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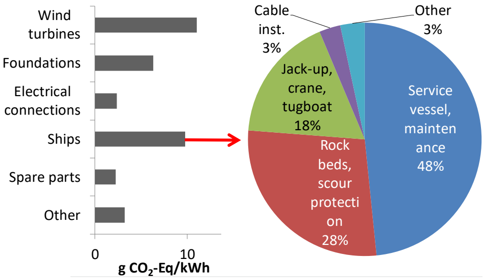
## ABSTRACT

We develop and assess life cycle inventories of a conceptual offshore wind farm using a hybrid life cycle assessment (LCA) methodology. Special emphasis is placed on aspects of installation, operation and maintenance, as these stages have been given only cursory consideration in previous LCAs. The results indicate that previous studies have underestimated the impacts caused by offshore operations and (though less important) exchange of parts. Offshore installation and maintenance activities cause 28% (10 g $CO_2$-Eq/kWh) of total greenhouse gas emissions and 31-45% of total impact indicator values at the most (marine eutrophication, acidification, particulates, photochemical ozone). Transport and dumping of rock in installation phase and maintenance of wind turbines in use phase are major contributory activities. Manufacturing of spare parts is responsible for 6% (2 g $CO_2$-Eq/kWh) of greenhouse gas emissions and up to 13% of total impact indicator values (freshwater ecotoxicity). Assumptions on lifetimes, work times for offshore activities and implementation of $NO_x$ abatement on vessels are shown to have a significant influence on results. Another source of uncertainty is assumed operating mode data for vessels determining fuel consumption rates.

## Table of Contents Art



# 1 Introduction

Wind energy is among the fastest growing sources of world electricity generation and the second largest contributor (after hydro) to global renewable power generation [1]. Due to, among other factors, lack of suitable space on land and better wind conditions offshore, the wind power sector is expected to increasingly turn towards development in ocean waters. For example, EU member states' action plans project offshore wind power capacity will increase from less than 1 GW in 2005 to 44 GW in 2020, providing 12% of EU combined renewable electricity in 2020 [2]. At the global level, the BLUE Map scenario of the International Energy Agency shows a jump in offshore wind power generation to 1700 TWh – or 4% of global electricity – in 2050 [3]. More global offshore wind electricity is likely to be needed with a stringent global climate policy, or if competing technologies fail to live up to their expectations [3, 4].

Offshore wind power technology is based on, and has many similarities with, onshore wind technology, but there are also important differences. For a given capacity installed, resource requirements are generally larger for offshore wind power systems than for land-based systems. One reason for this is that installation and maintenance activities become more complicated offshore; another is that heavier and longer cables may be required for electricity transmission. On the other hand, ocean-based systems typically benefit from better wind conditions. Although a fair number of life cycle assessment (LCA) studies have investigated the environmental impacts of electricity from offshore wind farms [5-12], weaknesses and gaps in knowledge exist [13]. In particular, for the current study three issues are of concern and are discussed below.

First, assessments of offshore activities associated with constructing and operating wind farms in LCAs are rather tentative, as they appear to lack detailed representations of different vessels involved, appear to be based on simplified theoretical calculations (using parameters such as theoretical transport lengths and speed, as opposed actual working times or fuel consumption) that are yet to be verified, and/or do not reveal key assumptions. Much more so than for typical projects on land, installation and maintenance costs are significant contributors to the overall costs of offshore projects [14, 15]. If these costs are to some considerable degree attributable to the burning of fuel oil in vessels, it is conceivable that some associated pollution is important. In the general case, global emissions of greenhouse gases, nitrogen and sulfur compounds and particulates from shipping activities are significant and growing [16, 17].

Second, as maintenance reports of operating wind farms have traditionally not been made public [18, 19], LCA analysts have had little basis for making substantiated assumptions regarding the rate at which wind turbine parts need to be replaced. To our knowledge, assumed replacement rates in previous LCAs are not made on empirical grounds. There is a need to verify assumptions about replacement rates in LCAs against operational experiences, and to begin to explore how to best extrapolate current knowledge to the future operation of modern, large-scale wind turbines.

Third, published LCAs of wind power predominantly employ process-LCA methodologies known to suffer from systematic underestimation of impacts [20, 21]. Hybrid LCA methodology, where monetary inventories are used to model the effects of operations that are omitted in process-LCA, is employed in only four of 40 wind power LCA studies surveyed in [13]; two of these [9, 10] study wind farms situated offshore.

The objectives of this paper are to provide insight into the contribution of installation, operation and maintenance (O&M), including operations by marine vessels and replacement of parts, to the life cycle impacts of offshore wind power. This is achieved through a case study of an offshore wind farm, the proposed Havsul I wind farm in Norway. A hybrid LCA methodology is employed.

