

Report

SUSTAINABLE INNOVATION

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GHG emissions and energy performance of wind power

LCA of two existing onshore wind power farms and six offshore wind power conceptual designs

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Summary

This study has been carried out as a part of the Energy Trading and Environment 2020 project, funded by the Norwegian Research Council and the partner consortium. The aim of the study was to present LCA GHG emissions and energy performance of two Norwegian onshore wind farms and six different offshore conceptual designs.

The LCA GHG emissions from the onshore wind power farms Kjøllefjord and Fjeldskår are 11.0 and 15.1 g CO₂-equivalents/kWh, respectively. The turbine components (nacelle, rotor and tower) are the main GHG emissions contributors representing about 80% and 72% of the total GHG emissions from Kjøllefjord and Fjeldskår wind farms, respectively. As these turbine components mainly consist of steel, this steel production activity is the main contributor to the overall GHG emissions.

The Energy Payback Ratio (EPR) is 21 and 14 for Kjøllefjord and Fjeldskår wind farms, respectively. Thus, for every unit invested energy the respective payback energy is 21 and 14. The respective Energy Payback Time (EPT) indicators are 0.9 and 1.4 years for Kjøllefjord and Fjeldskår wind farms.

The investigated offshore conceptual designs all result in higher LCA GHG emissions and lower energy performance compared with the results from the onshore wind farms. The GHG emissions vary between 18.0 and 31.4 g CO₂-equivalents/kWh, a difference representing 77% increase compared to the lowest GHG emissions. The foundation/platform materials contribute the most to the overall GHG emissions, varying from 35% to 63% of the total GHG emissions. The variations between the concepts are placed in this category, since the tower and RNA are identical. Thus, one major conclusion from this study is that specific platform/foundation steel masses are important for the overall GHG emissions relating to offshore wind power. The second largest contribution to GHG emissions comes from the installation and decommissioning activities.

The investigated concepts achieve EPR and EPT values between 7.5 and 13 and 1.5 and 2.7 years, respectively. The Umaine Semi-S and Spar concepts result in the worst energy performance, while the MIT TLP and OC4 Jacket give the best performance, which is in line with the GHG emissions result. This would be expected since the use of conventional energy within an analysed system generally represents the main contributor to GHG emissions from the same system.

It is significant for the further development of offshore wind turbines that there is an increased understanding of the parameters and activities which have the greatest impact on the overall GHG emissions and energy performance of wind power. This may be affected both by the various different platform concepts and by varying locations and weather conditions. Some platform concepts, for example, can handle larger turbines without increasing the platform sizes, while others have to be scaled up. In addition, some concepts may be more suitable for rough weather conditions than others. Further studies should focus on how such variations impact the resulting GHG emissions and energy performance.

Lastly, it should be emphasised that GHG emissions and energy performance represent only two environmental indicators. With regard to decision making and guiding policy, several other environmental indicators need to be taken into consideration. These include land use, visual aspects, biodiversity and noise. This is particularly relevant when comparing onshore and offshore turbines.

1 Introduction

This study has been carried out as a part of the Energy Trading and Environment 2020 (ET&E 2020) project (Fortum Market and Ostfold Research 2009), funded by the Norwegian Research Council and the partner consortium.

Life Cycle Assessments (LCA) of two existing Norwegian onshore wind farms have been conducted: The Kjøllefjord (Statkraft) wind farm, located in the north of Norway and consisting of seventeen 2.3 MW wind turbines, and the Fjeldskår (Agder Energi) wind farm, located in the south of Norway and consisting of five 0.75 MW turbines.

Furthermore, LCAs of six different offshore wind power conceptual designs have been carried out, representing five floating platforms and one bottom-fixed foundation. All concepts use the NREL 5 MW offshore reference wind turbine Rotor-Nacelle-Assembly (RNA). The hub height is 90 m and the rotor diameter is 126 m. The water depth is 200 m for the floating concepts and 50 m for the bottom-fixed concept. The wind farm (bottom-fixed or floating) is assumed to be located 200 km off the British Coast, at Doggerbank (independent of the real water depth), and consists of 100 wind turbines installed in a square layout (10*10 turbines).

The aim of the study was to present LCA GHG emissions and energy performance of the specific wind farms and conceptual designs. With regard to the offshore concepts, the study has focused on exploring the variations of the concepts rather than making a detailed ranking of different concepts.

2 LCA methodology

A Life Cycle Assessment (LCA) is a process that evaluates the environmental burdens associated with a product system or activity. This is done by identifying and describing the energy and material uses and releases into the environment. An LCA includes the entire life cycle of the product, from raw material extraction, through materials processing, use and disposal at the end of the product's life (from "cradle to grave"). All transportation steps involved are also considered. An LCA assesses the environmental impacts of the system in the areas of ecological systems, human health and resource depletion. It does not address economic or social effects. It gives a holistic approach to environmental aspects of products, thus helping producers and customers to understand more about the environmental problems which may be associated with a product. A short summary of the main applications for LCAs is given below:

- Knowledge development
 - What are the most important environmental problems and where in the life cycle do these arise?
 - What happens to our environmental profile if we make changes in our production process?
- Decision support
 - Where are the most effective areas for us to target resources (personnel, technology and education) to improve our performance?
 - What sort of product/marketing profile do we want?
 - Which materials and suppliers should we use?
- Information exchange/ communication
 - Information for employees (internal stakeholders), education as well as key environmental data (EPIs) and environmental product information (EPDs).
 - Communication of the effects of a company's environmental improvement efforts to authorities, neighbours, financial institutions and external stakeholders (EPIs).

The functional unit for the analyses in this study has been 1 kWh electricity generated and fed to the grid onshore. Thus, the GHG emissions and energy performance presented in this paper correspond to the generation of 1 kWh of wind power delivered to the grid onshore. The system boundaries include all the relevant life cycle stages, e.g. production of raw materials, transport, installation and decommissioning etc. This is in line with the Product Category Rules for electricity generation, in accordance with the International EPD System (The International EPD System 2011). Grid losses through cables from offshore to onshore have not been included.

Backup power necessary to provide a continuous electricity supply is excluded from the analyses. Thus, when comparing these results with other "stand-alone" technologies (e.g. hydro power with reservoir), it is important to be aware of the need for backup system in order to deliver a continuous electricity supply.

2.1 Analysed environmental indicators

An LCA can calculate different emissions and environmental impact categories. This study presents the environmental indicators, GHG emissions and energy performance, as described in the following sections

2.1.1 GHG emissions

The GHG emissions have been calculated as Global Warming Potential (GWP). GWP expresses the ability of a GHG to trap heat in the atmosphere relative to an equal amount of carbon dioxide. To compare GHG emissions from different sources, the gases are indexed according to their global warming potential (GWP) per unit of mass. According to the Intergovernmental Panel on Climate Change (IPCC), carbon dioxide (CO₂) assumes the value of 1 over a 100-year timespan. Other GHG emissions of importance are methane (CH₄) and nitrous oxide (N₂O) which, according to a re-evaluation of the IPCC in 2007, take a value of 25 and 298, respectively. GHG emissions can potentially cause effects such as increased temperature in the lower atmosphere, climate changes and raised sea level.

2.1.2 Energy performance

The main objective of an energy indicator is to give information regarding the energy efficiency relating to a delivered energy product. Several energy indicators exist today. In this study, two of the most common energy indicators for renewable electricity generation have been calculated: Energy Payback Ratio (EPR) and Energy Payback Time (EPT). A short description of these indicators is given below.

Energy Payback Ratio (EPR) expresses the amount of delivered energy during the power plant's lifetime, per energy unit invested in infrastructure and extraction/transport processes. It should be noted that the literature uses various different expressions for the EPR indicator. Examples of these are 'energy ratio', 'external energy ratio' and 'energy return on investment (EROI)', all of which refer to the same basic calculation as EPR (Gagnon 2008). In accordance with (Hall 2011), the EPR indicator refers to the amount of energy returned from one unit of energy invested in an energy-producing activity. A high EPR value means high energy efficiency. The energy in the fuel used in thermal power plants (embedded energy) is not included as invested energy in EPR calculations, thus making comparisons difficult between thermal and non-thermal electricity technologies.

Energy Payback Time (EPT) expresses the amount of time in months or years, taken to "pay back" the energy invested in infrastructure and extraction/transport processes. A low EPT value means high energy efficiency. As in calculations for EPR, embedded energy is not included as invested energy in the calculation of EPT.

EPR represents a good energy indicator for assessing whether a wind turbine actually produces more energy than it consumes during its life cycle. EPT, on the other hand, measures the amount of electricity-producing months or years, which are required in order to pay back the energy invested in the wind power plant. It should be emphasised that EPR is dependent on the lifetime assumed for the power plant while EPT is independent of this parameter. The relationship between the parameters is expressed using the following equation:

$$\text{EPR} = \text{Lifetime} / \text{EPT} \tag{1}$$

(H.L. Raadal et al. 2012) present a detailed investigation and discussion of different energy indicators for electricity generation.

3 LCA of existing onshore wind power

This section describes the main assumptions and results of the Life Cycle Assessments of two Norwegian onshore wind farms.

3.1 Description of the wind farms and data basis

3.1.1 Kjøllefjord (Statkraft) wind farm

The Kjøllefjord wind farm was established in 2006 with a total installed capacity of 39.1 MW. It consists of 17 turbines, each with a power rate of 2.3 MW. The average annual electricity production is about 116 GWh and the capacity factor is 34%. The wind farm is located in Lebesby municipality east of North Cape (Nordkapp), along the Finnmark coast.



Figure 1: Kjøllefjord wind farm (Statkraft 2012).

3.1.2 Fjeldskår (Agder Energi Produksjon) wind farm

The Fjeldskår wind farm was established in 1998 as the first Norwegian wind farm. The total installed capacity is 3.75 MW. It consists of 5 turbines, each with a power rate of 0.75 MW. The average annual electricity production is about 8 GWh (Agder Energi Produksjon 2012) and the capacity is 24%. The wind farm is located in Lindesnes municipality at the south of Norway.



Figure 2: Fjeldskår wind farm (Agder Energi Produksjon 2012).

3.1.3 Data collection

The data have been collected by the energy companies (Statkraft and Agder Energi Produksjon, respectively) by filling out specific addressed forms regarding materials, transports, etc., as well as the electricity generated by the wind farms.

