SIOT_Germany.xlsx','ModelB','ER15:ER143');
x_Greece = xlsread('SIOT_Greece.xlsx','ModelB','ER15:ER143');
x_Hungary = xlsread('SIOT_Hungary.xlsx','ModelB','ER15:ER143');
```

```
x_Ireland = xlsread('SIOT_Ireland.xlsx','ModelB','ER15:ER143');
x_Italy = xlsread('SIOT_Italy.xlsx','ModelB','ER15:ER143');
x_Latvia = xlsread('SIOT_Latvia.xlsx','ModelB','ER15:ER143');
x_Lithuania = xlsread('SIOT_Lithuania.xlsx','ModelB','ER15:ER143');
x_Luxembourg = xlsread('SIOT_Luxembourg.xlsx','ModelB','ER15:ER143');
x_Malta = xlsread('SIOT_Malta.xlsx','ModelB','ER15:ER143');
x_Netherlands = xlsread('SIOT_Netherlands.xlsx','ModelB','ER15:ER143');
x_Norway = xlsread('SIOT_Norway.xlsx','ModelB','ER15:ER143');
x_Poland = xlsread('SIOT_Poland.xlsx','ModelB','ER15:ER143');
x_Portugal = xlsread('SIOT_Portugal.xlsx','ModelB','ER15:ER143');
x_Romania = xlsread('SIOT_Romania.xlsx','ModelB','ER15:ER143');
x_Slovakia = xlsread('SIOT_Slovakia.xlsx','ModelB','ER15:ER143');
x_Slovenia = xlsread('SIOT_Slovenia.xlsx','ModelB','ER15:ER143');
x_Sweden = xlsread('SIOT_Sweden.xlsx','ModelB','ER15:ER143');
x_Switzerland = xlsread('SIOT_Switzerland.xlsx','ModelB','ER15:ER143');
x_Turkey = xlsread('SIOT_Turkey.xlsx','ModelB','ER15:ER143');
x_UnitedKingdom = xlsread('SIOT_UnitedKingdom.xlsx','ModelB','ER15:ER143');


save Matrices_IO.mat
```

Script 2

```
% This part makes the different A matrices:

x_Europe_temp = x_Austria + x_Belgium + x_Bulgaria +x_Cyprus +
x_CzechRepublic + x_Denmark + x_Espana + x_Estonia + x_Finland + x_France +
x_Germany + x_Greece + x_Hungary + x_Ireland + x_Italy + x_Latvia +
x_Lithuania + x_Luxembourg + x_Malta + x_Netherlands + x_Norway + x_Poland
+ x_Portugal + x_Romania + x_Slovakia + x_Slovenia +  x_Sweden +
x_Switzerland + x_Turkey + x_UnitedKingdom;
Z_Europe_temp = Z_Austria + Z_Belgium + Z_Bulgaria + Z_Cyprus +
Z_CzechRepublic + Z_Denmark + Z_Espana + Z_Estonia + Z_Finland + Z_France
+Z_Germany + Z_Greece + Z_Hungary + Z_Ireland + Z_Italy + Z_Latvia +
Z_Lithuania + Z_Luxembourg + Z_Malta + Z_Netherlands + Z_Norway + Z_Poland
+ Z_Portugal + Z_Romania + Z_Slovakia + Z_Slovenia + Z_Sweden +
Z_Switzerland + Z_Turkey +Z_UnitedKingdom;

x_Europe = xlsread('Zxe_new.xls','x_Europe','C5:C132');
Z_Europe = xlsread('Zxe_new.xls','Z_Europe_orig.','E7:EB134');

A_Europe = Z_Europe*(diag(x_Europe)^-1);
I = eye(128);
L_Europe = (I-A_Europe)^(-1);


save ZAx_new.mat
```

Script 3

```
%This script calculates the total emissions for Europe.
% 28 different stressors are included.
load Emissions_mat.mat

% Edit all S vectors (for each country), so that sector #83 is taken out.

S_AT = Emissions_mat(:,[1:82,84:129],1);
S_BE = Emissions_mat(:,[1:82,84:129],2);
S_BG = Emissions_mat(:,[1:82,84:129],3);
S_CY = Emissions_mat(:,[1:82,84:129],4);
S_CZ = Emissions_mat(:,[1:82,84:129],5);
S_DK = Emissions_mat(:,[1:82,84:129],6);
S_EE = Emissions_mat(:,[1:82,84:129],7);
S_FI = Emissions_mat(:,[1:82,84:129],8);
S_FR = Emissions_mat(:,[1:82,84:129],9);
S_DE = Emissions_mat(:,[1:82,84:129],10);
S_GR = Emissions_mat(:,[1:82,84:129],11);
S_HU = Emissions_mat(:,[1:82,84:129],12);
S_IE = Emissions_mat(:,[1:82,84:129],13);
S_IT = Emissions_mat(:,[1:82,84:129],14);
S_LV = Emissions_mat(:,[1:82,84:129],15);
S_LT = Emissions_mat(:,[1:82,84:129],16);
S_LU = Emissions_mat(:,[1:82,84:129],17);
S_MT = Emissions_mat(:,[1:82,84:129],18);
S_NL = Emissions_mat(:,[1:82,84:129],19);
S_NO = Emissions_mat(:,[1:82,84:129],20);
S_PL = Emissions_mat(:,[1:82,84:129],21);
S_PT = Emissions_mat(:,[1:82,84:129],22);
S_RO = Emissions_mat(:,[1:82,84:129],23);
S_SK = Emissions_mat(:,[1:82,84:129],24);
S_SI = Emissions_mat(:,[1:82,84:129],25);
S_ES = Emissions_mat(:,[1:82,84:129],26);
S_SE = Emissions_mat(:,[1:82,84:129],27);
S_GB = Emissions_mat(:,[1:82,84:129],28);
S_CH = Emissions_mat(:,[1:82,84:129],40);
S_TR = Emissions_mat(:,[1:82,84:129],42);


S_bar_EUR =
S_AT+S_BE+S_BG+S_CY+S_CZ+S_DK+S_EE+S_FI+S_FR+S_DE+S_GR+S_HU+S_IE+S_IT+S_LV+
S_LT+S_LU+S_MT+S_NL+S_NO+S_PL+S_PT+S_RO+S_SK+S_SI+S_ES+S_SE+S_GB+S_CH+S_TR;

% Divide on one million EUR so that the matrices are in per EUR.
S_Europe = (S_bar_EUR * (diag(x_Europe)^-1))/1000000;

% Investigate emissions from sectors and ourchases done by the cable sector
E_output = S_Europe*diag(L_Europe*y_1EUR);
E_purchases = S_Europe*L_Europe*diag(A_Europe*y_1EUR);

% For 1 EUR in y vector:
y_1EUR = xlsread('Zxe_new.xls','y_1EUR','B6:B133');
e_1EUR_Europe = S_Europe*L_Europe*y_1EUR;


save ResultsIO_33kV.mat
```

Appendix B - Matlab code for the LCA system

This code is written in order to read the inventory into a mat-file, so that it can be uploaded properly to the LCA GUI software. Here, only the file for the 33 kV cables is presented. The script will be the similar for the 132 kV cables and the 500 kV cable, just with different input data.

```
clear all
clc

% This m.file is used to read data from my excel file,
% properly into the LCA GUI programme in order to do the impact assessment.