### Installation and O&M phases in other studies

For the offshore wind power process in the Ecoinvent LCA database (which also forms the basis for the physical inventory modeling in [9]), barge, excavator and crane activities are represented through theoretical considerations of energy used in transporting a mass over an assumed distance, and in lifting a mass against gravity to a given height [6]. Operations during use phase do not appear to be included, however. A principally similar approach is taken in [7], but including also use phase activities. Other studies appear to neglect offshore activities [12] or do not report quantitative assumptions [5, 11]. In the above mentioned studies, emissions from offshore activities are either reportedly small or not specified in the results. Two recent LCAs show relatively more important contributions from marine activities: Installation contributes roughly 10-20% to total indicator values in [10], and vessel and helicopter operations during use phase are responsible for 17% in [8]. A very simplified approach is taken in the former study however (using reported energy use for an onshore project and assuming energy scales in proportion to costs when moving offshore), and the latter study lacks transparency as key assumptions are not reported.

Ecoinvent processes do not incorporate exchange of parts [6]. Other studies assume 0.5 gearbox replacement per wind turbine on average [5, 10, 22], 0.5 gearbox and 1.25 blade [8], 1 generator [23] and 0.05 complete wind turbine [7] over a 20-year lifetime. By comparison, as shown later in table 6, empirical data from Germany show a total annual exchange rate of large parts of 0.075 per wind turbine on average [19], while one O&M cost model assumes 0.12 annual replacements per unit [24].

## 2 Materials and methods

This study employs a hybrid LCA methodology to study the environmental effects arising from activities necessitated by the building, operating and decommissioning of an offshore wind farm. The proposed Havsul I wind farm off the coast of Møre og Romsdal in Norway is used as a model (table 1). We develop one reference plus eight alternative scenarios reflecting different assumptions (table 2).

**Table 1.** Key data for the Havsul 1 offshore wind farm.

| | | Reference |
|---|---|---|
| Wind farm capacity | 350 MW | [25, 26] |
| Wind turbine capacity | 5 MW | [26] |
| Full load hours, excl. loss and downtime | 3000 h | [25] |
| Loss, grid connection | 3.1% | [25] |
| Reduction in generation due to downtime | 4.0% | [25] |
| Annual electricity to grid | 982 GWh | Calculation |
| Foundation concept | Gravity-based | Assumption |
| Internal cabling (33 kV), length | 63.3 km | [25] |
| No. of offshore transformer stations | 2 | [25] |
| Cabling to shore (132 kV), length [a] | 54 km | [25, 27] |
| Onshore overhead line, length | 8.2 km | [25, 27] |
| Onshore underground cable, length | 0.4 km | [25, 27] |

[a] Combined length of two cables.

**Table 2.** Overview of assumptions in reference and eight alternative scenarios.

| | System lifetime (years) | Additional $NO_x$ abatement technology | Additional $SO_2$ abatement technology | Change in demand for replacement parts | Change in offshore work time (OWT) for vessels | Additional dismantling activities at end-of-life |
|---|---|---|---|---|---|---|
| Reference | 25 | | | | | |
| Lifetime20 | 20 | | | | | |
| Low-$NO_x$ | 25 | yes | | | | |
| Low-S | 25 | | yes | | | |
| Low-$NO_x$&S | 25 | yes | yes | | | |
| Max-Repl | 25 | | | +50% | | |
| Low-OWT | 25 | | | | -50% | |
| Optimistic | 30 | yes | yes | | -50% | |
| Pessimistic | 20 | | | +50% | | yes |

Light red (green) color indicates a change to the worse (better), compared with the reference.

Impact assessment is performed for twelve impact categories using ReCiPe characterization factors [28] (an explanation of exclusion of impact categories and results for additional categories are provided in Supporting Information). Direct emissions from sea-based activities are classified as occurring in low population density areas or unspecified areas (the latter is used when the former is not available).

## 2.1 Hybrid LCA

The hybrid LCA model combines physical inventories from the Ecoinvent database [29] and monetary inventories from environmentally extended input-output (IO) tables for the year 2000 developed for the EXIOPOL project [30] (table 3). The IO tables employed have 123 commodity sectors and two regions (Europe, rest-of-world) and are augmented with discharge coefficients by 25 types of air emissions (details are provided in the Supporting Information).

**Table 3.** Summary of important activities and data source.

| Activity | Database | Physical/monetary |
|---|---|---|
| Supply of fuels and electricity for manufacturing of main components | Ecoinvent | Physical |
| Supply of key materials used in components | Ecoinvent | Physical |
| Lorry and helicopter transport for installation, O&M and EOL | Ecoinvent | Physical |
| Direct emissions from ships during installation, O&M and EOL | Own (table S5) | Physical |
| Upstream activities in marine fuel and vessel product systems | Ecoinvent | Physical |
| Remaining (otherwise excluded) activities | EXIOPOL | Monetary |

O&M = Operations and maintenance. EOL = End-of-life.

A three-step procedure is taken to establish inputs from the IO sub-system: 1) Processes are assigned the same input distributions as the Europe region IO sectors to which they belong. For example, inputs to the process “gearbox” have the distribution of the Europe economic sector “manufacture of machinery and equipment”. 2) Inputs are scaled in relation to the cost of each process (e.g., gearbox) so that the sum of all monetary inputs and value added balance with the cost [31]. 3) Monetary inputs that are already covered in the physical inventory (e.g., iron and steel for the gearbox) are removed by setting the relevant monetary entries to zero.