The wind farms are assumed to have a 20 years life time. The functional unit for the analyses is 1 kWh electricity generated and fed to the grid. The system boundaries includes all relevant life cycle stages, e.g. production of raw materials, transport, installation and decommissioning etc., in line with the Product Category Rules for electricity generation in accordance with the International EPD System (The International EPD System 2011). All main data and assumptions for analysing the onshore wind farms are presented in Appendix 1.

3.2 Results GHG emissions onshore wind power

The LCA GHG emissions results for the main scenarios for the two wind farms are presented in Figure 3. The GHG emissions are separated into different life cycle stages/main components in order to show the contribution from the different stages/main components.

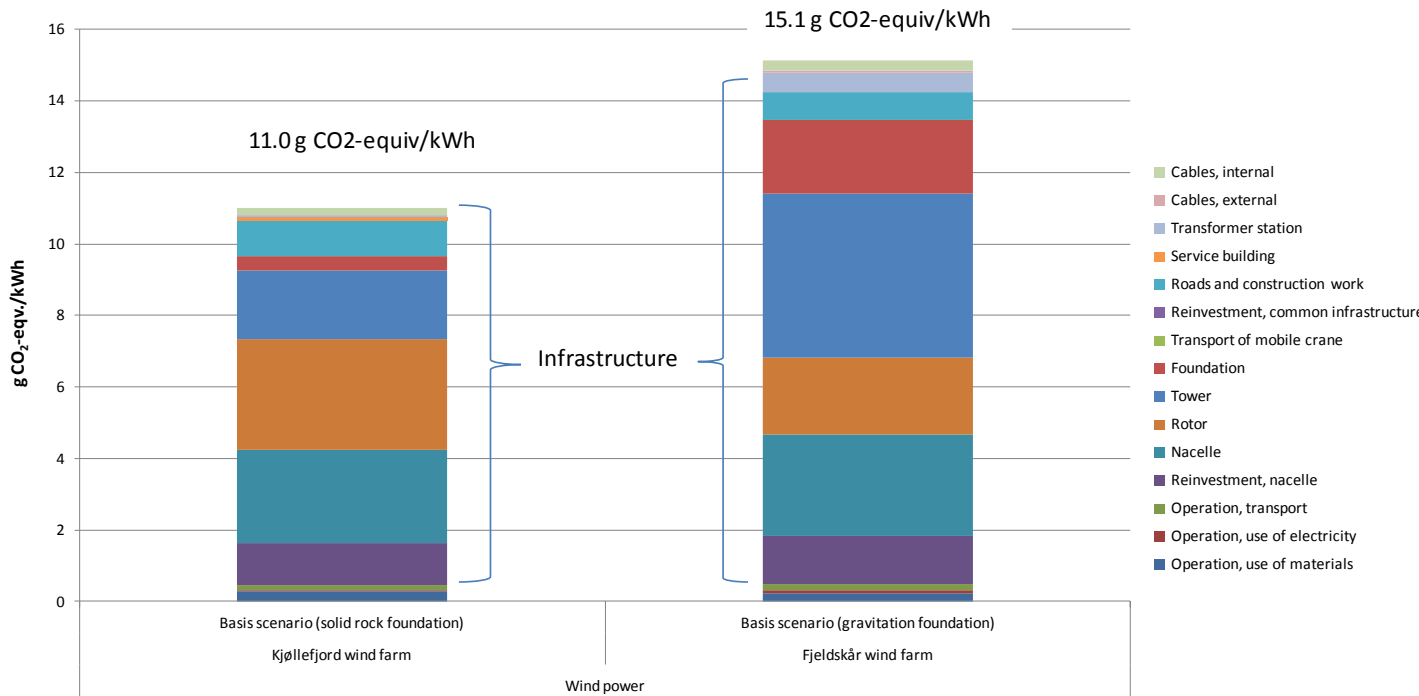


Figure 3: GHG emissions for the main scenarios for Kjøllefjord and Fjeldskår wind farms separated into the different life cycle stages/main components.

The figure shows that the total GHG emissions for wind power generation from Kjøllefjord and Fjeldskår are 11.0 and 15.1 g CO₂-equivalents/kWh, respectively. Thus, the wind farm with the largest turbines gives the lowest GHG emissions. This is in line with results from similar studies (Hanne Lerche Raadal et al. 2011). The figure also clearly shows that the infrastructure stage (production of the equipment and components, as well as roads and construction work) represents the major contribution to the total GHG emissions, accounting for about 80% and 72% of the total GHG emissions from Kjøllefjord and Fjeldskår wind farms, respectively. As these turbine components mainly consist of steel, this steel production activity is the main contributor to the overall GHG emissions from wind power generation, which also support the results from (Hanne Lerche Raadal et al. 2011). The operation activities contribute to less than 1 g CO₂-equivalents/kWh.

In order to analyse the impact of the electricity mix used for steel production (being the major contributor to the overall GHG emissions), scenarios have been calculated for each of the wind farms. The main scenarios include European average electricity consumption mix (Swiss Centre for Life cycle inventories 2011, 'Electricity, medium voltage, production UCTE, at grid/UCTE U') for the steel production. In addition, two scenarios have been constructed in order to analyse a representative 'worst case' (represented by (Electricity, medium voltage, production CENTREL, at grid/CENTREL U) (Swiss Centre for Life cycle inventories 2011) and 'best case' (hydroelectricity (Hydroelectricity, Energy intensive industry, high voltage, at grid/S) (M. Vold et al. 1998). In addition, Statkraft wanted to analyse the impact of a gravitation foundation compared with the base case's solid rock foundation. The results from these scenarios are presented together with the base cases in Figure 4.

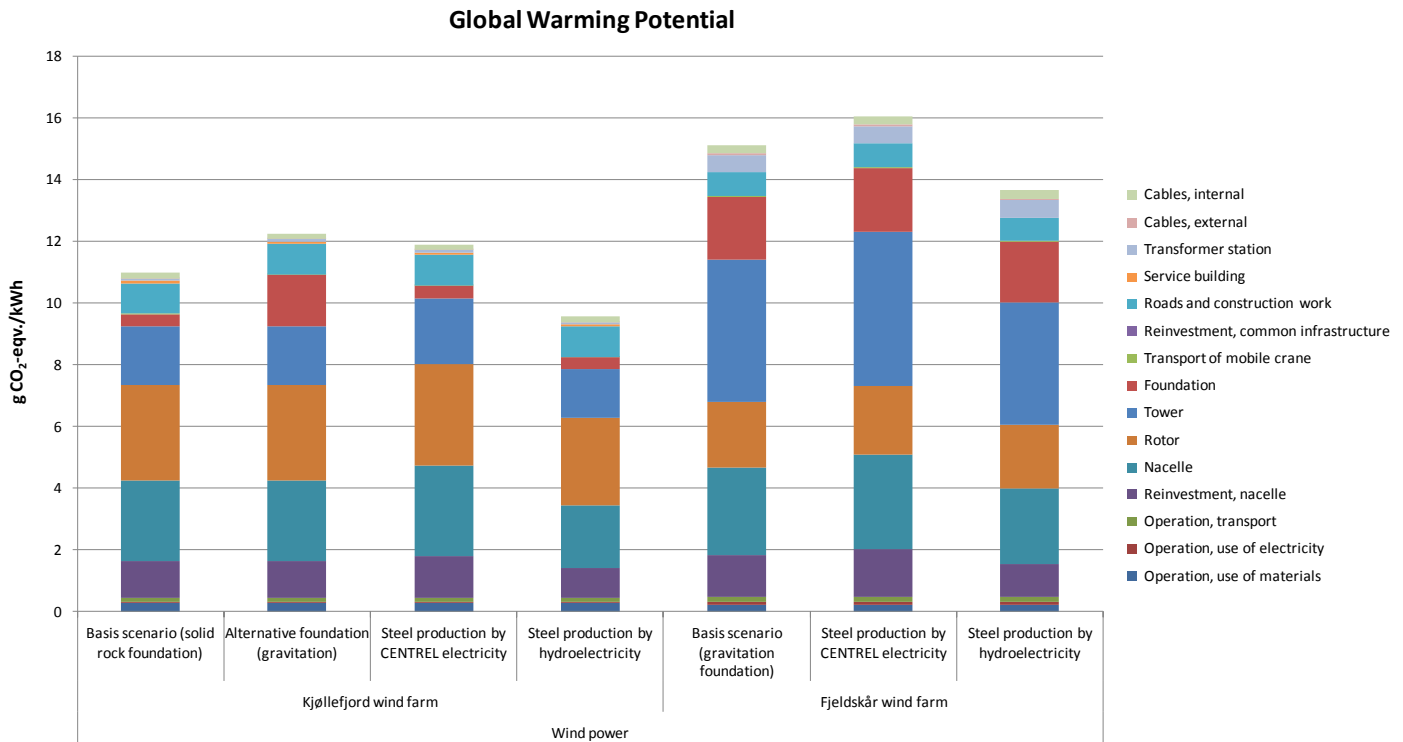


Figure 4: GHG emissions for additional scenarios compared to the basic scenarios for Kjøllefjord and Fjeldskår wind farms.

As seen in the figure, the change of electricity mix for steel production affects the results for the production of the main components nacelle, rotor and tower. However, the changes do not radically impact the results. Changing the mix to CENTREL electricity mix causes an emissions increase of 8% and 6% for Kjøllefjord and Fjeldskår, respectively, while changing to hydroelectricity causes an emissions reduction of 13% and 10%, respectively. Thus, the steel production itself seems to be of greater importance for the total GHG emissions arising from steel production than the applied electricity mix.

3.3 Results energy performance onshore wind power

The energy indicators EPR (Energy Payback Ratio) and EPT (Energy Payback Time) for the investigated offshore concepts are presented in the next sections. A short introduction of the investigated energy indicators (EPR and EPT) is given in section 2.1.2.

3.3.1 Energy Payback Ratio (EPR)

The Energy Payback Ratios (EPR) for the onshore wind farms and scenarios are shown in Figure 5.