% Reading in Aff, Abf and Ff matrixes from excel file

Abf_33kV_pre = xlsread('Cables.xls','Abf_structured_33kV','B4:D27');
Ff_33kV_pre = xlsread('Cables.xls','Ff_structured_33kV','B5:D29');

A_ff = xlsread('Cables.xls','Aff_33kV','K4:T13');
A_ff = A_ff(1:end-1,1:end-1);
A_ff(isnan(A_ff)) = 0;

[foo, foo, PRO_f] = xlsread('Cables.xls','Aff_33kV','C4:J12');
PRO_f(:,3:7) = {[]};


% Defining final demand and functional unit

y_f = zeros(length(A_ff),1);
y_f(1,1) = 1;


% Generate backfore matrixes

A_bf = sparse(zeros(4087,length(A_ff)));
F_f = sparse(zeros(1613,length(A_ff)));


   for i=1:size(Abf_33kV_pre,1)
      A_bf(Abf_33kV_pre(i,1),Abf_33kV_pre(i,2)) = Abf_33kV_pre(i,3);
   end


  for i=1:size(Ff_33kV_pre,1)
      F_f(Ff_33kV_pre(i,1),Ff_33kV_pre(i,2)) = Ff_33kV_pre(i,3);
  end


save BaseCase_33kV.mat
```

Appendix C - Inventories for the 33 kV, 132 kV and 450 kV cables

The calculation of material amounts required for the different types of cables, are done by using the technical data for the cables. The cross-sections for different material layers in the cable are stated in the data sheets provided by the cable producers. From this, material amounts are calculated by using the different material densities. It is taken into account that the cables might have different cross-sections of the conductor, dependent on for instance water depths. When it is known what sizes of cross-sections that are utilized, and the cable length of each of these cable sizes, then a material amount can be calculated.

Table C-1. Inventory list for the 33 kV submarine HVAC power cable.

Foreground processes with respective process inputs below	Amount/Unit	Unit
Cable (LCA system)		***unit***
Steel, low-alloyed, at plant/RER U	0,206	kg
Copper, at regional storage/RER U	0,106	kg
Lead, at regional storage/RER U	0,136	kg
Polyethylene, HDPE, granulate, at plant/RER U	0,032	kg
Wire drawing, copper/RER U	0,106	kg
polypropylene, granulate, at plant/ RER/ kg	0,021	kg
Transport, lorry >32t, EURO5 (from prod. site to harbour, 100 km)		***unit***
Operation, lorry >32t, EURO5/RER U	8,56E-02	tkm
Lorry 40t/RER/I U	1,59E-07	unit
Maintenance, lorry 40t/CH/I U	1,59E-07	unit
Road/CH/I U	1,20E-03	ma
Operation, maintenance, road/CH/I U	1,00E-04	ma
Disposal, lorry 40t/CH/I U	1,59E-07	unit
Disposal, road/RER/I U	1,20E-03	ma
Transport, lorry >32t, EURO5 (from harbour to treatment, 100 km)		***unit***
Operation, lorry >32t, EURO5/RER U	8,56E-02	tkm
Lorry 40t/RER/I U	1,59E-07	unit
Maintenance, lorry 40t/CH/I U	1,59E-07	unit
Road/CH/I U	1,20E-03	ma
Operation, maintenance, road/CH/I U	1,00E-04	ma
Disposal, lorry 40t/CH/I U	1,59E-07	unit
Disposal, road/RER/I U	1,20E-03	ma
Cable lay vessel with plough (installation cables)		***unit***
Diesel, burned in building machine/ GLO/ MJ	476663	MJ
Inspection of cables during operation (40 years) (O&M)		***unit***
Diesel, burned in building machine/ GLO/ MJ	124799	MJ

Cable lay vessel with plough (EOL)		***unit***
Diesel, burned in building machine/ GLO/ MJ	476663	MJ

Table C-2. Inventory list for the 132 kV submarine HVAC power cable.

Foreground processes with respective process inputs below	Amount/Unit	Unit
Cable (LCA system)		***unit***
Steel, low-alloyed, at plant/RER U	0,1792	kg
Copper, at regional storage/RER U	0,1253	kg
Lead, at regional storage/RER U	0,1259	kg
Polyethylene, HDPE, granulate, at plant/RER U	0,0446	kg
Wire drawing, copper/RER U	0,1253	kg
polypropylene, granulate, at plant/ RER/ kg	0,0249	kg
Transport, lorry >32t, EURO5 (from prod. site to harbour, 100 km)		***unit***
Operation, lorry >32t, EURO5/RER U	8,56E-02	tkm
Lorry 40t/RER/I U	1,59E-07	unit
Maintenance, lorry 40t/CH/I U	1,59E-07	unit
Road/CH/I U	1,20E-03	ma
Operation, maintenance, road/CH/I U	1,00E-04	ma
Disposal, lorry 40t/CH/I U	1,59E-07	unit
Disposal, road/RER/I U	1,20E-03	ma
Transport, lorry >32t, EURO5 (from harbour to treatment, 100 km)		***unit***
Operation, lorry >32t, EURO5/RER U	8,56E-02	tkm
Lorry 40t/RER/I U	1,59E-07	unit
Maintenance, lorry 40t/CH/I U	1,59E-07	unit
Road/CH/I U	1,20E-03	ma
Operation, maintenance, road/CH/I U	1,00E-04	ma
Disposal, lorry 40t/CH/I U	1,59E-07	unit
Disposal, road/RER/I U	1,20E-03	ma
Cable lay vessel with plough (installation cables)		***unit***
Diesel, burned in building machine/ GLO/ MJ	476663	MJ
Inspection of cables during operation (40 years) (O&M)		***unit***
Diesel, burned in building machine/ GLO/ MJ	124799	MJ
Cable lay vessel with plough (EOL)		***unit***
Diesel, burned in building machine/ GLO/ MJ	476663	MJ

Table C-3. Information about vessels used during installation, operation, maintenance and dismantling of the 33 kV cables.

Activity/Vessel	No. Of vessels	Fuel type	Work time for 78 units of 5MW turbines (days)	Fuel consumption [l/h]	Reference Fuel consumption
Cable lay vessel with plough (installation cables)	1	Diesel	8	572,9	(Pirelli 2004)
Inspection of cables during operation (40 years) (O&M)	1	Diesel	156	150	(Vroon offshore services 2010)
Cable lay vessel with plough (EOL)	1	Diesel	6,8	572,9	(Pirelli 2004)