Total capital expenditures for Havsul I are approximately 7 billion NOK [26], which we assume corresponds to 2200 Euro/kW in 2000 prices. Capital costs of today’s offshore wind farms generally fall within a range of 1800-2500 Euro/kW [14, 15]. We adopt the capital cost breakdown for a generic offshore wind farm developed in a previous study [10] based on data in [14, 15, 32]. Variable costs, excluding the costs of spare parts, amount to 1.20 Eurocent/kWh (2000 prices) and are divided equally between maintenance and other variable costs (e.g., management, administration). Decommissioning costs are added and amount to 8% of installation costs (assumption based on fuel oil consumption ratio).

## 2.2 Physical inventory data collection

In addition to the inventories described in the following sub-sections, transport with lorry from production site to port (100 km; subsumed under installation phase) and from port to waste handling (100 km; end-of-life) is included for all components. Impacts or benefits resulting from waste treatment or recycling of components are not considered.

### 2.2.1 Wind turbine and foundation

Table S3 (supporting information) shows assumed material compositions of wind turbine components and foundation. Total weights of the rotor, hub, nacelle and tubular steel tower are consistent with the offshore reference wind turbine defined in [33]. We include energy use incurred in the manufacturing of a wind turbine based on data from [34], and add sheet rolling of steel used in the tower and wire drawing for copper used in the generator and transformer. Material requirements for a gravity-based foundation are from information provided by a supplier [35].

### 2.2.2 Electrical connections

Based on cable data from manufacturers [36, 37], we estimate material composition of cables. Material requirements for aerial lines are adopted from [38]. Direct energy use in cable manufacturing is modeled using data from [39]. We derive material requirements and direct energy use during manufacturing of high-voltage transformers from reports by manufacturers [40, 41]. The transformer stations also include helipads and various electrical equipments, as well as a steel structure. We assume total topside weight as in [42] and model the remaining mass (apart from the transformer) as low-alloy steel. Substation foundation is identical to one wind turbine foundation.

### 2.2.3 Offshore operations

We adopt assumptions on marine vessel operations and work time from a technical report published as part of the impact assessment for Anholt wind farm [43], with the following adjustments: For wind turbines and foundations, work times from [43] are multiplied by a factor of 70/80 (a wind farm of 80 units is assumed in [43], 70 units are modeled here); similarly, requirements for substations are multiplied by a factor of 2. We add two activities not considered by [43]: the replacement of components by use of a jack-up vessel with crane (15 hours of vessel operation for every replacement at the rate indicated later in table 6) and helicopter transport in special cases where difficult weather conditions prevent access by boat (100 flight-hours per wind turbine). Table 4 lists activities and states assumptions about marine vessel activities. Two types of fuel are distinguished: Marine gas oil (MGO) is a distillate fuel with typically low sulfur content. Heavy fuel oil (HFO) is made from residual oil and contains higher levels of impurities.

Maintenance of ocean-based wind turbines typically comprises scheduled maintenance 1-2 times and unscheduled (corrective) maintenance 1-4 times per year per wind turbine. The Havsul I license application report [25] indicates scheduled maintenance 2 times a year. The work time 4400 days for 'support vessel, maintenance of wind turbines' in table 4 is based on [43], but is consistent with assuming a total of 4 maintenance incidents per unit per year and that each incident involves 15 vessel-hours ($4 \cdot 25 \cdot 70 \cdot 15 / 24 = 4400$, where 25 years is the lifetime and 70 the number of units). Further discussion on O&M work times and fuel oil consumption is given in the Supporting Information.

Included in all scenarios is the decommissioning and transport of wind turbines after the useful life. Removal of other components is not included by default, however, on the assumption that foundations, transformers and cabling are either retained for further use or left in situ. As an alternative, the Pessimistic scenario models the demolition and transport of all offshore components (table 4).

Ecoinvent processes for barge (MGO) and freight ship (HFO) are used to model upstream effects in fuel and vessel product systems. Data sources in Ecoinvent for emissions from marine vessels are fairly old however, and thus, we may infer, not wholly representative for our case. Therefore, we use instead direct emission factors for 25 air pollutants (including $CO_2$, $NO_x$, $SO_2$ and particulates) compiled from other sources, notably [47]. Tables S5-S6 (Supporting Information) summarize data sources and assumptions and provide numerical values. $SO_2$ factors are calculated assuming fuel sulfur contents of 0.1% (MGO) and 1.5% (HFO) by weight, which are the maximum allowable levels for sulfur emission control areas according to [48]. $SO_2$ and particulate emissions may be reduced by scrubbing systems; $NO_x$ may be reduced by selective catalytic reduction (SCR) [49]. Effects of implementing $SO_2$ abatement on HFO-fuelled vessels are investigated in Low-S scenario. In another scenario, Low-$NO_x$, $NO_x$ emissions are reduced to 2 g/kWh (equivalent to a reduction of roughly 70-80% in our case), in compliance with restrictions that will apply for engines installed in 2016 when operating in $NO_x$ emission control areas [50].