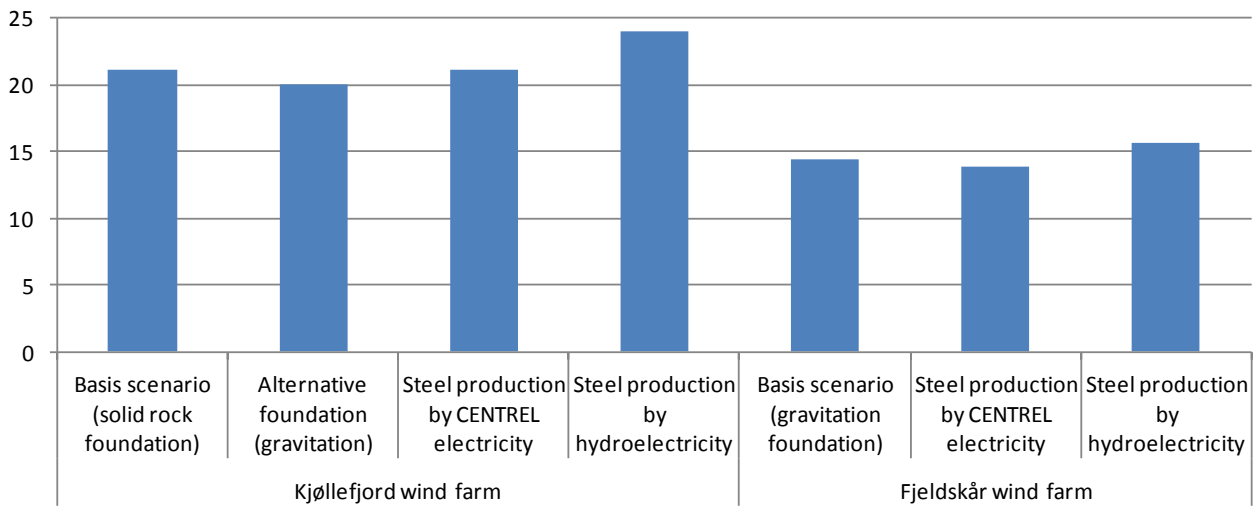


Figure 5: Energy Payback Ratio for the different Kjøllefjord and Fjeldskår wind farms scenarios.

As seen from the figure, the Kjøllefjord wind farm case achieves the best EPR values, varying between 20 and 24, while Fjeldskår achieves EPR values around 15. The EPR values for the two basic scenarios are 21 and 14 for Kjøllefjord and Fjeldskår, respectively. Thus, for every unit invested energy, the payback is 21 and 14.

3.3.2 Energy Payback Time (EPT)

The Energy Payback Times (EPT) for the onshore wind farms and scenarios are shown in Figure 6.

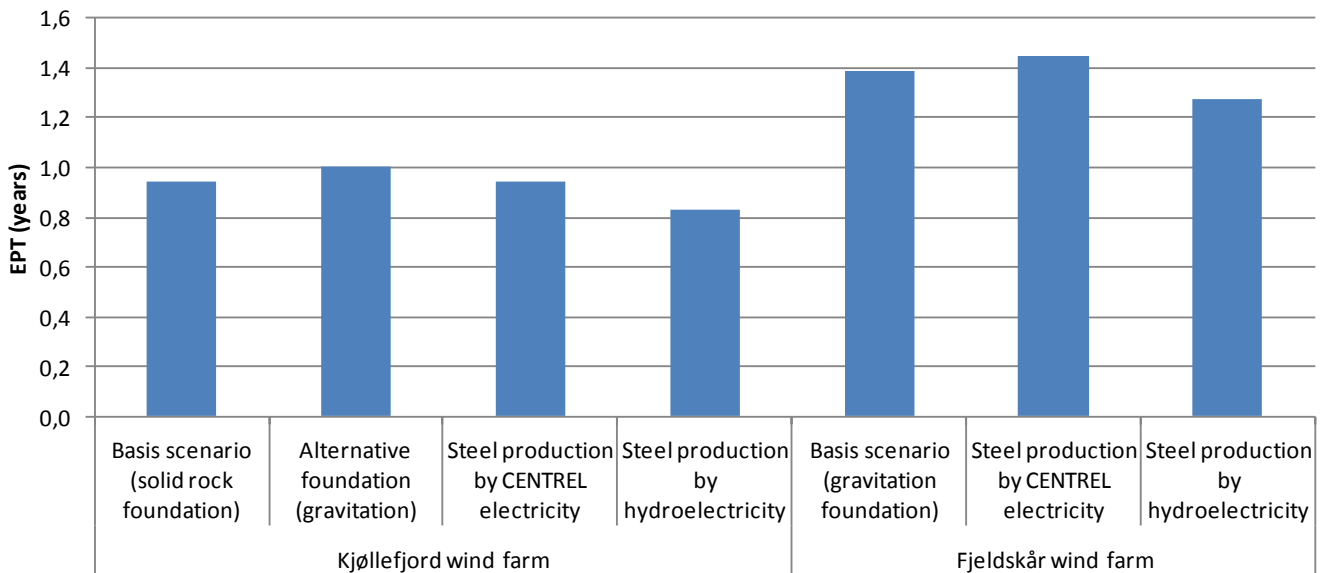


Figure 6: Energy Payback Time (years) for the Kjøllefjord and Fjeldskår wind farms scenarios.

As seen in with Figure 6, and in accordance with the EPR results, the Kjøllefjord base case achieves the best payback time (0.9 years), while the energy invested in Fjeldskår base case will be paid back in about 1.4 years.

4 LCA of different offshore wind power concepts

4.1 Description of the offshore concepts and data basis

The following six offshore wind turbine concepts have been analysed, representing five floating and one bottom-fixed concept:

| Concept | Name | General description | Reference |
|--------------|---------------|---|----------------------------------|
| Floating | SWAY | Tension-Leg-Spar (TLS) similar to the SWAY concept | (Borgen 2010) |
| | UMaine Semi-S | UMaine Semi-Submersible | (Robertson & J. M. Jonkman 2011) |
| | UMaine Spar | UMaine Spar-Buoy (same as OC3-Hywind, at water depth of 200m) | |
| | UMaine TLP | Tension-Leg-Platform with vertical tendons | |
| | | MIT TLB | MIT Tension-Leg-Buoy (TLB), |
| Bottom-fixed | OC4 Jacket | IEA OC4 Jacket | (Fabian Vorpahl et al. 2011) |

Table 1: Short description of the analysed concepts

All concepts use the NREL 5 MW offshore reference wind turbine Rotor-Nacelle-Assembly (RNA), based on (J. Jonkman et al. 2009). The hub height is 90 m and the rotor diameter is 126 m. The water depth is 200 m for the floating concepts and 50 m for the bottom-fixed concept. The wind farm (bottom-fixed or floating) is assumed to be located 200 km off the British Coast, at Doggerbank (independent of the real water depth), and consists of 100 wind turbines installed in a square layout (10*10 turbines). The different concepts are illustrated in Figure 7.

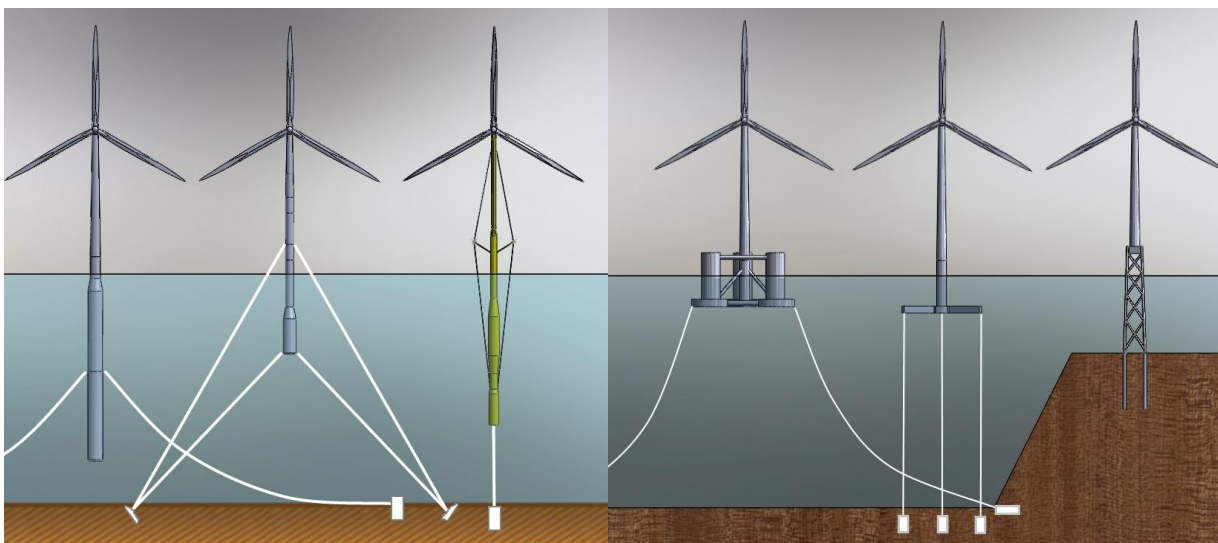


Figure 7: Illustration of the concepts, from left to right; UMaine Spar, MIT TLB, SWAY, UMaine Semi-Sub, UMaine TLP and OC4 Jacket.

The Sway Tension-Leg Spar (TLS) is a single spar with excess buoyancy, one vertical tendon and a downwind turbine. The tower structure utilises external axial stiffening rods. More information can be found in (Borgen 2010).

The UMaine Semi-Submersible concept was developed in the DeepCwind project at the University of Maine. The concept consists of a generic semisubmersible platform with the tower on a central column and three larger offset vertical columns connected by slender pontoons. The column stabilised platform has an overall draft of 20 m and utilises a catenary mooring system, water ballast and heave damper plates (Robertson & J. M. Jonkman 2011).

In the IEA OC3 project, the OC3-HYWIND was defined and made available to the research communities (J. M. Jonkman et al. 2010). The UMaine spar buoy is essentially the same, but applied at a water depth of 200 meters with a mooring system designed for that depth. The OC3-HYWIND was again largely based on the HYWIND concept developed by Statoil and combined with an adapted version of the NREL 5 MW tower and turbine. The spar buoy relies on ballast stabilisation, deep draft and a catenary mooring system with crow-foot delta connections.

A small and relatively low mass TLP system is represented by the UMaine TLP consisting of a ballasted cylindrical platform with three horizontally extended legs, supporting the vertical tethering tendons, from its base. The concept relies on excess buoyancy to ensure taut tendons as in both the Sway TLS concept and MIT TLB.