Transport, lorry >32t, EURO5 (from port to treatment, 100 km)	-	Diesel	182660 tkm	0,24804	(Ecoinvent 2010)
Transport, lorry >32t, EURO5 (from port to treatment, 100 km)	-	Diesel	182660 tkm	0,24804	(Ecoinvent 2010)

Table C-4. Information about vessels used during installation, operation, maintenance and dismantling of the 132 kV cables.

Activity/Vessel	No. Of vessels	Fuel type	Work time for 78 units of 5MW turbines (days)	Fuel consumption [l/h]	Reference Fuel consumption
Cable lay vessel with plough (installation cables)	1	Diesel	8	572,9	(Pirelli 2004)
Inspection of cables during operation (40 years) (O&M)	1	Diesel	156	150	(Vroon offshore services 2010)
Cable lay vessel with plough (EOL)	1	Diesel	6,8	572,9	(Pirelli 2004)
Transport, lorry >32t, EURO5 (from port to treatment, 100 km)	-	Diesel	205319 tkm	0,24804	(Ecoinvent 2010)
Transport, lorry >32t, EURO5 (from port to treatment, 100 km)	-	Diesel	205319 tkm	0,24804	(Ecoinvent 2010)

The amount of transportation required for the 33 kV and 132 kV cables are assumed to be the same except for transport by lorry which is dependent on cable weight.

Table C-5. Inventory list for the 450 kV submarine HVDC power cables.

Foreground processes with respective process inputs below	Amount/Unit	Unit
Cable (LCA system)		***unit***
Steel, low-alloyed, at plant/RER U	0,2135	kg
Copper, at regional storage/RER U	0,0846	kg
Lead, at regional storage/RER U	0,1484	kg
Kraft paper, unbleached, at plant/ RER/ kg	0,0345	kg
Wire drawing, copper/RER U	0,0846	kg
polypropylene, granulate, at plant/ RER/ kg	0,0190	kg
Transport, lorry >32t, EURO5 (from prod. site to harbour, 100 km)		***unit***
Operation, lorry >32t, EURO5/RER U	8,56E-02	tkm
Lorry 40t/RER/I U	1,59E-07	unit
Maintenance, lorry 40t/CH/I U	1,59E-07	unit
Road/CH/I U	1,20E-03	ma
Operation, maintenance, road/CH/I U	1,00E-04	ma
Disposal, lorry 40t/CH/I U	1,59E-07	unit
Disposal, road/RER/I U	1,20E-03	ma
Transport, lorry >32t, EURO5 (from harbour to treatment, 100 km)		***unit***
Operation, lorry >32t, EURO5/RER U	8,56E-02	tkm
Lorry 40t/RER/I U	1,59E-07	unit
Maintenance, lorry 40t/CH/I U	1,59E-07	unit
Road/CH/I U	1,20E-03	ma
Operation, maintenance, road/CH/I U	1,00E-04	ma
Disposal, lorry 40t/CH/I U	1,59E-07	unit
Disposal, road/RER/I U	1,20E-03	ma
Cable lay vessel with plough (installation cables)		***unit***
Diesel, burned in building machine/ GLO/ MJ	476663	MJ
Inspection of cables during operation (40 years) (O&M)		***unit***
Diesel, burned in building machine/ GLO/ MJ	124799	MJ
Cable lay vessel with plough (EOL)		***unit***
Diesel, burned in building machine/ GLO/ MJ	476663	MJ

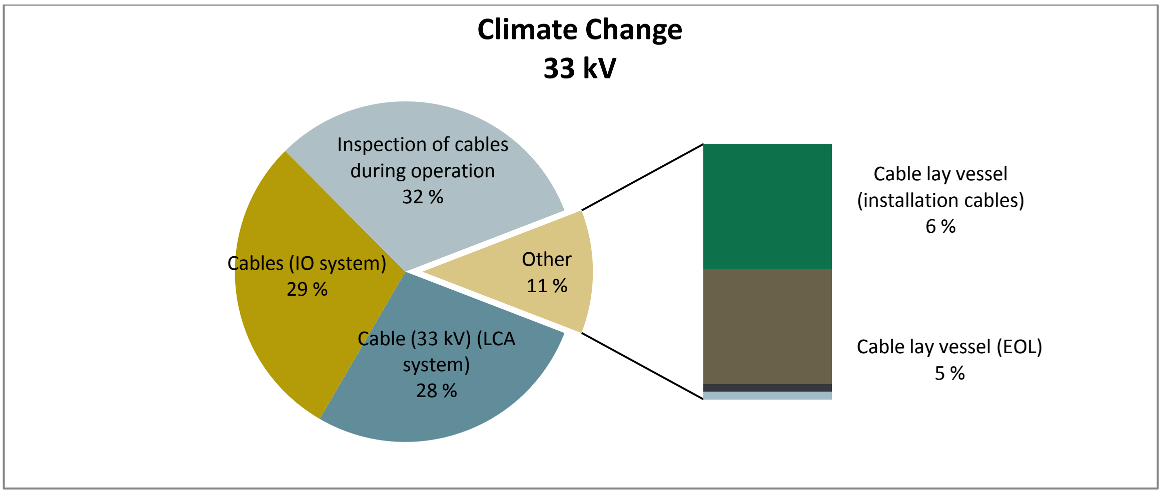
Table C-6. Information about vessels used during installation, operation, maintenance and dismantling of the 450 kV cables.

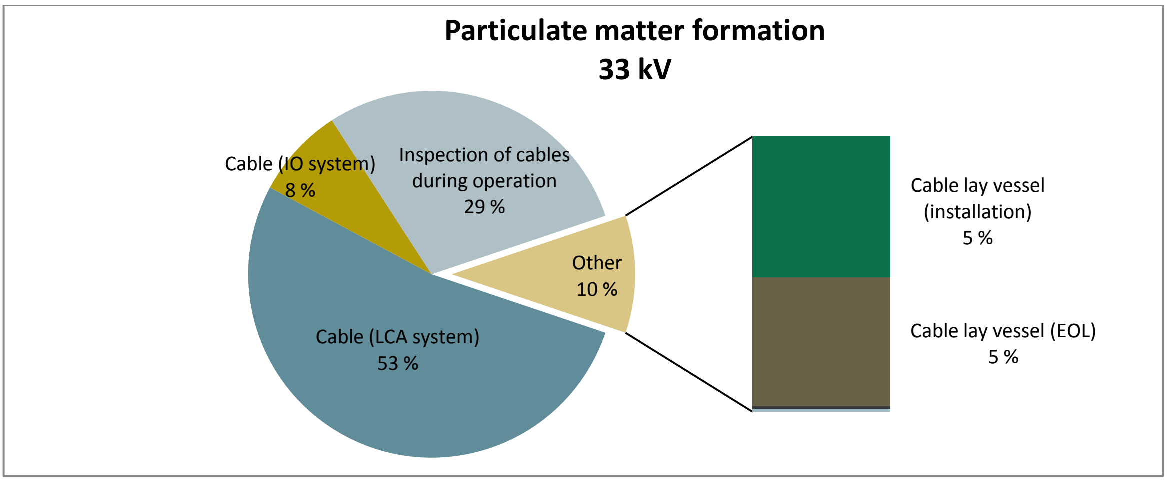
Activity/Vessel	No. Of vessels	Fuel type	Work time for 78 units of 5MW turbines (days)	Fuel consumption [l/h]	Reference Fuel consumption
Cable lay vessel with plough (installation cables)	1	Diesel	270	572,9	(Pirelli 2004)
Inspection of cables during operation (40 years) (O&M)	1	Diesel	280	150	(Vroon offshore services 2010)
Cable lay vessel with plough (EOL)	1	Diesel	270	572,9	(Pirelli 2004)
Transport, lorry >32t, EURO5 (from port to treatment, 100 km)	-	Diesel	11245465 tkm	0,24804	(Ecoinvent 2010)
Transport, lorry >32t, EURO5 (from port to treatment, 100 km)	-	Diesel	11245465 tkm	0,24804	(Ecoinvent 2010)

Appendix D - Distribution of impacts from the different cables

Table D-1. Environmental impacts cause by the 33 kV cables.

Impact category	Cable (LCA system)	Cable (IO system)	Cable lay vessel with plough (installation)	Inspection of cables during operation (40 years)	Cable lay vessel with plough (EOL)	Transport, lorry (from prod. site to harbor)	Transport, lorry (from harbor to treatment)
Climate change [kg CO_2-Eq]	62,87968	66,6605	13,14222	72,2019	12,06499	0,790363	0,790363
Freshwater eutrophication [kg P-Eq]	0,461171	0	0,000642	0,003525	0,000589	7,86E-05	7,86E-05
Marine eutrophication [kg N-Eq]	0,16458	0,014498	0,020478	0,112502	0,018799	0,000436	0,000436
Freshwater ecotoxicity [kg 1,4-DCB-Eq]	10,02278	0,000444	0,018435	0,101277	0,016923	0,002244	0,002244
Marine ecotoxicity [kg 1,4-DCB-Eq]	11,58082	0,018854	0,021645	0,118913	0,01987	0,002582	0,002582
Terrestrial ecotoxicity [kg 1,4-DCB-Eq]	0,047167	0,002333	0,00121	0,00665	0,001111	0,000124	0,000124
Human toxicity [kg 1,4-DCB-Eq]	980,2652	5,419797	0,670639	3,684417	0,615669	0,102425	0,102425
Terrestrial acidification [kg SO_2-Eq]	1,355599	0,243016	0,106471	0,58494	0,097744	0,002486	0,002486
Fossil depletion [kg oil-Eq]	23,67218	0	4,612644	25,34135	4,234558	0,303445	0,303445
Metal depletion [kg Fe-Eq]	307,7457	0	0,321222	1,764759	0,294892	0,043313	0,043313
Water depletion [m^3]	0,571816	0	0,007406	0,040688	0,006799	0,000955	0,000955
Ozone depletion [kg CFC-11-Eq]	3,24E-06	0	1,64E-06	9E-06	1,5E-06	1,3E-07	1,3E-07
Ionising radiation [kg U235-Eq]	13,22097	0	0,380107	2,088269	0,348951	0,072487	0,072487
Particulate matter formation [kg PM10-Eq]	0,536082	0,081582	0,053689	0,294963	0,049288	0,001103	0,001103