**Table 4.** Overview of marine vessel operations during installation (Inst), operation and maintenance (O&M) and end-of-life (EOL) life cycle phases.

| Activity/Vessel [43] | Phase | No. of vessels [43] | Work time (d) [43] | Fuel type [43] | Fuel rate (l/h) | Data source/assumptions for fuel rate values P = Engine power. SFC = Specific fuel consumption (fuel rate per unit of power produced). AL = Average load. |
|---|---|---|---|---|---|---|
| **Foundations** | | | | | | |
| Excavator, preparation of seabed | Inst | 1 | 210 | MGO | 99 | P = 1500 kW [43]. SFC = 190 g/kWh. AL = 30% |
| Barge, transport of excavator and disposal of seabed material | Inst | 1 | 370 | HFO | 58 | P = 1000 kW [43]. SFC = 190 g/kWh. AL = 30% |
| Vessel, transport of rock for stone bed | Inst | 1 | 320 | HFO | 360 | P = 6250 kW [43]. SFC = 190 g/kWh. AL = 30% |
| Vessel, transport of rock for scour protection | Inst | 1 | 320 | HFO | 360 | |
| Vessel, dumping of rock for stone bed | Inst | 1 | 210 | HFO | 210 | P = 3700 kW [43]. SFC = 190 g/kWh. AL = 30% |
| Vessel, dumping of rock for scour protection | Inst | 1 | 210 | HFO | 210 | |
| Jack-up vessel, transport and installation of foundations | Inst | 1 | 70 | HFO | 87 | P = 1500 kW [43]. SFC = 190 g/kWh. AL = 30% |
| Tugboats, transport of foundations and jack-up vessels | Inst | 2 | 140 | MGO | 320 | Average tugboat operation value [45] |
| Jack-up vessel, dismantling and transp. of foundations [a, b] | EOL | 1 | 70 | HFO | 87 | P = 1500 kW [43]. SFC = 190 g/kWh. AL = 30% |
| Tugboats, transport of foundations and jack-up vessels [a, b] | EOL | 2 | 140 | MGO | 320 | Average tugboat operation value [45] |
| **Wind turbines** | | | | | | |
| Crane vessel, installation of wind turbines | Inst | 1 | 70 | HFO | 160 | P = 2750 kW [43]. SFC = 190 g/kWh. AL = 30% |
| Tugboats, transport and installation of wind turbines | Inst | 2 | 140 | MGO | 320 | Average tugboat operation value [45] |
| Support vessel, maintenance of wind turbines | O&M | 1 | 4400 | MGO | 99 | P = 2000 kW [43]. SFC = 190 g/kWh. AL = 30% |
| Crane vessel, replacement of large parts [a] | O&M | 1 | 81 | HFO | 160 | Assume as for installation of wind turbines |
| Crane vessel, dismantling of wind turbine [a] | EOL | 1 | 70 | HFO | 160 | P = 2750 kW [43]. SFC = 190 g/kWh. AL = 30% |
| Tugboats, dismantling and transport of wind turbines [a] | EOL | 2 | 140 | MGO | 320 | Average tugboat operation value [45] |
| **Electrical connections, including substation** | | | | | | |
| Cable lay vessel with plough (33kV and 132 kV cables) | Inst | 1 | 19 | MGO | 450 | Central value for cable laying operation [46] |
| Vessel, tie-in of cables (pull-through J-tubes) | Inst | 1 | 87 | MGO | 360 | Assume as lower value for cable laying [46] |
| Jack-up vessel, transp. and install. of foundations (substation) | Inst | 1 | 23 | HFO | 87 | P = 1500 kW [43]. SFC = 190 g/kWh. AL = 30% |
| Tugboats for transport of jack-up vessel, etc. | Inst | 2 | 12 | MGO | 320 | Average tugboat operation value [45] |
| Crane vessel, installation of substation topside | Inst | 1 | 23 | HFO | 160 | P = 2750 kW [43]. SFC = 190 g/kWh. AL = 30% |
| Vessel, inspection of cables (33kV and 132 kV cables) | O&M | 1 | 450 | MGO | 99 | Assume as for maintenance of wind turbines |
| Vessel for maintenance of substation | O&M | 1 | 150 | MGO | 99 | |
| Vessel, removal of cables [a, b] | EOL | 1 | 19 | MGO | 450 | Central value for cable laying operation [46] |

Work time represents total work time in units of ship-days (d; 24 hours per ship-day) for the wind farm as a whole, and apply to reference scenario (in alternate scenarios, work time values for the O&M phase are scaled to adjust for different lifetimes or exchange rates). Work time values from [43] are subject to adjustments for scale as explained in the text. Average engine load (AL) is set to 30%, which is the average of suggested values for non-oceangoing vessels (construction ships, work/crew boats, etc.) in 'slow-cruise' (40%) and 'maneuvering' (20%) modes in [44]. (A third mode, 'cruise', is also defined in [44] with suggested load factor 80%. We here assume that slow-cruise and maneuvering modes are more representative of all activities, especially for a wind farm situated close to shore). For conversion of units, we use conversion factors 0.86 kg/l (MGO) and 0.983 kg/l (HFO). [a] denotes activity is not included in [43]; [b] means activity is included in Pessimistic scenario only.