The MIT TLB is a hybrid platform based on the same concept as Sway TLS but with a different solution for the mooring system. Two sets of inclined mooring lines are attached at two heights. One set of mooring lines has crow-foot deltas to control the yaw motions of the platform. All platform degrees-of-freedom are thereby stiffness-controlled, and all eigen periods are below the energetic part of the wave spectrum (Sclavounos et al. 2010)

The OC4 Jacket is a space-frame installed at 50 m depth. The transition piece connecting the platform and the tower is made of concrete. The structure was designed for the IEA OC4 project (W. Popko et al. 2012)

The default wind farm is assumed to have a 20 years lifetime and a capacity factor of 46 %. The Capacity Factor (CF) expresses the actual annual electricity generation divided by the maximum possible annual electricity generation (operating at full power). It is expressed as a fraction, or a percentage. The functional unit for the analyses in this study has been 1 kWh electricity generated and fed to the grid onshore. Thus, the GHG emissions and energy performance presented in this paper correspond to the generation of 1 kWh of wind power delivered to the grid onshore. The system boundaries include all the relevant life cycle stages, e.g. production of raw materials, transport, installation and decommissioning etc. This is in line with the Product Category Rules for electricity generation, in accordance with the International EPD System (The International EPD System 2011). Grid losses through cables from offshore to onshore have not been included.

The wind farms consist of 100 wind turbines installed in a square layout (10*10 turbines), as shown in Figure 8, and located 200 km off the British Coast, at Dogger Bank. To put this in perspective, such a fictive wind park will have an installed capacity of 500 MW, representing 5.5 % of the targeted wind power

capacity at Dogger Bank¹. The water depth is 200 m for the floating concepts and 50 m for the bottom-fixed concept.

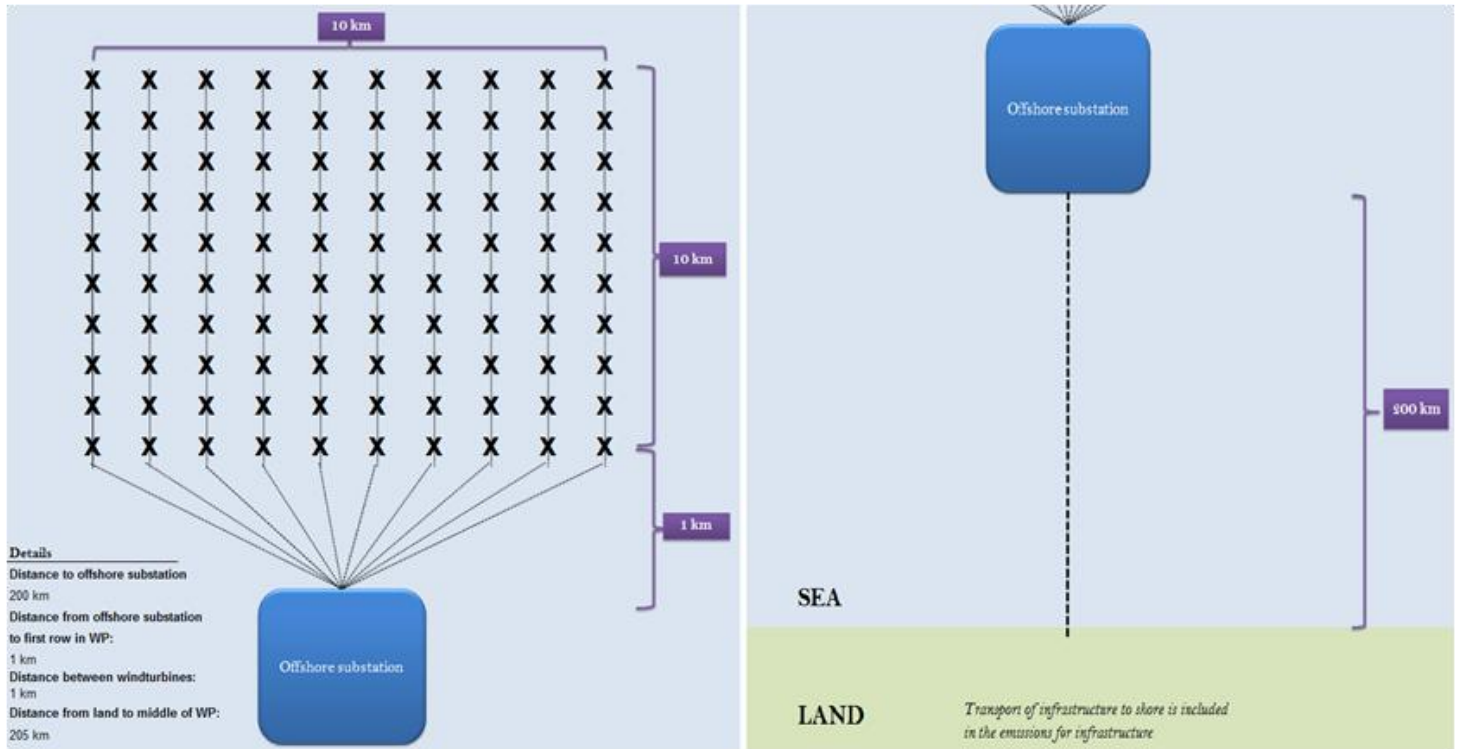


Figure 8: Principles for the theoretical constructed wind parks with regard to turbine formation and distances from shore.

As described in section 4.1, the same NREL 5MW offshore reference wind turbine (J. Jonkman et al. 2009) is used for all the six offshore concepts. The data have, however, been modified by starting from +10 m with a diameter of 6.5 meters and wall thickness of 0.027 meters. The material composition is interpolated with respect to the material mass relationship for a Vestas V82-1.65 MW turbine (Vestas Wind System A/S 2006a). From (Tveten 2009) a material mass relationship between rotor, nacelle and tower structure has been found and applied for calculating the specific infrastructure data for rotor and nacelle, as well as for the tower. Material and masses for the adjusted NREL 5 MW turbine are shown in Table 2.

¹ The consortium Forewind has received the rights to develop offshore wind farms on the Dogger Bank. The consortium consists of Statoil, Statkraft, Scottish and Southern Energy plc (SSE) and RWE npower. Forewind has agreed a target to develop 9 GW of Doggerbank, while the upper potential is estimated at 13 GW (<http://www.statkraft.no/presesenter/pressemeldinger/2010/tildelt-havvindsone-doggerbank-i-storbritannia.aspx>).

| Turbine NREL 5 MW (all values in tons per WT) | Rotor (hub and blades) | Nacelle | Tower structure | Sum |
|---|------------------------|------------|-----------------|------------|
| Steel | 60 | 197 | 233 | 489 |
| Aluminium | | 8 | 5 | 13 |
| Electronics | | | 4 | 4 |
| Plastic | | | 4 | 4 |
| Copper | | 32 | 2 | 35 |
| Oil | | | 2 | 2 |
| Glass reinforced plastic | 50 | 2 | | 53 |
| Sum | 110 | 240 | 250 | 599 |

Table 2: Materials and masses for the adjusted NREL 5 MW turbine.

Since the Rotor-Nacelle-Assembly (RNA) is the same for all the concepts, the major differences between the concepts remain with the platforms/foundation. * *Increased tower mass due to upper mooring line tethering system.*

Table 3 shows the steel and concrete masses for the investigated foundation/platforms (including the platform +10 meter and down). The steel processing (hot rolling) is included.

| Foundation/platforms, anchor and mooring cables (tons per WT) | Steel | | | | Concrete | | | |
|---|---------------------|---------|---------------------|----------------|--------------|------------|---------|----------------|
| | Platform | | Anchor | Mooring cables | Total steel | Platform | | Total concrete |
| | (standard offshore) | (rebar) | (standard offshore) | | | (standard) | (grout) | |
| OC4-Jacket | 539 | 67 | 153 | | 759 | 59 | 66 | 126 |
| SWAY | 1 050 | | 188 | 20 | 1 258 | | | |
| Umaine Semi-S | 3 000 | 2 | 45 | 294 | 3 341 | 205 | | 205 |
| Umaine Spar | 1 600 | 1 | 60 | 204 | 1 865 | 143 | | 143 |
| Umaine TLP | 525 | | 354 | 60 | 939 | | | |
| MIT TLB* | 400 | 25 | 121 | | 546 | | | |

* *Increased tower mass due to upper mooring line tethering system.*

Table 3: Materials and masses for the different foundation/platform concepts ((Borgen 2010), (Robertson & J. M. Jonkman 2011), (Sclavounos et al. 2010) and (Fabian Vorpahl et al. 2011)).

Installation and decommissioning operations for the floating concepts have been assumed to follow equal procedures, based on data from (Sanden & B. I. Vold 2010), (Myhr 2012), (Reitan 2012) and (Stuart 2012). As a simplification, the run of the installation of the floating concepts has been assumed to be equal and consisting of towing, stabilising and installing activities. For the bottom-fixed concept the data have been based on (Sanden & B. I. Vold 2010), (Myhr 2012) and (Nielsen 2012). The run of the installation of the bottom-fixed platform includes transport and installation. In order to simplify, the operational time for installing the bottom-fixed and floating wind turbine concepts has been set equal. The bottom-fixed operational window is, however, assumed to be 65 % which is 5 % higher than for the floating concept, due to more complex operations. Maintenance is assumed equal for all the concepts and is based on data from Sanden and Vold (Sanden & B. I. Vold 2010). More details are given in Appendix 2.

The impact from the vessels used for installing, decommissioning and maintenance operations for the wind farms is based on fuel consumption for an estimated number of operating days. Thus, the emissions related to the production and relocation of these vessels have been excluded. However, the operating days represent a relatively small fraction of the vessel's total lifetime which means that the operating days' share of the total production emissions is insignificant.