Photochemical oxidant formation [kg NMVOC]	0,479459	0,225107	0,181723	0,998364	0,166827	0,003944	0,003944
Natural land transformation [m^2]	0,013834	0	0,006489	0,035652	0,005957	0,000289	0,000289
Urban land occupation [m2a]	1,715562	0	0,02499	0,137291	0,022941	0,008183	0,008183
Agricultural land occupation [m2a]	1,809933	0	0,017187	0,094421	0,015778	0,003394	0,003394





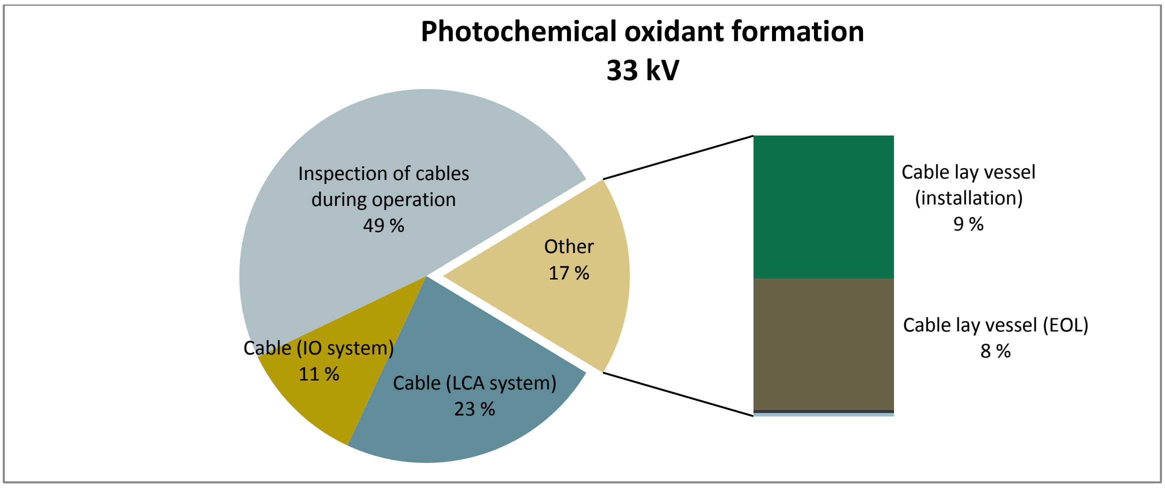
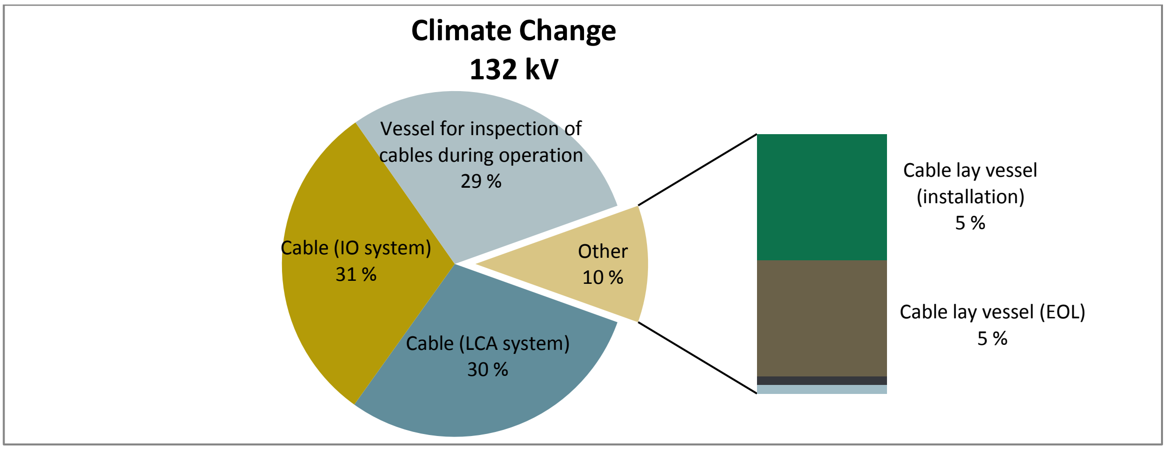
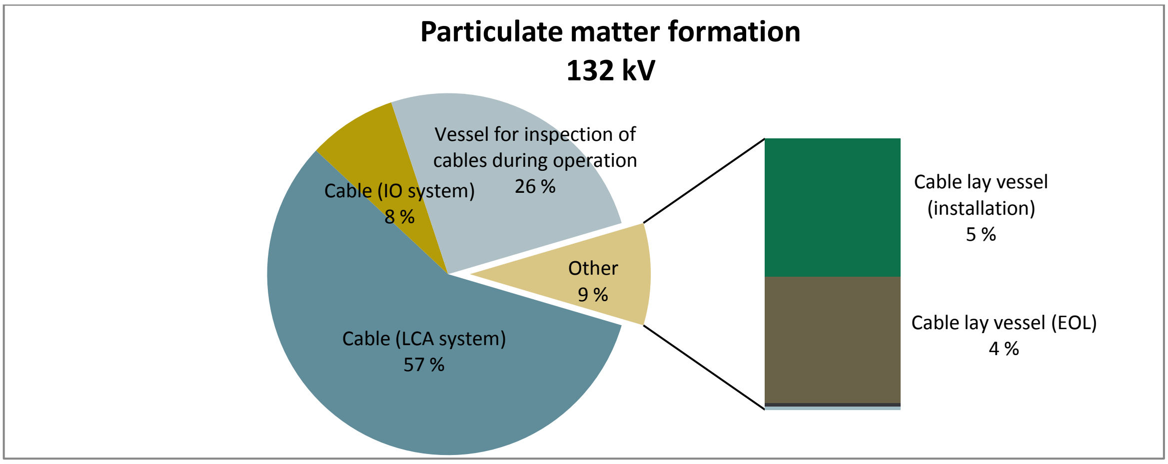


Figure D-1. A more detailed presentation of which processes that contributes to the three impact categories; Climate change, Particulate matter formation and Photochemical oxidant formation.For the 33 kV cables.

Table D-2. Environmental impacts cause by the 33 kV cables

Impact category	Cable (LCA system)	Cables (IO system)	Cable lay vessel with plough (installation)	Inspection of cables during operation (40 years)	Cable lay vessel with plough (EOL)	Transport, lorry (from prod. site to harbor)	Transport, lorry (from harbor to treatment)
Climate change [kg CO_2-Eq]	153,0778	158,1023	27,73008	152,346	25,45712	1,874547	1,874547
Freshwater eutrophication [kg P-Eq]	1,271879	0	0,001354	0,007438	0,001243	0,000187	0,000187
Marine eutrophication [kg N-Eq]	0,439474	0,034386	0,043208	0,23738	0,039666	0,001034	0,001034
Freshwater ecotoxicity [kg 1,4-DCB-Eq]	27,34207	0,001054	0,038897	0,213695	0,035709	0,005322	0,005322
Marine ecotoxicity [kg 1,4-DCB-Eq]	31,6909	0,044718	0,04567	0,250906	0,041927	0,006124	0,006124
Terrestrial ecotoxicity [kg 1,4-DCB-Eq]	0,128802	0,005533	0,002554	0,014031	0,002345	0,000295	0,000295
Human toxicity [kg 1,4-DCB-Eq]	2700,942	12,85442	1,415048	7,774119	1,299061	0,242926	0,242926
Terrestrial acidification [kg SO_2-Eq]	3,598962	0,576373	0,224654	1,234223	0,206239	0,005896	0,005896
Fossil depletion [kg oil-Eq]	60,4646	0	9,732678	53,47026	8,934917	0,719696	0,719696
Metal depletion [kg Fe-Eq]	829,6396	0	0,677779	3,723641	0,622223	0,102727	0,102727
Water depletion [m^3]	1,504752	0	0,015627	0,085851	0,014346	0,002264	0,002264
Ozone depletion [kg CFC-11-Eq]	7,85E-06	0	3,46E-06	1,9E-05	3,17E-06	3,09E-07	3,09E-07
Ionising radiation [kg U235-Eq]	32,05294	0	0,802027	4,406247	0,736287	0,171921	0,171921
Particulate matter formation [kg PM10-Eq]	1,400646	0,193493	0,113284	0,622371	0,103999	0,002617	0,002617
Photochemical oxidant formation [kg NMVOC]	1,24579	0,533899	0,383435	2,106548	0,352006	0,009354	0,009354
Natural land transformation [m^2]	0,035172	0	0,013693	0,075225	0,01257	0,000685	0,000685
Urban land occupation [m2a]	4,529268	0	0,052728	0,289683	0,048406	0,019409	0,019409
Agricultural land occupation [m2a]	4,393232	0	0,036264	0,199229	0,033291	0,008051	0,008051





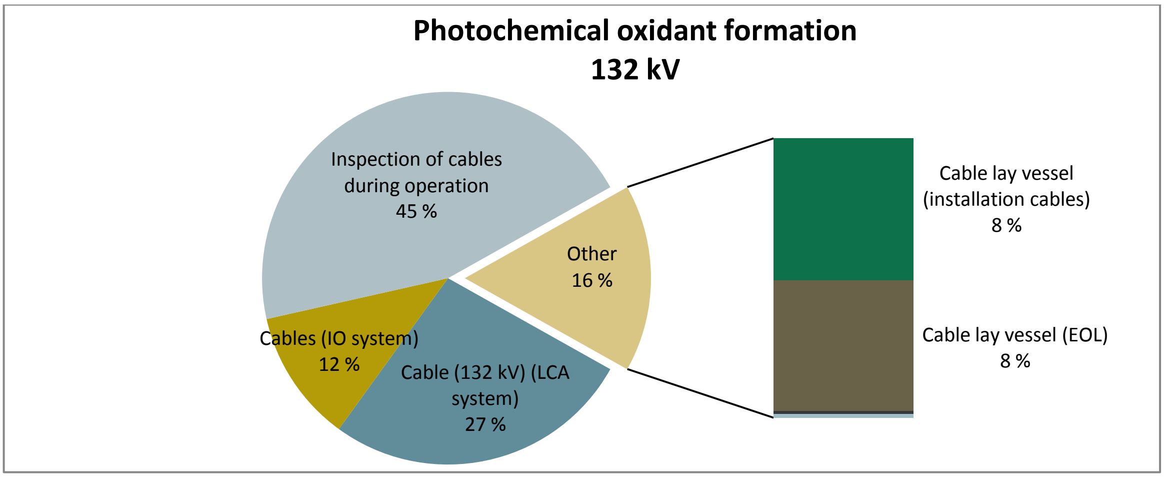
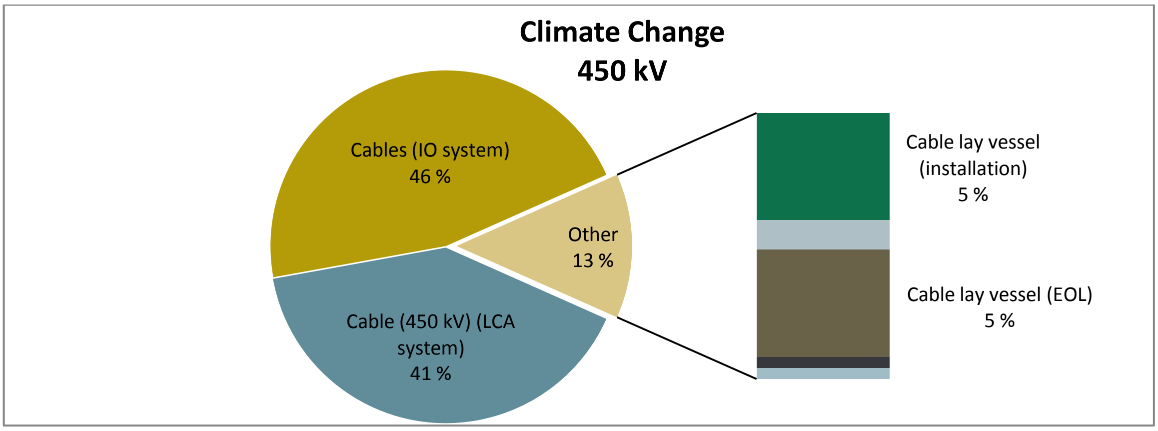
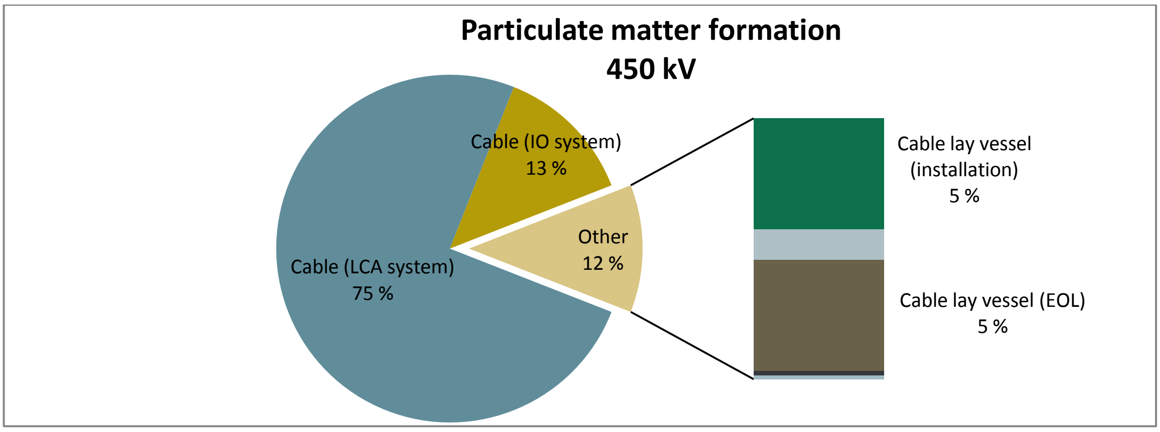


Figure D-2. A more detailed presentation of which processes that contributes to the three impact categories; Climate change, Particulate matter formation and Photochemical oxidant formation. For the 132 kV cables.

Table D-3. Environmental impacts cause by the 450 kV cables.

Impact category	Cable (LCA system)	Cable (IO system)	Cable lay vessel with plough (installation)	Cable vessel for inspection (40 years)	Cable lay vessel with plough (EOL)	Transport, lorry (from prod. site to harbor)	Transport, lorry (from harbor to treatment)
Climate change [kg CO_2-Eq]	86,9278462	99,13363585	11,52936576	3,13039749	11,52936576	1,175382497	1,175382497
Freshwater eutrophication [kg P-Eq]	0,559467931	0	0,000562863	0,00015283	0,000562863	0,000116963	0,000116963
Marine eutrophication [kg N-Eq]	0,214965138	0,02156105	0,01796461	0,00487766	0,01796461	0,000648264	0,000648264
Freshwater ecotoxicity [kg 1,4-DCB-Eq]	12,31254916	0,00066099	0,016172184	0,00439099	0,016172184	0,003336916	0,003336916
Marine ecotoxicity [kg 1,4-DCB-Eq]	14,15837776	0,028038906	0,018988254	0,0051556	0,018988254	0,003840171	0,003840171
Terrestrial ecotoxicity [kg 1,4-DCB-Eq]	0,05949318	0,003469494	0,001061848	0,00028831	0,001061848	0,000185055	0,000185055
Human toxicity [kg 1,4-DCB-Eq]	1193,040058	8,060008619	0,588336131	0,15974217	0,588336131	0,152319799	0,152319799
Terrestrial acidification [kg SO_2-Eq]	1,74627835	0,361398596	0,093404521	0,02536074	0,093404521	0,003696889	0,003696889
Fossil depletion [kg oil-Eq]	29,10583362	0	4,046565852	1,09870394	4,046565852	0,451265495	0,451265495
Metal depletion [kg Fe-Eq]	381,1991943	0	0,28180072	0,07651317	0,28180072	0,064412061	0,064412061
Water depletion [m^3]	0,750326585	0	0,006497095	0,00176406	0,006497095	0,001419825	0,001419825
Ozone depletion [kg CFC-11-Eq]	4,83106E-06	0	1,43676E-06	3,901E-07	1,43676E-06	1,93506E-07	1,93506E-07
Ionising radiation [kg U235-Eq]	20,10164727	0	0,333459548	0,09053932	0,333459548	0,107797963	0,107797963
Particulate matter formation [kg PM10-Eq]	0,697876953	0,121324424	0,047100335	0,01278845	0,047100335	0,001640617	0,001640617
Photochemical oxidant formation [kg NMVOC]	0,628568798	0,334766571	0,159421089	0,04328524	0,159421089	0,00586498	0,00586498