### 2.2.4 Replacement of parts

Empirical evidence on exchange of parts is scarce in the public domain. To our knowledge, the only available evidence that covers a fleet of wind turbines comes from the German '250 MW Wind' monitoring program (WMEP) [19]. Here we assume a total annual exchange of large parts of 0.075 per wind turbine, which we obtain from real observations over a ten-year period of WMEP for 538 wind turbines [19]. As is evident from table 6, 0.075 is lower but in the same order as the corresponding rate assumed in [24]. We assume 0.362 annual replacements of small parts [24] (table 5). Assumptions about parts to be replaced are set out in table 5. Max-Repl scenario incorporates a 50% rise in spare parts demand. For more thorough discussions on failure statistics and reliability characteristics of wind turbines, we refer to [18, 19, 51].

**Table 5.** Annual rate of failures per wind turbine by four failure categories in O&M cost model [24] and experiences from WMEP [19], and parts to be replaced.

| Failure category (following [24]) | Annual rate in [24] | Annual rate in [19] | Annual rate modeled here | Spare part modeled here as |
|---|---|---|---|---|
| Repl. heavy component | 0.012 | - | - | - |
| Repl. large part [a] | 0.111 | 0.075 | 0.075 | 1/3 set of 2 blades, 1/3 generator, 1/3 gearbox [c] |
| Repl. small part [b] | 0.362 | - | 0.362 | 500 kg low-alloy steel |
| Repl. man-carried part or no part | 1.066 | - | - | - |

Repl. = Replacement. [a] > 50 t is assumed in [24]. We classify all replacements reported in [19] as repl. large parts. [b] < 1 t, excluding man-carried parts, is assumed in [24]. [c] Rotor blades, generators and gearboxes require replacement more often than other components [19]. WMEP incident reports (provided in [18]) and results [19] do not specify whether 1 blade or a set of blades are replaced; here we assume one blade replacement incident involves on average 2 blades.

# 3 Results

Total impact indicator results by all scenarios are in table 6, which also shows relative changes from the reference case. Further, figure 1 shows, for the reference scenario, the breakdown of the contribution of environmental stressor sources (nine categories stacked horizontally within each bar) to the total impact indicator values for components of the wind park (eight bars). Among the nine categories of stressor sources, seven represent stressors elicited in the physical sub-system: Electricity represents stressors occurring at power plants, heat covers stressors incurred in burning of fuels in boilers, furnaces or similar for heat, etc. Direct emissions from marine vessels are subsumed under transportation.

**Table 6.** Total impact indicator values by scenarios (upper numbers in larger letters) and their relative change compared with the reference (lower numbers given as percentages in smaller letters).

| | Reference | Lifetime20 | Low-$NO_x$ | Low-S | Low-$NO_x$&S | Max-Repl | Low-OWT | Optimistic | Pessimistic |
|---|---|---|---|---|---|---|---|---|---|
| **Climate change** | 35.1 | 41.7 | 35.1 | 35.1 | 35.1 | 36.2 | 32.7 | 28.4 | 43.7 |
| (g $CO_2$-Eq/kWh) | | +19% | 0.0% | +0.1% | +0.1% | +3.3% | -6.9% | -19% | +25% |
| **Freshwater ecotoxicity** | 399 | 484 | 399 | 399 | 399 | 425 | 393 | 337 | 512 |
| (g 1,4-DCB-Eq/MWh) | | +21% | 0.0% | 0.0% | 0.0% | +6.6% | -1.4% | -16% | +29% |
| **Freshwater eutrophication** | 13.1 | 16.0 | 13.1 | 13.1 | 13.1 | 13.8 | 12.8 | 10.9 | 16.8 |
| (g P-Eq/MWh) | | 22% | 0.0% | 0.0% | 0.0% | 5.3% | -2.4% | -17% | 28% |
| **Human toxicity** | 23.2 | 28.2 | 23.2 | 23.2 | 23.2 | 24.6 | 22.9 | 19.6 | 29.7 |
| (g 1,4-DCB-Eq/kWh) | | 22% | 0.0% | 0.0% | 0.0% | 5.8% | -1.1% | -15% | 28% |
| **Marine eutrophication** | 28.1 | 33.3 | 23.2 | 28.0 | 23.2 | 29.5 | 24.4 | 19.0 | 35.5 |
| (g N-Eq/MWh) | | 19% | -18% | -0.2% | -18% | 4.9% | -13% | -32% | 27% |
| **Metal depletion** | 12.3 | 15.0 | 12.3 | 12.3 | 12.3 | 13.0 | 12.2 | 10.4 | 15.7 |
| (g Fe-Eq/kWh) | | 22% | 0.0% | 0.0% | 0.0% | 5.7% | -0.3% | -15% | 28% |
| **Particulate matter** | 75.6 | 90.6 | 67.2 | 73.0 | 64.7 | 78.3 | 66.3 | 52.4 | 95.2 |
| (g PM10-Eq/MWh) | | 20% | -11% | -3.4% | -14% | 3.6% | -12% | -31% | 26% |
| **Photoc. oxidant formation** | 162 | 191 | 123 | 161 | 122 | 166 | 132 | 98.3 | 201 |
| (g NMVOC/MWh) | | 18% | -24% | -0.7% | -24% | 2.6% | -18% | -39% | 25% |
| **Terrestrial acidification** | 191 | 228 | 170 | 181 | 160 | 197 | 166 | 131 | 238 |
| (g $SO_2$-Eq/MWh) | | 19% | -11% | -5.4% | -16% | 3.3% | -13% | -31% | 25% |
| **Terrestrial ecotoxicity** | 2.8 | 3.4 | 2.8 | 2.8 | 2.8 | 3.0 | 2.6 | 2.2 | 3.6 |
| (g 1,4-DCB-Eq/MWh) | | 20% | 0.0% | 0.2% | 0.2% | 4.3% | -7.4% | -20% | 28% |
| **Water depletion** | 45.4 | 55.3 | 45.4 | 45.4 | 45.4 | 47.0 | 42.5 | 36.2 | 57.9 |
| ($m^3$/GWh) | | 22% | 0.0% | 0.1% | 0.1% | 3.6% | -6.3% | -20% | 28% |