The GHG emissions results are separated into the life cycle stages as shown in Table 4.

| Life cycle stage | Description |
|--|---|
| Installation (fuel) | Fuel consumption related to the transportation of all the equipment from shore to offshore site in order to install the wind farm. |
| Turbine materials | Production, processing and transport of all the infrastructure material related to the turbine production. Disposal of materials is also included (credits from material to recycling are not included). |
| Platform materials | Production, processing and transport of all the infrastructure material related the platform production, including production of internal and external (from offshore to shore) cables. Disposal of materials is also included (credits from material to recycling are not included). |
| Maintenance (fuel) | Fuel consumption related to the transportation from shore to offshore site due to maintenance. |
| Maintenance (infrastructure/ reinvestment) | Production, processing and transport of all the material used for maintenance during the lifetime of the wind farm. The reinvestments needed are given annually and multiplied with the lifetime. Disposal of materials used for maintenance is included in this life stage. |
| Maintenance (others) | Production, processing and transport of support materials used for maintenance (oil, cotton etc.) and treatment of waste. |
| Decommissioning (fuel) | Fuel consumed for decommissioning the wind farm. For simplification the decommissioning is assumed equal to the installation (fuel) and operation (reversed). Disposal of materials is included in the life cycle stages Turbine and platform materials, respectively. |

Table 4: Short description of the life cycle stages being included in the analyses.

Appendix 2 gives a detailed description of the required initial infrastructure for the different offshore concepts and material specifications, as well as information about the fleet, boats and vessels used for installing, maintaining and decommissioning the wind parks.

4.2 Results LCA GHG emissions offshore wind power concepts

Figure 9 shows the resulting GHG emissions (grams CO₂-equivalents/kWh) for the investigated offshore wind farm concepts in relation to the life cycle stages described in Table 4.

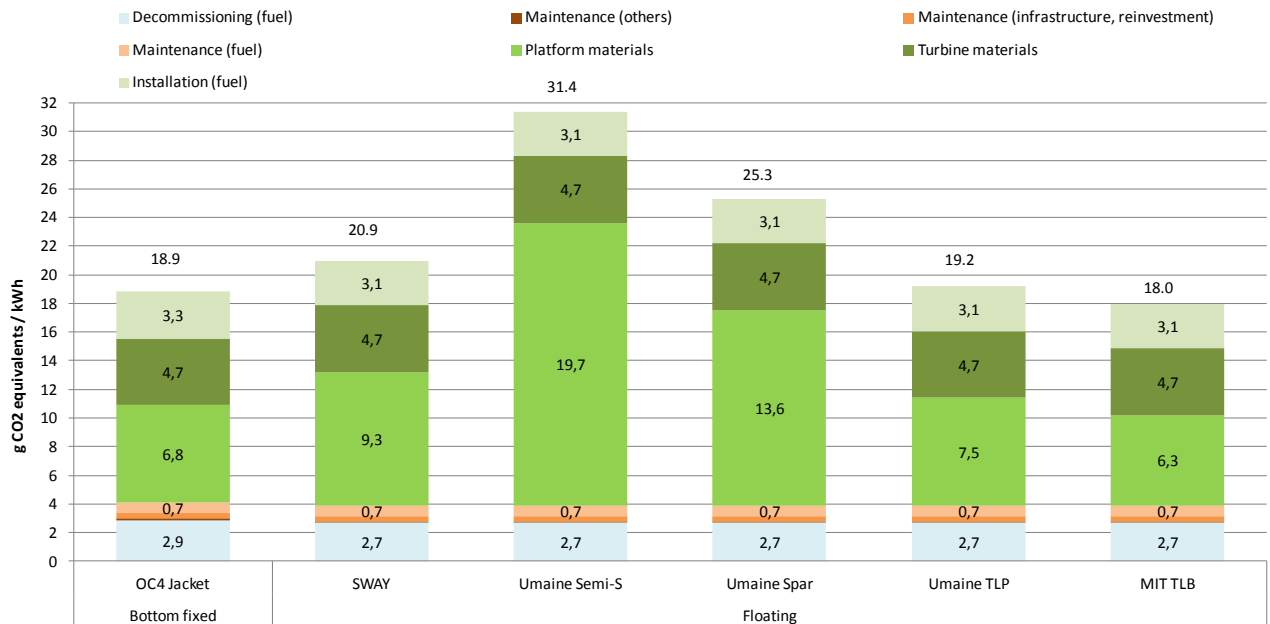


Figure 9: GHG emissions (g CO₂ -equivalents/kWh) for the investigated offshore wind park concepts related to the different life cycle stages.

As seen from the figure, the total GHG emissions from the investigated offshore concepts vary between 18.0 (MIT TLB) and 31.4 (Umaine Semi-S) g CO₂-equivalents/kWh, a difference which represents a 75% increase in relation to the MIT TLB concept (representing the lowest GHG emissions).

Further, the figure clearly shows that the turbine and foundation/platform materials contribute most to the overall GHG emissions. The platform contribution varies between 6.3 (MIT TLB) and 19.7 (Umaine Semi-S) g CO₂-equivalents/kWh, corresponding to 35% and 63% of the total GHG emissions from each installation, respectively. The variations between the concepts are placed in this category, since the tower and RNA are identical. The different platform concepts are further analysed in order to investigate the most important parameters affecting these GHG emissions. This is presented in Figure 10.

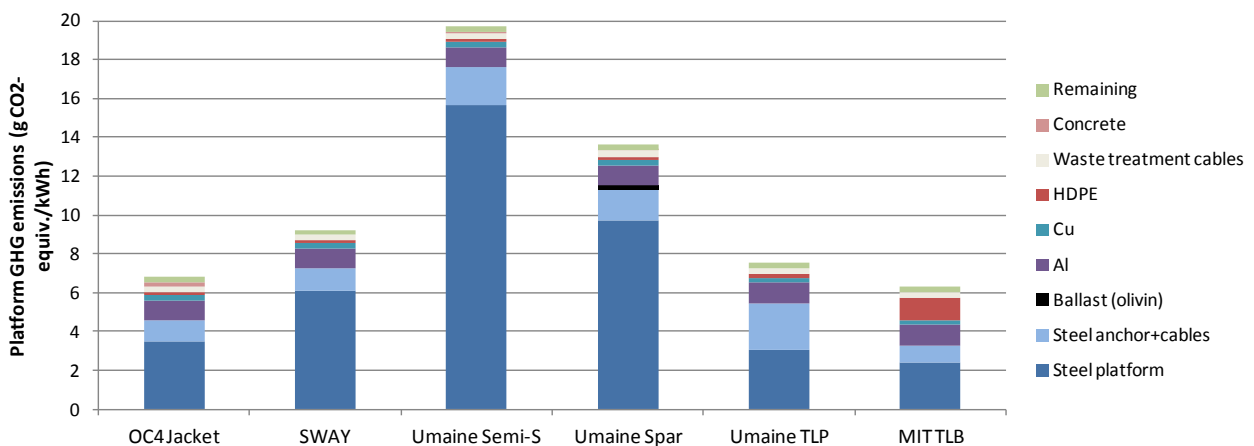


Figure 10: Platform GHG emissions separated into the main contributors.

As seen from Figure 10 the main contributor to the overall platform GHG emissions for all the concepts is steel production (separated into steel related to the platform and anchor/cables, respectively). The steel production activity contributes to 50% to 89% of overall platform GHG emissions, depending on the concept. Generally, apart from the MIT TLB, the second largest platform contributor is the production of aluminium in connection with internal and external cables. Overall contribution from external cables is 1.95 g CO₂-equivalents/kWh.

As shown in Figure 10, the GHG emissions relating to the turbine materials (assumed to be equal for all the concepts) are 4.7 g CO₂-equivalents/kWh, thus contributing to a range between 15% (Umaine Semi-S) and 26% (MIT TLB) of the total GHG emissions. The main parameters affecting the turbine GHG emissions are presented in Figure 11.

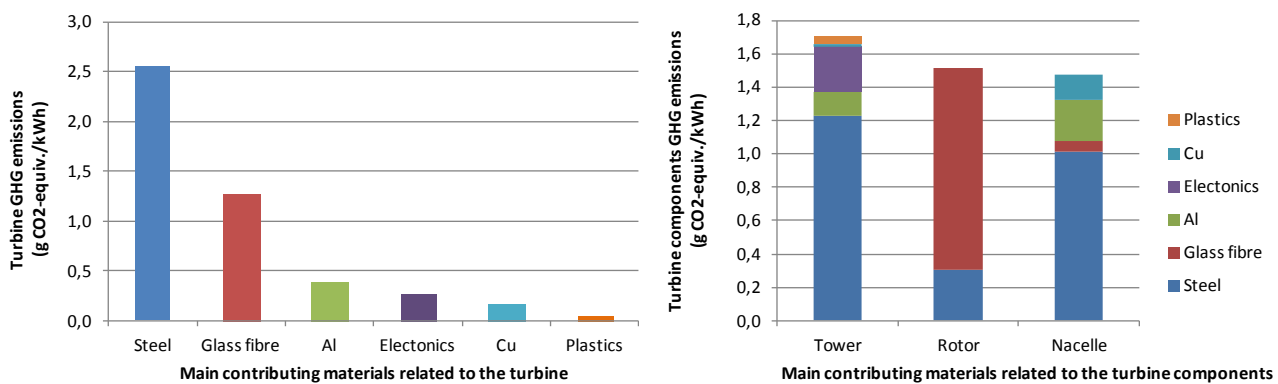


Figure 11: Turbine GHG emissions separated into the main contributors.

The figure clearly shows that the main materials affecting the turbine GHG emissions are steel and glass fibre, contributing to 55% and 27%, respectively. In addition, it can be seen that the main components of the turbine (tower, rotor and nacelle) contribute about one third each to the total turbine GHG emissions.

From Figure 9 it can also be seen that the installation and decommissioning life cycle activities contribute respectively 6.2 and 5.8 g CO₂-equivalents/kWh for the bottom fixed and floating concepts. This represents a range varying from 18% to 33% of total GHG emissions relating to each installation.

4.3 Results energy performance offshore wind power concepts

The energy indicators EPR (Energy Payback Ratio) and EPT (Energy Payback Time), as defined in section 2.1.2, are presented in Figure 12. The greater the EPR indicator value, the better the energy performance, while the opposite applies in the case of EPT (the smaller the value the better the performance).