Natural land transformation [m^2]	0,022850011	0	0,005692956	0,00154572	0,005692956	0,000429365	0,000429365
Urban land occupation [m2a]	2,757280251	0	0,021922875	0,00595239	0,021922875	0,012169927	0,012169927
Agricultural land occupation [m2a]	37,32498486	0	0,015077423	0,00409375	0,015077423	0,005047979	0,005047979





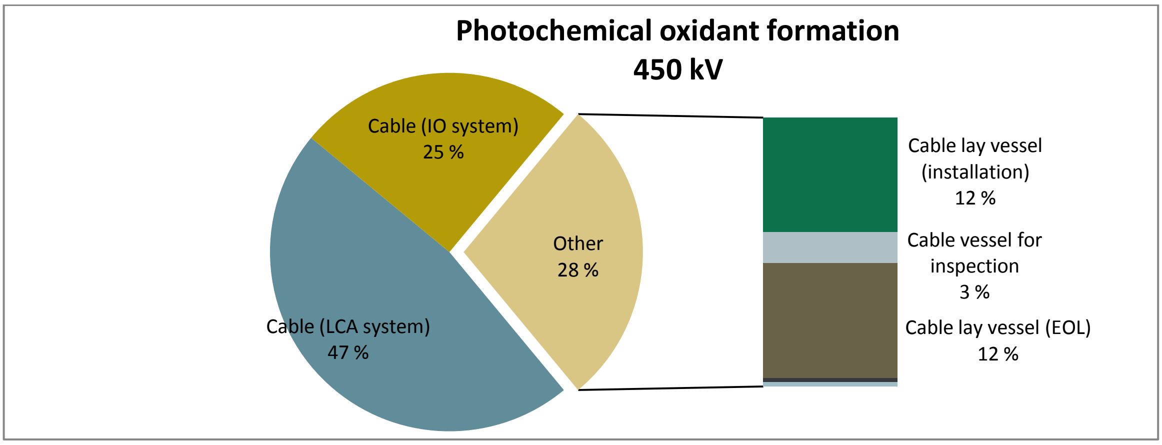


Figure D-3. A more detailed presentation of which processes that contributes to the three impact categories; Climate change, Particulate matter formation and Photochemical oxidant formation.For the 450 kV cables.

Appendix E - Data for material distribution in one windmill

Here, data for the mass distribution and material mix used in the LCA for the windmill is presented. Mass distribution used for the nacelle is from the study “A guide to an offshore wind farm” done by The Crown Estate (The Crown Estate 2009). This report gives an overview on what is needed in order to build an offshore wind farm, and includes a quite well decomposition of the nacelle. For the mass distribution of rotor and tower, numbers derived from Vestas are used and scaled to apply for a 5 MW wind turbine (Arvesen & E. Hertwich 2011). For the foundation, data received directly from Trond Landbø in Vici Ventus Technology AS are used for mass and material distribution (Vici Ventus Technology AS 2010a).

Table E-1. Distribution of mass on windmill components.

Component	Average V80-2 MW, V90-3 MW	Unit
Rotor blades	8,2	t/MW
Hub	8,2	t/MW
Nacelle	28,9	t/MW
Tower (average)	69,3	t/MW

Table E-2. Further disaggregation of the windmill. Mass distribution.

Component	Used in calculations	Unit
Nacelle	154500	kg
Main bearing	25000	kg
Main shaft	30000	kg
Gear box	65000	kg
Generator	20000	kg
Control system	500	kg
Yaw bearing	6000	kg
Hydraulic pitch system	3000	kg
Electrical pitch system	5000	kg
Rotor	81958	kg
Blade	13708	kg
Hub	40833	kg
Tower	346333	kg
Foundation	8744333*	kg
Total	**9327125**	**kg**

Table E-3. Mass distribution in the foundation.

Concrete volume	3033333	kg
Steel reinforcement	560000	kg
Solid ballast	5151000	kg
Total mass	**8744333**	**kg**

Table E-4. Material distribution in the windmill. In percentage distribution.

Component/Material (% of weight)		Pre-processed concrete	Steel	Aluminum	Copper	Glass reinforces platsic	Olivine	Silica
Rotor								
	Hub		95 %	5 %				
	Blades		5 %			95 %		
Nacelle			65 %	3 %		1 %		
	Gearbox		98 %	1 %	1 %			
	Generator		60 %		35 %			2,5 %
	Frame, machinery and shell		85 %	9 %	6 %			0,5 %
Tower		2 %	98 %					
Foundation		85 %	15 %					
Ballast							100 %	

Table E-5. Material distribution in the windmill. In units.

		Hub	**Rotor blades**	**Gearb ox**	**Generator**	**Bed frame/plate**	**LV transformer**	**Nacelle other**	**Tower**	**Foundatio n**	**Ballast**
	Unit	unit	unit	unit	unit	unit	Unit	unit	unit	unit	unit
Cast iron	kg	38791,7				26250					
Concrete	m3								2,8	1300	
Steel, low alloy	kg		2056,3		11400		8250	24575	339406,7		
Chromium steel	kg			63700	600						
Steel, reinforcem.	kg									560000	
Aluminium	kg	2041,7		650				6255			
Copper	kg			650	7000		3750	420			
Glass reinforced plastic	kg		39068,8								
Olivine	kg										5151000
Silica	kg				500		375				
Total	**kg**	**40833**	**41125**	**65000**	**19500**		**69875**		**339409**	**561300**	**5151000**

Appendix F - Material distributions in the different replacement of parts categories

Table F-1. Material distribution in the different "replacement of part" categories.

	Unit	Replacement bed frame/plate Unit	Replacement generator Unit	Replacement gearbox Unit	Replacement nacelle other Unit	Replacement LV transformer Unit
Cast iron	**kg**	8138				
Concrete	**m3**					
Steel, low alloy	**kg**				7618	2558
Chromium steel	**kg**		186	157976		
Steel, reinforcement	**kg**					
Aluminium	**kg**			1612	1939	
Copper	**kg**		2170	1612	130	1163
Glass reinforced plastic	**kg**					
Olivine	**kg**					
Silica	**kg**		155			116
Total		**8138**	**2511**	**161199**	**9687**	**3837**

Appendix G - Failure distribution in wind farm

Table G-1. Occurence of failures distributed on four failure categories, for the wind farm. Based on (Rademakers et al. 2003) and (Salzmann 2009).

Failure Category	Required Action[1]	Equipment[1]	Occurrence[1]	Failures (per turbine)	# of failures for 78 turbines per year
1	Replacement of heavy component	Vessel + Jack-up	1 %	0,0155	1,2
2	Replacement of large part	Vessel + Build up Internal Crane	7 %	0,1085	8,5
3	Replacement of small part (<1t)	Vessel + Permanent Internal crane	23 %	0,3565	27,8
4	Replacement of small part (man carried) or no part (inspection)	Vessel or Helicopter	69 %	1,0695	83,4

Table G-1 gives a percentage distribution of failure occurrences, in the four maintenance categories, for a wind farm. The table also includes vessels assumed to be needed for each type of failure. To decide how many vessel hours are needed, due to corrective maintenance of the wind farm, the failure rate of 1.55 for one wind turbine is distributed on these four failure categories. The number of failures per turbine per failure category is then multiplied by number of wind turbines. This gives an estimate of failures per year for 78 wind turbines. By approximating the travel time, in hours, to the wind farm for these particular vessels, number of days used per vessel type and failure type are estimated.