Photoc. = Photochemical.

From figure 1 it is seen that installation and maintenance phases in many cases give significant contributions to overall indicator values: respectively 15% and 14% for climate change, 17% and 14% for marine eutrophication, 19% and 12% for particulate matter, 25% and 21% for photochemical oxidant formation, and 22% and 15% for acidification (replacement parts not included). Half of GHG emissions from installation arise due to transport and dumping of rock for stone bed and scour protection; roughly 20% is contributed by jack-up vessel, crane vessel and tugboat operations taken together. Installation of cables and onshore lorry transport causes 6-7% each of GHG emissions due to installation. The main culprit behind emissions due to maintenance is the ‘Support vessel, maintenance of wind turbines’ process (table 4), which is responsible for 85% of total GHG emissions from maintenance (Tables S38-S39 in Supporting Information).

The contribution of supply of spare parts to total indicator values is typically of the order 5-10%, and 13% at the most (freshwater ecotoxicity). Large (small) parts cause 99% (1%) of totals due to spare parts. Mining operations to acquire iron, nickel, copper and manganese together constitute 98% of metal depletion burden. As for toxic releases from waste handling, disposal of tailings in relation with mineral resource extraction and disposal of smelter slag are dominant pollution sources. Eutrophying emissions to freshwater stem in large part from disposal of tailings and spoil in connection with mineral resource extraction.