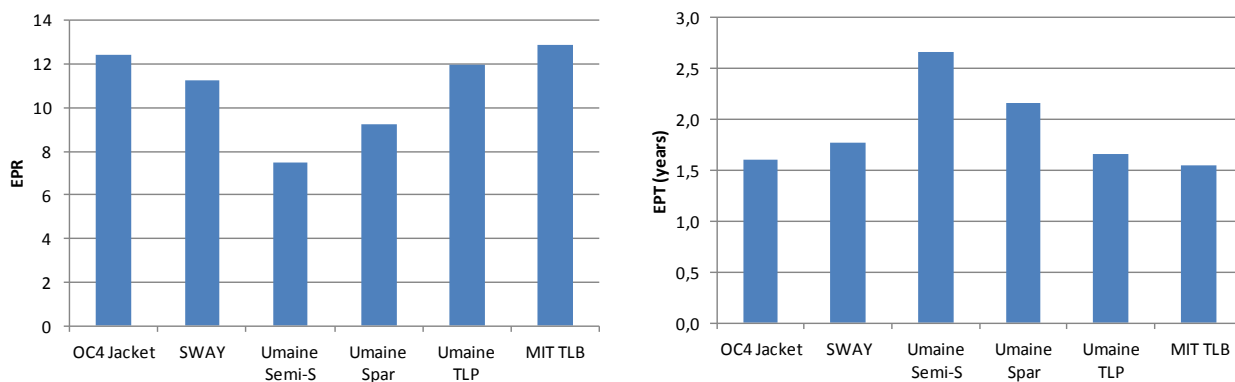


Figure 12: Energy Payback Ratio (EPR) and Energy Payback Time (EPT) for the different offshore concepts.

The figure shows that the investigated concepts achieve EPR and EPT values of between 7.5 and 13, and 1.5 and 2.7 years, respectively. The MIT TLB and OC4 Jacket give the best performance, being in line with the results for GHG emissions. This is to be expected since the use of conventional energy within an analysed system generally represents the main contributor to GHG emissions.

5 Conclusions

The study documents LCA GHG emissions and energy performance for two Norwegian onshore wind farms (Kjøllefjord and Fjeldskår) and 6 offshore wind power conceptual designs.

Onshore wind power

The LCA GHG emissions from the onshore wind power farms Kjøllefjord and Fjeldskår are 11.0 and 15.1 g CO₂-equivalents/kWh, respectively. Thus, the wind farm with the largest turbines gives the lowest GHG emissions, which is in line with results from similar studies (Hanne Lerche Raadal et al. 2011). The turbine components (nacelle, rotor and tower) are the main GHG emissions contributors representing about 80% and 72% of the total GHG emissions from Kjøllefjord and Fjeldskår wind farms, respectively. As these turbine components mainly consist of steel, this steel production activity is the main contributor to the overall GHG emissions.

In order to analyse the impact of the electricity mix used for steel production, two scenarios representing 'GHG low' and 'GHG high' electricity mix for steel production have been calculated. The results show these radical changes of the electricity mix do not radically impact the GHG emissions results. Thus, the steel production itself seems to be of greater importance for the total GHG emissions arising from the production than the applied electricity mix.

The Energy Payback Ratio (EPR) is 21 and 14 for Kjøllefjord and Fjeldskår wind farms, respectively. Thus, for every unit invested energy the respective payback energy is 21 and 14. The respective Energy Payback Time (EPT) indicators are 0.9 and 1.4 years for Kjøllefjord and Fjeldskår wind farms.

Offshore wind power

The investigated offshore conceptual designs all result in higher LCA GHG emissions and lower energy performance compared with the results from the onshore wind farms. The GHG emissions vary between 18.0 and 31.4 g CO₂-equivalents/kWh, a difference representing 77% increase compared to the lowest GHG emissions (MIT TLB). The foundation/platform materials contribute the most to the overall GHG emissions (varying from 35% to 63% of the total GHG emissions). The variations between the concepts are placed in this category, since the tower and RNA are identical. Thus, one major conclusion from this study is that specific platform/foundation steel masses are important for the overall GHG emissions relating to offshore wind power. The second largest contribution to GHG emissions (varying from 18% to 33% of the total GHG emissions) comes from the installation and decommissioning activities.

The investigated concepts achieve EPR and EPT values between 7.5 and 13 and 1.5 and 2.7 years, respectively. The Umaine Semi-S and Spar concepts result in the worst energy performance, while the MIT TLP and OC4 Jacket give the best performance, which is in line with the GHG emissions result. This would be expected since the use of conventional energy within an analysed system generally represents the main contributor to GHG emissions from the same system.

It is significant for the further development of offshore wind turbines that there is an increased understanding of the parameters and activities which have the greatest impact on the overall GHG emissions and energy performance of wind power. This may be affected both by the various different platform concepts and by varying locations and weather conditions. Some platform concepts, for example, can handle larger turbines without increasing the platform sizes, while others have to be scaled up. In

addition, some concepts may be more suitable for rough weather conditions than others. Further studies should focus on how such variations impact the resulting GHG emissions and energy performance.

For more detailed studies on installation procedures, variations between the different platform conceptual designs should be included. This would enable analysis of the way in which these variations impact the results. Some platforms can be assembled in port and towed out while other conceptual designs installation procedures have still to be fully developed and proven. Further studies should focus on these aspects. In addition, more specific data regarding maintenance and reinvestment rates should be included when they are available.

Lastly, it should be emphasised that GHG emissions and energy performance represent only two environmental indicators. With regard to decision making and guiding policy, several other environmental indicators need to be taken into consideration. These include land use, visual aspects, biodiversity and noise. This is particularly relevant when comparing onshore and offshore turbines.

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Appendix 2 Data collection and main assumptions offshore concepts

Anchors and ballast

Anchors and ballast for the different concepts are given in table A

| Anchors and ballast | | |
|------------------------|-------------------------------|---------|
| | Anchor | Ballast |
| OC4-Jacket | Monopiles | - |
| SWAY | Suction anchors | Water |
| Umaine Semi-Sub | Fluke anchor | Water |
| Umaine Spar | Fluke anchor | Olivine |
| Umaine TLP | Suction anchors | Water |
| MIT TLB | DPA (Deep Penetrating Anchor) | Water |

Table A: Anchor types and ballast material for the different conceptual designs.

The TLP suction anchor is extrapolated on the basis of the preliminary design of the anchor to the MIT TLB. The size of the anchor loads are based on simplified load assessments and cases. Secondary steel constructions, such as ladders, cable leads, bolts, flanges and personnel platforms are not included in the analyses.

Infrastructure materials

Low density concrete (2190 kg/m³) has been used as grout material (included in the bottom-fixed foundation), while a density of 2380 kg/m³ has been assumed for standard offshore concrete. The applied steel density is 7850 kg/m³ (the analyses do not adjust for bolts and flanges). Coatings are not included in infrastructure. For standard offshore steel and rebar steel, the Ecoinvent processes “Steel, converter, low-alloyed, at plant/RER U” and “Steel, low-alloyed, at plant/RER U” have been used, respectively (Swiss Centre for Life cycle inventories 2011). Table B specifies necessary infrastructure materials/elements for the offshore conceptual designs while the respective amounts, cable lengths etc. of the materials/elements are presented in Tables C and D.

| | Material | Amount | Reference |
|--|----------------------|---|---------------------------------------|
| Data relevant the floating concepts | | | |
| Anchoring cable (HDPE) • TLB | HDPE | 50 kg/ meter | (Tor Anders Nygaard 2012) |
| Anchoring cable (steel) • SWAY • Umaine Semi-S • Umaine Spar • Umaine TLP | Steel | 110,2 kg/ meter 113,4 kg/meter 145 kg/meter 116 kg/meter | (Robertson & J. M. Jonkman 2011) |
| Misc add-ons | Steel | 1 kg/kg misc add-ons | |
| Ballast (olivin) | Aggregate, coarse | 1 kg/ kg ballast (olivin) | |
| Data relevant for all the offshore concepts | | | |
| Anchor | Steel | 1 kg / kg anchor | |
| Internal cable | Project confidential | 19 ton / km internal cable | (Nexans 2010), (Kaiser & Snyder 2011) |
| External cable | Project confidential | 64 ton/km external vable | (Mathisen 2011) |

| | | | |
|-----------------------------|--|-------------------------------|---------------|
| Offshore substation* | 93,8 % steel, 6 % copper, 0,2% aluminium | 508,25 ton / 500 MVA offshore | (Tveten 2009) |
|-----------------------------|--|-------------------------------|---------------|

* Processing is included for steel, copper and aluminium.

Table B: Specification of necessary infrastructure materials/elements for the offshore concepts.

The offshore internal cables, which typically are three-phase 30-36 kV cables, have the function of connecting the turbines in collection circuits and feed the substation. The type and composition are given by (Nexans 2010). The weight of one internal cable for a circuit of 800 meter is 10-20 tons, which corresponds to 12.5 – 25 kg/m internal cable (Kaiser & Snyder 2011). On the basis of this, a mean value of 19 kg/meter internal cable has been used in the analyses.

The external cables (high voltage transmission cables) represent typically 100 and 220 kV and their function is to transmit the power from the offshore wind farm to shore. The offshore landing cable (145 kV) at Sheringham Shoal has been used as external cable and data is given as confidential data by (Mathisen 2011). Production of the cable material is included in the analyses.

The offshore substation steps up the voltage for the transmission to shore and/or converts the electricity from HVAC to HVDC. The transmission can be done by HVAC or HVDC. A HVDC transmission requires HVAC/HVDC converter stations both offshore and onshore. The high voltage (HV) is needed for long distance transmission in order to reduce the electricity losses. The required infrastructure for one 220 MVA offshore substation (Tveten 2009) has been up scaled in order to represent one 500 MVA offshore substation being able to support the 100 5 MW turbines. The substation is to located 200 km offshore.

Table C shows the specified amounts of anchoring/mooring cables, anchors, cables, ballast and others for the different offshore concepts, while Table D shows the specified lengths of internal and external cables, as well as the offshore substation.

| Needed material support for WP | | | | | |
|--------------------------------|--|---|------------------|-----------------------------|-------------------------|
| Wind Turbine (WTG) specific | Anchoring/mooring cables (steel) [per WTG] | Anchoring/mooring cables (HDPE) [per WTG] | Anchor [per WTG] | Ballast (olivine) [per WTG] | Misc. add-ons [per WTG] |
| OC4-Jacket | - | - | 153 ton | - | - |
| SWAY | 200 m | - | 188 ton | - | 50 ton |
| Semi | 2506 m | - | 45 ton | - | - |
| Spar | 1404 m | - | 60 ton | 4100 ton | - |
| TLP | 514 m | - | 354 ton | - | - |
| TLB | - | 1551 m | 121 ton | - | - |

Table C: Amounts of anchoring/mooring cables, anchors, ballast and others for the different offshore concepts.

| Needed material support for WP | | | |
|--------------------------------|--------------------------|--------------------------|---------------------------------|
| Wind Park (WP) specific | Internal cables [per WP] | External cables [per WP] | Offshore substation |
| OC4-Jacket | 117,9 km | 200,15 km | One 500 MVA offshore substation |
| SWAY | 118,1 km | | |
| Semi | | | |
| Spar | | | |
| TLP | | | |
| TLB | | | |

Table D: Cable lengths (internal and internal) for the different offshore concepts and size of offshore substation.