Including use of vessel hours for replacing of parts will not include the extra materials used by actually replacing components. In order to obtain a more complete assessment, extra material used in replacing components are included in this analysis. As it is not possible to say exactly which components or parts that are needed throughout the lifetime of a wind turbine, following assumptions are made;

- For category 1; a nacelle is used to include extra materials used for new parts.
- For category 2; a gearbox is used to include extra materials used for new parts.
- For category 3 and 4; the material quantity is assumed to be small compared to the extra material use in category 1 and 2, that it is not included here

The assumptions about failure rates in components of a wind turbine are made on basis of Table 5.3. The highest failure rates are those of the electrical system, the control system and the gearbox. On behalf of this, assumption one is made. Failure category number two is represented by a gearbox because gearboxes are the part having the highest failure rate except of electrical systems. Other studies have also found that often, the main area of concern is gearboxes which are vulnerable to a lot of wear and tear (Wallace et al. 2009). Crawford states that 50% of gearboxes have to be replaced over the service life (Crawford 2009). Vestas also expects replacement of parts, and states that replacement of gearboxes, generators, blades and LV transformers should be expected throughout lifetime (Poulsen 2004). Vestas does not specify number of replaced parts.

Based on this, these components (nacelle and gearboxes) are assumed to give good estimates of the material requirement of replacing components in category one and two. See appendix F for material distribution of all replaced parts.

Appendix H - Transportation required in the offshore wind farm

Vessels used for installation, operation, maintenance and dismantling of the offshore wind farm. Working hours are assessed based on the working hours for a single unit and compared with the total number of turbines. In addition, the working hours for the transport of foundations, turbines, and rock for scour protection are based on typical distances from potential delivery locations and typical sailing speeds. The same goes for cable laying and inspection activities (Rambøll 2009). The engine powers of the vessels are derived from data sheets for the type of vessels and equipment that has been used in building other, newer wind farms.

Table H-1. Information about vessels used during installation, operation, maintenance and dismantling of the wind farm.

Activity/Vessel	No. Of vessels	Fuel type	Work time for 78 units of 5MW turbines (days)	Fuel consumption [l/h]	Reference Fuel consumption
Excavator[1]	1	Diesel	234	0,455	(Ecoinvent 2010)
Barge for excavator[1]	1	Heavy fuel oil	234	100	(Vroon offshore services 2010)
Barge for disposal of seabed material[1]	1	Heavy fuel oil	175,5	100	(Vroon offshore services 2010)
Vessel for transport of rock for stone bed[1]	1	Heavy fuel oil	355,4	100	(Vroon offshore services 2010)
Vessel for dumping of rock for stone bed[1]	1	Heavy fuel oil	234	100	(Vroon offshore services 2010)
Tugboats for transport of foundations (Installation foundation) [1]	2	Diesel	156	322,6	(Clean Air Agency 1999)
Jack- up for foundations (installation foundation) [1]	1	Heavy fuel oil	78	170	(Fred. Olsen Windcarrier AS 2006)
Tugboats for jack-up vessel (installation foundation) [1]	2	Diesel	156	322,6	(Clean Air Agency 1999)
Vessel for transport of rock for scour protection[2]	1	Heavy fuel oil	355,4	100	(Vroon offshore services 2010)
Vessel for dumping of rock for scour protection[2]	1	Heavy fuel oil	234	100	(Vroon offshore services 2010)
Jack- up for transport and installation of turbines (installation WT) [2]	1	Heavy fuel oil	78	170	(Fred. Olsen Windcarrier AS 2006)
Tugboats for jack-up vessel (installation WT) [2]	2	Diesel	156	322,6	(Clean Air Agency 1999)
Cable lay vessel with plough (installation	1	Diesel	16,1	572,9	(Pirelli 2004)

cables) [3]					
Vessel for tie-in of cables (installation cables) [3]	1	Diesel	84,8	100,0	(Vroon offshore services 2010)
Jack-up vessel for installation of foundation (installation HV – transf.) [4]	1	Heavy fuel oil	22,8	170	(Fred. Olsen Windcarrier AS 2006)
Tugboats for jack-up vessel (installation HV – transf.) [4]	2	Diesel	12	322,6	(Clean Air Agency 1999)
Crane vessel for installation of topside (installation HV – transf.) [4]	1	Heavy fuel oil	22,8	170	(Fred. Olsen Windcarrier AS 2006)
Tugboats for barge for transport of foundation, topside etc. (installation HV – transf.) [4]	2	Diesel	12	322,6	(Clean Air Agency 1999)
Vessel for maintenance of transformer station during operation (O&M) [5]	1	Diesel	300	262,5	(Austal 2010)