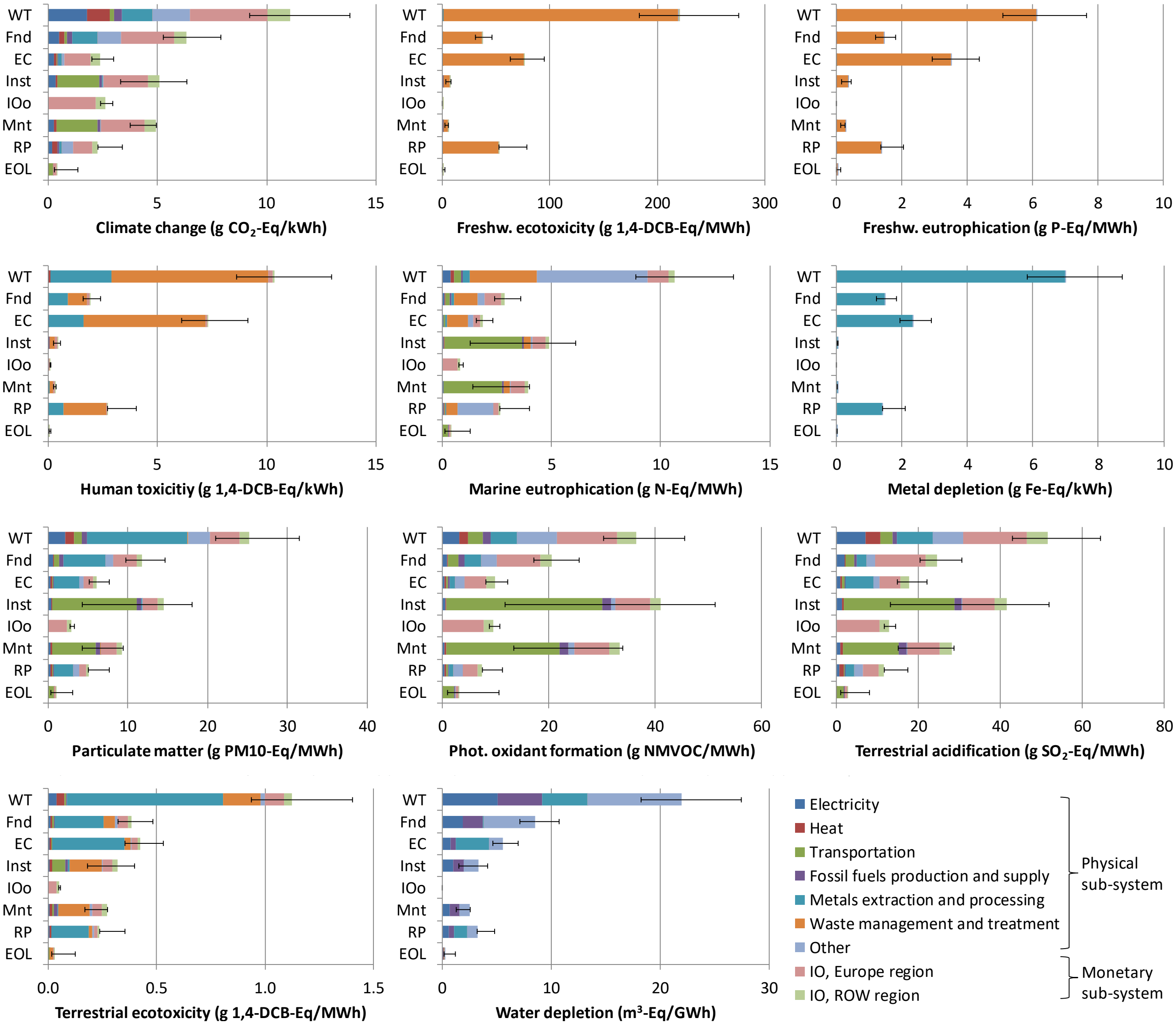


**Figure 1.** Reference scenario impact indicator values by eight components and nine stressor sources. Negative error bars give total values in Optimistic scenario and positive error bars in Pessimistic scenario. Components: WT = Wind turbine; Fnd = Foundation; EC = Electrical connections, including substation; Inst = Installation; IOo = Input-output, other; Mnt = Maintenance, excluding replacement parts; RP = Replacement parts; EOL = End-of-life.

The monetary sub-system generates 52% (climate change), 44% (acidification), 38% (photochemical oxidants), 26% (particulate matter), 19% (marine eutrophication) and 16% (terrestrial ecotoxicity) of total emissions, of which 70-80% is due to activities in the Europe region. The completeness of the monetary sub-system with respect to coverage of relevant stressor types vary depending on impact category. For example, the IO data covers the important greenhouse gases ($CO_2$, $CH_4$, $N_2O$), but overlooks nitrate emissions to water that, solely due to the physical sub-system, cause 40% of marine eutrophication. For yet other impact categories (e.g., metal and water depletion), the assessment becomes, de facto, a process-LCA.

Under optimistic assumptions about implementation of $NO_x$ abatement, total emissions of particulates, acidifying and eutrophying substances and smog-forming gases are reduced markedly, in the latter case they are reduced by 24%. Under the given assumptions, implementation of sulfur abatement does not produce corresponding benefits as $NO_x$ abatement, though there is a 5% reduction in acidification impact potential. Increases in total indicator values if including additional dismantling activities (marked with superscript 2 in table 4) are 3% or lower. Lowering the assumed lifespan by five years increases total impact potentials by 18-22% (Lifetime20 scenario). Max-Repl scenario shows only modest increases (~5%) for most categories.

# 4 Discussion

LCA results for wind power differ appreciably across studies, among other reasons due to differences in the systems under study (e.g., extent of grid connection), capacity factor and lifetime assumptions, and differences in methodologies (e.g., process-LCA or hybrid LCA) [13, 52]. A recent literature survey suggests a carbon footprint of offshore wind power of 12 (9-22) g $CO_2$-Eq/kWh, looking at the median values (interquartile ranges) of surveyed results [13]. The climate change impact potential of 35 g $CO_2$-Eq/kWh in the current analysis is comparable to the two highest estimates in the literature [13]: 32 g $CO_2$-Eq/kWh in [8] using process-LCA and 33-34 g/kWh in [9] with hybrid LCA. Greenhouse gas emissions (GHG) elicited in the IO system amounts to 18 g $CO_2$-Eq/kWh in the present study and 19 g/kWh in [9]. The reference case lifetime of 25 years in this study is comparatively optimistic; 20 years as assumed in Lifetime20 scenario is consistent with most previous LCAs. On the other hand, the capacity factor value used in this work, especially when taking into account downtime and transmission loss, is lower than typical values in existing literature [13].