Fleet (boats and vessels)

This section provides information about the fleet (boats and vessels) which are assumed to be used for installing, maintaining and decommissioning the wind farms. The chosen fleet should be regarded as one possible fleet composition. It is also important to mention that this analysis is set up for one run of installation and that other runs of installations, most likely, will require other solutions. Table E gives information about the offshore fleet which is used in this analysis.

| Speed and fuel consumption on transport modes in use | | | | |
|---|------------|-------|-----------------|----------------------------|
| Installation and decommissioning - floating | | | | |
| | Fuel | Km/h | Ton/day | Reference |
| AHTS (Anchor Handling Tug Supply) – own transport | Bunker oil | 27,78 | 32,5 (25-40) | (Sanden & B. I. Vold 2010) |
| AHTS (Anchor Handling Tug Supply) – towing foundation | Bunker oil | 9,26 | 32,5 (25-40) | |
| AHTS (Anchor Handling Tug Supply) – whole WTGs | Bunker oil | 3,704 | 32,5 (25-40) | |
| PSV (Power Supply Vessel) | Bunker oil | 24,1 | 20 (15-25) | |
| Crane Vessel Saipem S7000 | Bunker oil | 18 | 48,7* (33-120) | (Stuart 2012) |
| Trenching ship | Bunker oil | | 12,4 (ton/km) | (Fløtre & Hauge 2003) |
| Installation and decommissioning – bottom-fixed | | | | |
| | | | Ton/day | Reference |
| Rebuilt Navion Savonita (FIV) | Bunker oil | | 51,75** (12-65) | (Nielsen 2012) |
| SealInstaller | Bunker oil | | 48,7*** | (Nielsen 2012) |
| Trenching ship | Bunker oil | | 12,4 (Ton/km) | (Fløtre & Hauge 2003) |
| Maintenance | | | | |
| | | Km/h | Kg/h | Reference |

| | | | | |
|--------------------------------------|------------|-----|-------|----------------------------------|
| Small boat | Diesel | 30 | 138,6 | (Sanden and Vold 2010) |
| Specialised vessel | Diesel | 48 | 268,6 | (Sanden and Vold 2010) |
| Crane vessel | Bunker oil | 18 | 1375 | (Reitan 2012) |
| Offshore helicopter Sikorsky S-76 | Jet A | 265 | 335 | (Sikorsky Helicopter 2007) |

* Adjusted for idle consumption and steaming offshore, see revised fuel consumption in Table F.

** Fuel consumption given by idle consumption at loading and full consumption in transit and operation offshore.

*** Set equal to S7000, assumption done by author and Myhr (2012).

Table E: Speed and fuel consumption for boats and vessels.

Revised fuel consumptions for installation

In order to take into consideration that the fuel consumption is dependent on the operating mode (idle/steam) of the vessels, mean values have been calculated based on data from (Stuart 2012) and (Nielsen 2012). The fuel consumption of Saipem 7000 (crane vessel used for the floating installations) has been assumed to equal the fuel consumption the SealnStaller, which is the crane vessel used for the bottom-fixed installation ((Myhr 2012) and the authors). The calculated mean values for the fuel consumptions are given in Table F.

| | Idle consumption (tons/day) | Full steam (tons/day) | Mean consumption (ton fuel/day) |
|--|--------------------------------|--------------------------|------------------------------------|
| Saipem 7000 (floating) | 33 | 120 | 48,7 |
| Rebuilt Navion Savonita FIV (bottom-fixed) | 12 | 65 | 51,7 |
| SealnStaller* (bootom-fixed) | | | 48,7* |

* The fuel consumption of Saipem 7000 has been assumed to equal the consumption of SealnStaller (the authors and (Myhr 2012).

Table F: Revised fuel consumption

Installation and decommissioning (fuel)

When calculating the acquired fleet, time and fuel consumption related to the installation of the wind parks, a combination of information from (Sanden & B. I. Vold 2010), (Myhr 2012), (Nielsen 2012), (Reitan 2012) and (Stuart 2012) has been used.

Installing the floating concepts

As a simplification, the run of the installations has been assumed to be equal for all the floating concepts. The run of the installation includes the following activities in this analysis:

- The foundations/platforms are towed to site by 3 Anchor Handling Tug Supplies (AHTS) , 200 km offshore
- Stabilising and installing the foundations
- One Power Supply Vessel (PSV) carries 3 turbines offshore

- One offshore crane vessel (S7000) installs the turbines while being supported by one AHTS.

The calculations have been based on assumptions made by the authors, (Sanden & B. I. Vold 2010) and (Myhr 2012). Table G shows the main assumptions which have been made for installing the floating wind turbine concepts. It should be mentioned that this information is case specific and therefore only valid for the same set-up as in this analysis.

| Fleet needed per wind turbine installed (floating concepts) | | |
|--|---------|--|
| | | Assumptions and comments |
| AHTS (Anchor Handling Tug Supply) – handle the WTGs after the lift | 1 | One AHTS is used both for supporting the towing process as well as to handle the WTGs after the lift offshore. |
| Small AHTS –tow the foundation offshore | 2* +1** | Based on vessel specification one AHTS uses 22 hours for towing and 7 hours for return. In addition it uses 2 hours for preparations and loading. Assumed that one towing process can handle two foundations at a time. |
| PSV (Power Supply Vessel) | 1 | Based on vessel specification on PSV uses a total of 17 hours of transport. In addition to this it has been assumed 12 hours for loading and 60 hours for unloading. An important assumption is that one PSV can load and carry 3 turbines per trip. |
| Offshore crane vessel | 1 | The crane vessel is position offshore during the whole installation operation. Uses 10 hours on each WTG and 4 hours to rig and transport between each turbine. Gives a total of 2 WTGs installed per day. |

* Two foundations are towed at a time gives 1 small AHTS per turbine.

** The same AHTS that handle the WTGs after lift does also contribute to the towing operation.

Table G: Fleet needed per floating wind turbine installed.

Figure A illustrates the vessels needed for the installation operations in this analysis.



Figure A: Three AHTS', one PSV and one offshore crane is needed per installed wind turbine (Photo: Hayvord Group, NauticExpo, and Wikipedia)

In order to calculate the required number of days for installing (and thereby also decommissioning) the wind turbines, the following steps have been followed:

1. Fleet needed to install one wind turbine

2. Multiply with the number of wind turbines in the wind park
3. Find an appropriate operational window (set to 60 %)

The number of days needed for installing the wind park for each vessel type is calculated based on the following formula:

$$\frac{\text{Number of days (100 \% operational window)}}{\text{Operational window (\%)}} = \text{Number of days (installation)}$$

The number of days (installation) is further been multiplied by the fuel consumption per day (given by Table E) for the respective vessel, which gives the total amount of fuel used for installation:

$$\frac{\text{Fuel(ton)}}{\text{Day}} * \text{Number of days (installation)} = \text{Fuel used for installation}$$

Further, the total fuel consumption from the trenching ships is calculated by multiplying fuel consumed (ton bunker oil) by km trenched.

The offshore substation is installed 200 km offshore. As a simplification it is assumed that installing the 220 MVA offshore substation acquires the same potential impact as for one installed floating concept. Decommissioning of the substation is not included as it is assumed to be used after the wind park's lifetime.

Installing the bottom fixed concept

The run of the installation includes the following activities in this analysis:

- The jackets, 4 at a time, are transported by the rebuild Navion Savonita (FIV) to site, 200 km offshore
- The jackets are installed using the FIV.
- SealInstaller places the turbine upon the jacket.

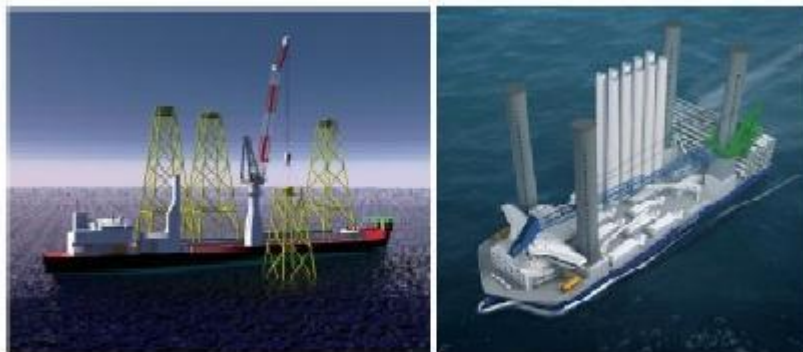


Figure B: The rebuild Navion Savonita and SealInstaller (photo: Nielsen, 2012)

The calculations have been based on assumptions made by the authors, as well as (Sanden & B. I. Vold 2010), (Myhr 2012) and (Nielsen 2012). Data regarding fleet, time consumption and installing the turbine on the platform, as well as fuel consumption are based on (Nielsen 2012). The installation of the bottom-fixed wind turbine needs a set of operations in order to fix the jacket to the seabed at the same ways as

the floating concepts need a set of operation due to the need of docking the wind turbine. As a simplification, the same operational time for installing a bottom-fixed and floating wind turbine has been used. However, the bottom-fixed operational window is set to 65%, which is 5% higher than for the floating concept due to more complex operations. In order to calculate total fuel consumption for the trenching ships, the fuel consumption (ton bunker oil) is multiplied by km trenched.

The 500 MVA offshore substation is installed 200 km offshore. As a simplification it is assumed that installing the substation acquires the same operations as the installation of a bottom-fixed platform except the following two adjustments: The FIV does all the work and the time consumption is 3 days/substation (which represents half of the time compared to the platform installation). Decommissioning of the substation is not included as it is assumed to be used after the wind park's lifetime.