Inspection of cables during operation (20 years) (O&M) [5]	1	Diesel	312	150	(Vroon offshore services 2010)
Vessel for maintenance of turbines during operation (20 years) (O&M) [5]	1	Diesel	3900	262,5	(Austal 2010)
Jack- up for replacement of heavy components (O&M) [6]	1	Heavy fuel oil	0,2	170	(Fred. Olsen Windcarrier AS 2006)
Vessel for replacement of large parts (jack up) (O&M) [6]	1	Diesel	1,4	170	(Fred. Olsen Windcarrier AS 2006)
Vessel for transport of small parts and O&M personnel (O&M) [6]	1	Diesel	8,7	262,5	(Austal 2010)
Vessel for inspection (O&M) [6]	1	Diesel	26,1	262,5	(Austal 2010)
Transport, helicopter /GLO U (O&M) [6]	1	Kerosene	88,5	33 hours	(Ecoinvent 2010)
Tugboats for transport of foundations (EOL foundations) [7]	2	Diesel	156	322,6	(Clean Air Agency 1999)
Jack- up for removing foundations and HV - transf. (EOL) [7]	1	Heavy fuel oil	78	170	(Fred. Olsen Windcarrier AS 2006)
Tugboats for jack-up vessel (Foundations, EOL) [7]	2	Diesel	156	322,6	(Clean Air Agency 1999)
Jack- up for transport and removement of turbines and HV- transf. (EOL) [7]	1	Heavy fuel oil	80	170	(Fred. Olsen Windcarrier AS 2006)
Tugboats for jack-up vessel (WT, EOL) [7]	2	Diesel	156	322,6	(Clean Air Agency 1999)
Cable lay vessel with plough (EOL) [7]	1	Diesel	13,65	572,9	(Pirelli 2004)
Transport, lorry >32t, EURO5 (from prod. site to port, 100 km (WT components)) [2]	-	Diesel	4567740 tkm	0,24804	(Ecoinvent 2010)
Transport, lorry >32t, EURO5 (from prod.	-	Diesel	28746667 tkm	0,24804	(Ecoinvent 2010)

site to port, 100 km (Foundations)) [1]					
Transport, lorry >32t, EURO5 (from prod. site to port, 100 km (Cables)) [3]	-	Diesel	387979 tkm	0,24804	(Ecoinvent 2010)
Transport, lorry >32t, EURO5 (from port to treatment, 100 km (WT components)) [7]	-	Diesel	4567740 tkm	0,24804	(Ecoinvent 2010)
Transport, lorry >32t, EURO5 (from port to treatment, 100 km (Foundations)) [7]	-	Diesel	28746667 tkm	0,24804	(Ecoinvent 2010)
Transport, lorry >32t, EURO5 (from port to treatment, 100 km (Cables)) [7]	-	Diesel	387979 tkm	0,24804	(Ecoinvent 2010)

1. Installation of foundations.
2. Installation of wind turbines.
3. Installation of cables.
4. Installation of HV transformers.
5. Preventive maintenance.
6. Corrective maintenance.
7. Dismantling of components.

Appendix I - The complete inventory list for the offshore wind farm

Table I-1. Inventory list for the wind farm.

Foreground processes with respective process inputs below	Amount/unit	Unit
Wind turbine misc		***unit***
Diesel, burned in building machine/ GLO/ MJ	285642	MJ
Electricity, production mix RER/RER U	226782	kWh
Lubricating oil, at plant/RER U	2875	kg
Natural gas, burned in industrial furnace >100kW/RER U	92878	MJ
Sheet rolling, aluminium/RER U	8947	kg
Sheet rolling, chromium steel/RER U	64300	kg
Heat from waste, at municipal waste incineration plant/CH U	161188	MJ
Heat, at cogen 1MWe lean burn, allocation exergy/RER U	161188	MJ
Propylene glycol, liquid, at plant/RER U	4030	kg
Epoxy resin, liquid, at plant/RER U	1368	kg
Gravel, unspecified, at mine/CH U	300000	kg
Polyvinylchloride, bulk polymerised, at plant/RER U	8765	kg
Welding, arc, steel/RER U	570	m
Wire drawing, copper/RER U	3975	kg
Polyethylene, HDPE, granulate, at plant/RER U	68	kg
Polyvinylchloride, bulk polymerised, at plant/RER U	250	kg
Synthetic rubber, at plant/RER U	105500	kg

Rotor blades		*unit*
Steel, low-alloyed, at plant/RER U	2056	kg
Glass fibre reinforced plastic, polyamide, injection moulding, at plant/RER U	39069	kg
Hub		***unit***
Aluminium, production mix, at plant/RER U	2042	kg
Cast iron, at plant/RER U	38792	kg
Bed/ frame plate		***unit***
Cast iron, at plant/RER U	26250	kg
Generator		***unit***
Steel, low-alloyed, at plant/RER U	11400	kg
Chromium steel 18/8, at plant/RER U	600	Kg
Copper, at regional storage/RER U	7000	kg
Silica sand, at plant/DE U	500	kg
Gearbox		***unit***
Chromium steel 18/8, at plant/RER U	63700	kg
Copper, at regional storage/RER U	650	kg
Aluminium, production mix, at plant/RER U	650	kg
Nacelle other		***unit***
Steel, low-alloyed, at plant/RER U	24575	kg
Copper, at regional storage/RER U	420	kg
Aluminium, production mix, at plant/RER U	6255	kg
LV transformer		***unit***
Steel, low-alloyed, at plant/RER U	8250	kg
Copper, at regional storage/RER U	3750	kg
Silica sand, at plant/DE U	375	kg
Tower		***unit***
Steel, low-alloyed, at plant/RER U	339407	kg
Sheet rolling, steel/RER U	339407	kg
Concrete, normal, at plant	3	m3
Foundation		***unit***
Reinforcing steel, at plant/RER U	560000	kg
Concrete, normal, at plant	1300	m3
Gravel, unspecified, at mine/CH U	5151000	kg
HV transformer		***unit***

Electricity, production mix RER/RER U	65046	kWh
Lubricating oil, at plant/RER U	26743	kg
Steel, low-alloyed, at plant/RER U	62811	kg
Copper, at regional storage/RER U	13498	kg
Aluminium, production mix, at plant/RER U	1107	kg
Natural gas, burned in industrial furnace >100kW/RER U	996705	MJ
Kraft paper, unbleached, at plant/RER U	825	kg
Sulphate pulp, average, at regional storage/RER U	2949	kg
Glass fibre, at plant/RER U	618	Kg
Alkyd paint, white, 60% in solvent, at plant/RER U	53	Kg