The estimated environmental effects of marine vessel operations are subject to considerable uncertainty; three major sources of uncertainty are the assumed work times, fuel rate consumptions and engine loads. We have compared total fuel oil consumption during installation and use phases in the current model with similar estimates by an industry representative [53] for Sheringham Shoal offshore wind farm: Fuel consumption during installation is some three times lower in our model, while fuel oil needed for O&M is lower but reasonably consistent with that expected for Sheringham Shoal, when measured on a per MW wind farm capacity basis. Similarly, installation fuel is some two times lower and O&M fuel very similar when measured per wind turbine unit. In a further comparison for O&M, total direct $CO_2$ emissions of 1.8 g/kWh in the present analysis compares with 0.8 g/kWh (Kentish Flats wind farm; 10 km from shore) and 4.6 g/kWh (London Array; 45 km) estimated in [54] (for scenarios representing current practices and annual failure rate of 2 per wind turbine). As the current model utilizes assumptions on work times in [43] for a wind farm situated approximately 20 km from shore, failure rate and distance to shore do not appear as explicit parameters; results in [54] show high sensitivity to these parameters, however. In reality, strategies for installing and maintaining offshore wind farms vary depending on site conditions (e.g., distance from shore, foundation concept) and the individual developer or contractor, and corrective maintenance requirements vary depending on wind turbine characteristics affecting reliability. More efficient strategies may be adopted in the future as developers gather experience and harvest R&D efforts (e.g., in remote monitoring) – results of Low-OWT scenario are relevant in this respect. On the other hand, future developments will on the whole take place farther from shore than in the past.

Other sources of uncertainty include the emission factors for marine vessels and associated impact characterization factors. We consider $CO_2$, $NO_x$ and $SO_2$ emission factors to be fairly reliable, while numbers for particulate matter have large uncertainty. Emission factors for heavy metals and persistent organic pollutants are uncertain but not important for the final results. The lack of spatial specificity – both in connection with stressor source characteristics and receiving environment sensitivity – is a recognized limitation of current impact assessment methods [55, 56]. Generic characterization factors from ReCiPe [28] are used in this work, but sea vessel-specific or Norwegian environment-specific characterization may have yielded different results for some impact categories [57, 58]. As for the IO system contributions to impact indicator results, uncertainty comes from the assumed capital and variable cost levels.

A comparison of exchange rates in LCAs versus [19] and [24] suggests that LCA research on onshore and offshore wind power tend to underestimate demand for spare parts (section 2 in Supporting Information). Despite the comparatively high replacement rate in this study, the contributions from spare parts to total indicator values are moderate, but it should also be noted that the substantial impacts attributed to installation and other O&M in this work lessen the relative importance of spare parts. Furthermore, some observations suggest that the assumed replacement rates are too optimistic. First, following reliability engineering principles technical systems are expected to exhibit increasing failure rate due to wear-out in late stages of the operating life [59], but wear-out is not reflected in numbers from [19] (because data comes from the first ten years or so of operation) and [24] (wear-out is not considered) used in the current analysis (table 5). Second, there are experiences [19, 51, 60] indicating significantly higher failure rates for MW-sized wind turbines than for smaller units that form the bulk of the survey sample in [19]. Third, some evidence suggests moderately higher failure rates for near-coastal sites and highlands than for lowlands [18]. At the same time, advances in technology or innovations in failure-preventive maintenance may lead to improved reliability in the future.

Figure S3 (Supporting Information) compares impact indicator results for offshore wind power with that of fossil fuel-based power generation technologies often perceived to be clean, namely natural gas power using best available technology, and natural gas and coal power with carbon capture and storage (CCS) [61]. Results indicate superior performance of wind power with respect to GHG emissions, four times better than natural gas power with CCS. For marine eutrophication, particulate matter and acidification, emissions of offshore wind are lower but of the same order as that of natural gas with or without CCS. Freshwater ecotoxicity and human toxicity indicator values are several times higher for wind than for natural gas with or without CCS. The juxtaposition of unit-based indicator values for different energy technologies needs to be interpreted with care because one, it carries no notion of aspects of scale and time that may differentiate technologies [10, 62], and two, the need to balance variable outputs from wind power may cause additional emissions [63].

Notwithstanding the significant uncertainty, the present results indicate that previous studies have underestimated the contributions from installation and use phases to the total life cycle impacts of offshore wind power. Traditional perceptions that 'emissions from the manufacturing stage dominate overall lifecycle GHG emissions' [64] (p. 48) and that GHG emissions from the operational phase are 'almost negligible in relation to the total' [52] or 'negligible' [65] may be due for reconsideration for offshore wind power; and furthermore, such conclusions may not always be extendable to non-GHG pollutants (e.g., $NO_x$, $SO_2$ and particulates). Future LCA research on offshore wind power should strive to develop detailed inventories for installation and maintenance life cycle phases while ensuring transparency in the reporting of materials.

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## Supporting Information Available

Description of IO system and monetary inventories, complete account of physical inventories, numerical results in tabulated form, and additional discussion on the comparison with fossil power. This material is available free of charge via the Internet at http://pubs.acs.org.

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