Installing the wind turbines – a summary

Table H gives the total fuel consumption for installing the different wind turbine concepts given the chosen site and run of installation. In addition to this fuel consumption, the fuel used for trenching and installing the offshore substation is calculated (not included in the table). The fuel consumption for trenching and installing the offshore substation is not differed between the floating and bottom-fixed concepts.

| Floating | "Vessels/day" | Wind park | | |
|-------------------------------|---------------|-----------|---------------|----------|
| | | Days | Ton fuel /day | Ton fuel |
| AHTS- towing and support | 1 | 386 | 32,5 | 12 545 |
| AHTS- towing | 2 | 219 | 32,5 | 14 235* |
| PSV | 1 | 206 | 20 | 4 120 |
| Offshore crane vessel | 1 | 83 | 48,7 | 4 058 |
| Bottom-fixed | | | | |
| Rebuilt Navion Savonita (FIV) | 1 | 437 | 51,75 | 22 618 |
| SealInstaller | 1 | 150 | 48,7 | 7 332 |

* 3 AHTS tow 2 foundations at a time, 1 of these AHTS is also used for support during installation.

** Decommissioning of subsea station is not included; these are often used after WP lifetime.

Table H: Fuel consumption for installing the wind turbines (floating and bottom-fixed).

Maintenance

The maintenance activity has been separated into three activities: "Fuel", "Reinvestment infrastructure" and "Others" (e.g. waste and operation materials needed for maintenance). This is illustrated in Figure C. The maintenance activities are assumed equal for all the offshore conceptual designs.

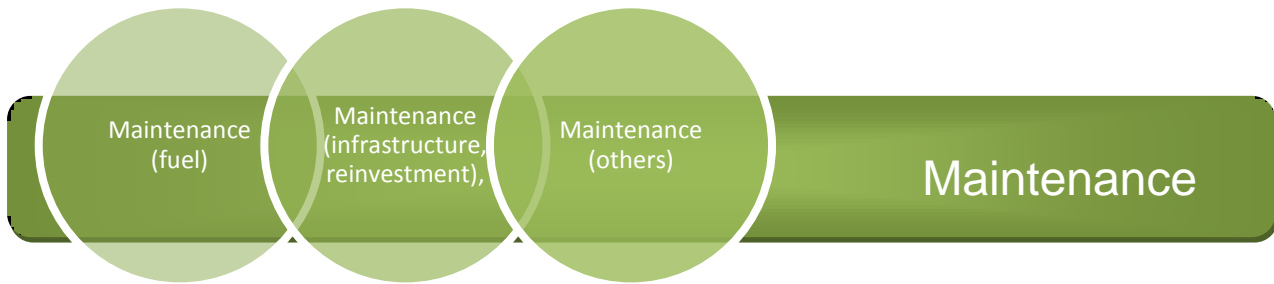


Figure C: The maintenance activities.

Fuel maintenance

The fuel maintenance has been further separated into the following 4 different types: “Scheduled maintenance”, “Unplanned minor maintenance”, “Unplanned major maintenance” and “Major overhaul”. This is shown in Figure D.

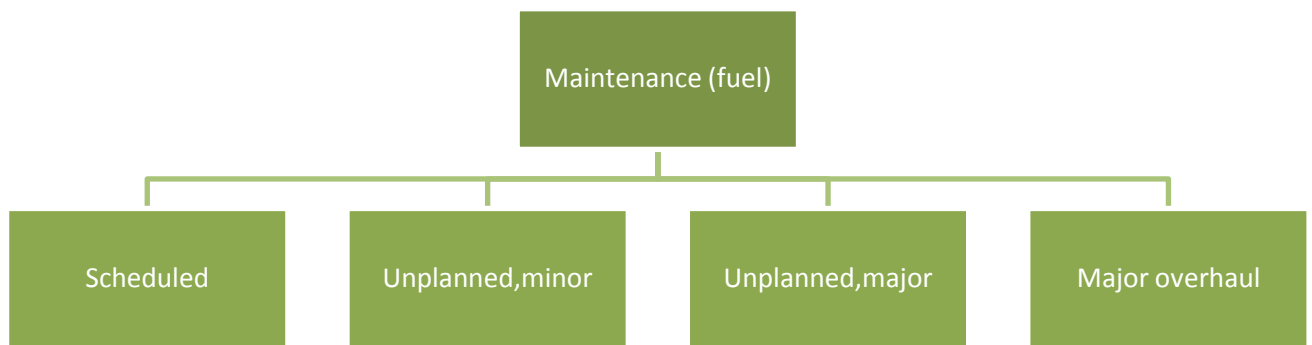


Figure D: Model for the maintenance activity fuel.

Scheduled or planned maintenance

Scheduled or planned maintenance is assumed to take place once a year per wind turbine (Heggset 2009).

Unplanned minor and major unplanned maintenance

The study distinguishes between minor and major unplanned maintenance, as these require different vessels for the maintenance operations. Minor maintenance is defined as maintenance occurring as a result of electrical failures, where there is no need to replace mechanical components. Thus, minor maintenance can be performed by using a small vessel (either a small boat or a specialised vessel) carrying crew and equipment to the particular wind turbine. Major maintenance, on the other hand, is defined as operations which replaces mechanical components. Thus, the operations necessarily need an offshore crane vessel.

Table I gives an overview of the various components divided into minor and major maintenance. The data are given in (Sanden & B. I. Vold 2010), partly based on van Bussel & Zaaijer in (Sanden & B. I. Vold 2010).

| Minor maintenance | |
|--------------------------|---|
| Component | Failure frequency (failures/year) |
| Control | 0.17 |
| Electric systems | 0.1 |
| Brake -electric | 0.025 |
| Parkingbrake - electric | 0.025 |
| Generator | 0.05 |
| Inverter | 0.16 |
| Pitch mechanism | 0.14 |
| Yaw system | 0.15 |
| Blades | 0.099 |
| Blade tips | 0.126 |
| Gearbox | 0.135 |
| Total | 1.18 |

| Major maintenance | |
|--------------------------|---|
| Component | Failure frequency (failures/year) |
| Blades | 0.011 |
| Blade tips | 0.014 |
| Brake - mechanic | 0.025 |
| Parking brake - mechanic | 0.025 |
| Gearbox | 0.015 |
| Shaft and bearings | 0.02 |
| Total | 0.11 |

Table K: *Unplanned maintenance* (Sanden & B. I. Vold 2010).

(Sanden & B. I. Vold 2010) have chosen to divide the failure of the brakes and parking brake to a mechanical part (major maintenance) and an electrical part (minor maintenance). The reason for this is that the failure of the braking system can be both a mechanical and electrical fault and that the entire break system is worn out and needs replacing. Equal error rates are assumed for these two categories. Also blades, blade tips and gearbox have been divided into minor and major failures, but with different error rates. The total failure rates have been allocated between the two categories, which means that 90% (1.18 error/yr) of the total failure rates represent minor maintenance and 10% (0.11 error/yr) represent major maintenance.

It should, however, be mentioned that is expected that the error rates will decrease with regard to the progress and research on low-maintenance components such as Smart Motor and ChapDrive. The selected error frequencies used in this analysis is thus a conservative estimate as they are based on offshore turbine error frequency numbers from 2001 (van Bussel & Zaaijer in (Sanden & B. I. Vold 2010).

Major overhaul

One major overhaul of the wind turbine is assumed to be needed every ten years (Myhr 2012). This means full service of the wind turbine and security check of climbing equipment.

Transports related to maintenance

For maintenance it is assumed that the transport vessels are moored during the maintenance operation. Added is also standby time which covers some fuel consumption during operation of maintenance at the wind farm and transport between the wind turbines. Fixed standby time is set to 3 hours (Sanden & B. I. Vold 2010). The formulas which have been used in order to calculate the fuel consumption for maintenance are shown as a step-by-step manual below:

I: Traveltime

$$\frac{\text{Distance to the middle of the windpark(km)}}{\text{Transport speed } \left(\frac{\text{km}}{\text{h}}\right)} = \text{Trip return to WP (hours)}$$

II: Traveltime + operation

$$\text{Trip return to WP (hours)} + \text{StB in WP (hours)} = \text{Hours used for maintenance(hours)}$$

III: Calculating the fuel consumption with regard to hours used and fleet info given in table 6.

$$\text{Hours used for maintenance(hours)} * \frac{\text{fuel (kg)}}{\text{hour}} = \text{Fuel used for maintenance}$$

Table J shows the numbers of wind turbines which is assumed to be handled per day for each of the different maintenance routines.

| Maintenance | Number of turbines / day given | Comments |
|------------------|--------------------------------|--|
| Scheduled | 3 | Small boat, specialised vessel or helicopter. |
| Unplanned, small | 6 | Small boat, specialised vessel or helicopter. |
| Unplanned, major | 1 | Drives in and out for each occurrence. Crane vessel is needed for this occurrence. |
| Major overhaul | 1 | The crane vessel is permanently placed offshore and carries out major overhaul on all wind turbines. One small boat and PSV provides weekly respectively personnel and material. |

Table J: Numbers of turbines assumed being handled per day for the different maintenance routines.

Table L shows the number of occurrences every maintenance type is assumed to have per year per turbine and for the wind farm as a whole. In addition alternative choices with regard to transport modes in order to conduct the maintenance are shown.

| Maintenance | Transport modes | | | | | |
|-----------------------|-----------------------------|------------------------------|------------|--------------------|--------------|---------------------|
| | Maintenance a year /turbine | Maintenance a day for the WP | Small boat | Specialised vessel | Crane vessel | Offshore helicopter |
| Scheduled Maintenance | 1 | 0,27 | X | X | | X |
| Unplanned, small | 1,18 | 0,32 | X | X | | X |
| Unplanned, larger* | 0,11 | 0,03 | X | X | X | |
| Major overhaul** | 0,1 | 0,027 | X | X | X | |

| Default set-up | | | | | | |
|-----------------------|--|--|------------|--------------------|--------------|---------------------|
| | | | Small boat | Specialised vessel | Crane vessel | Offshore helicopter |
| Scheduled Maintenance | | | X | | | |
| Unplanned, small | | | | X | | |
| Unplanned, larger | | | X | | X | |
| Major overhaul* | | | | X*2 | X | |

*Must include crane vessel

** Must include 2 vessels in addition to the crane vessel.

Table M: Maintenance, vessel set-up.

Reinvestment and Other maintenance

Reinvestment infrastructure per wind turbine (1 – 3% of total infrastructure masses) is based on data given for the Kjøllefjord wind farm (as documented in section 3 in this report). Other maintenance, such as waste and operation materials needed for maintenance are obtained from the same study.