Epoxy resin insulator (Al2O3), at plant/RER U	104	Kg
Electrical collection system (materials) (33kV)		***kg***
Steel, low-alloyed, at plant/RER U	0,206	kg
Copper, at regional storage/RER U	0,110	kg
Lead, at regional storage/RER U	0,136	kg
Wire drawing, copper/RER U	0,11	kg
Polyethylene, HDPE, granulate, at plant/RER U	0,0315	Kg
Polypropylene, granulate, at plant/ RER/ kg	0,0212	Kg
Cables connected to grid (materials) (132 kV)		***kg***
Steel, low-alloyed, at plant/RER U	0,179	kg
Copper, at regional storage/RER U	0,125	kg
Lead, at regional storage/RER U	0,126	Kg
Wire drawing, copper/RER U	0,125	Kg
Polyethylene, HDPE, granulate, at plant/RER U	0,0446	Kg
Polypropylene, granulate, at plant/ RER/ kg	0,0249	kg
Transmission network, electricity, high voltage (on land)		***km***
Steel, low-alloyed, at plant/RER U	210	kg
Copper, at regional storage/RER U	268	kg
Aluminium, production mix, at plant/RER U	3150	kg
Lead, at regional storage/RER U	134	kg
Light fuel oil, at regional storage/RER U	67	kg
Packaging film, LDPE, at plant/RER U	67	kg
Polyvinylchloride, at regional storage/RER U	67	kg
Steel, converter, unalloyed, at plant/RER U	7740	kg
Transport, lorry >16t, fleet average/RER U	590	tkm
Transport, freight, rail/RER U	5710	tkm
Excavation, hydraulic digger/RER U	58	m3
Building, hall, steel construction/CH/I U	0,181	m2
Building, multi-storey/RER/I U	7,1	m3
Disposal, polyethylene, 0.4% water, to municipal incineration/CH U	67	kg
Disposal, polyvinylchloride, 0.2% water, to municipal incineration/CH U	67	kg
Disposal, used mineral oil, 10% water, to hazardous waste	67	kg

incineration/CH U		
Replacement of parts (combined/merged)		***unit***
Cast iron, at plant/RER U	8138	kg
Chromium steel 18/8, at plant/RER U	161696	kg
Copper, at regional storage/RER U	5075	kg
Silica sand, at plant/DE U	271	kg
Aluminium, production mix, at plant/RER U	3551	kg
Steel, low-alloyed, at plant/RER U	10176	kg
Marine transport (merged)		***ship day***
Hydraulic digger/RER/I U	0,167	unit
diesel, burned in building machine/ GLO/ MJ	4324011	MJ
heavy fuel oil, burned in industrial furnace 1MW, non-modulating/ RER/ MJ	1697338	MJ
Flight transport		***flight hour***
Helicopter/GLO/I U	0,0001	unit
kerosene, at regional storage	26,4	kg
Road transport (merged)		***tkm***
Operation, lorry >32t, EURO5/RER U	0,513744	tkm
Lorry 40t/RER/I U	9,5136E-07	unit
Maintenance, lorry 40t/CH/I U	9,5136E-07	unit
Road/CH/I U	0,007212	ma
Operation, maintenance, road/CH/I U	0,00060216	ma
Disposal, lorry 40t/CH/I U	9,5136E-07	unit
Disposal, road/RER/I U	0,007212	ma

Appendix J – Environmental impacts caused by an offshore wind farm of 390 MW

This is a synopsis of all the environmental impacts that are caused by the different parts of the foreground system of the offshore wind farm. The table shows the distribution of contribution in the different impact categories, from the different parts of the system, per kWh of electricity delivered to the grid onshore

Table J-1. Distribution of contribution to total impacts from the different parts of the system, per kWh of electricity delivered to the grid onshore.

Impact category	Windmill	HV transformer stations	Transmission (on land)	Transmission (submarine)	Replacement of parts	Transport (onshore and offshore)	Total impacts
Climate change [kg CO_2-Eq]	1,12E-02	2,38E-05	1,18E-05	3,02E-04	2,69E-03	6,37E-03	**2,06E-02**
Freshwater eutrophication [kg P-Eq]	7,30E-06	7,24E-08	1,28E-08	1,16E-06	2,21E-06	3,46E-07	**1,11E-05**
Marine eutrophication [kg N-Eq]	1,08E-05	3,17E-08	9,98E-09	4,39E-07	2,20E-06	8,28E-06	**2,18E-05**
Freshwater ecotoxicity [kg 1,4-DCB-Eq]	2,68E-04	1,64E-06	2,53E-07	2,50E-05	2,09E-04	9,97E-06	**5,13E-04**
Marine ecotoxicity [kg 1,4-DCB-Eq]	2,82E-04	1,87E-06	2,87E-07	2,90E-05	2,20E-04	1,41E-05	**5,48E-04**
Terrestrial ecotoxicity [kg 1,4-DCB-Eq]	1,41E-06	8,91E-09	2,18E-09	1,23E-07	5,42E-07	8,30E-07	**2,92E-06**
Human toxicity [kg 1,4-DCB-Eq]	1,07E-02	1,43E-04	2,03E-05	2,47E-03	3,73E-03	5,03E-04	**1,76E-02**
Terrestrial acidification [kg SO2-Eq]	4,41E-05	2,21E-07	7,44E-08	3,89E-06	1,46E-05	4,81E-05	**1,11E-04**
Fossil depletion [kg oil-Eq]	3,82E-03	1,17E-05	3,85E-06	5,70E-05	8,02E-04	2,24E-03	**6,94E-03**
Metal depletion [kg Fe-Eq]	1,04E-02	5,82E-05	8,50E-05	7,63E-04	4,82E-03	1,81E-04	**1,63E-02**
Water depletion [m^3]	3,35E-05	1,21E-07	3,90E-08	1,40E-06	1,01E-05	3,88E-06	**4,90E-05**
Ozone depletion [kg CFC-11-Eq]	8,11E-10	3,22E-12	1,19E-12	7,57E-12	1,43E-10	8,04E-10	**1,77E-09**
Ionising radiation [kg U235-Eq]	2,18E-03	5,28E-06	1,80E-06	3,09E-05	5,59E-04	2,15E-04	**2,99E-03**
Particulate matter formation [kg PM10-Eq]	3,16E-05	1,02E-07	4,70E-08	1,50E-06	1,33E-05	2,30E-05	**6,95E-05**
Photochemical oxidant formation [kg NMVOC]	3,75E-05	1,25E-07	4,35E-08	1,69E-06	9,50E-06	7,35E-05	**1,22E-04**
Natural land transformation [m^2]	1,88E-06	1,08E-08	1,48E-08	3,32E-08	2,93E-07	3,09E-06	**5,32E-06**
Urban land occupation [m2a]	1,02E-04	3,82E-07	7,14E-07	4,20E-06	4,17E-05	1,47E-05	**1,63E-04**
Agricultural land occupation [m2a]	2,64E-04	3,50E-06	7,38E-07	4,24E-06	6,83E-05	9,69E-06	**3,50E-04**