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A model for estimating life cycle environmental impacts of offshore wind electricity considering specific characteristics of wind farms

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Abstract
Offshore wind electricity is becoming an important source of renewable energy due to its global warming potential (GWP). However, the GWP can vary significantly, depending on many factors, including the capacity of the installation, distance from the shore, supporting structure and maintenance requirements. Currently, there is a lack of life cycle assessment (LCA) studies that take these specific conditions into account. As a consequence, developers and policy makers rely on average GWP values which could lead to inaccurate estimates of the GWP and other impacts. To address this gap, this paper presents a new model for estimating the life cycle impacts of offshore wind electricity taking into account specific technical characteristics of individual installations and whole wind farms. Aimed at non-experts, the model provided freely with this paper is developed in Excel and follows the ISO 14040/44 LCA methodology. Supported by the built-in background LCA databases, it requires users to specify only a few key characteristics of an existing or proposed installation, thus facilitating quick and yet robust estimations of impacts. Eleven impacts can be considered, including GWP, depletion of resources, human toxicity and eco-toxicities. The application of the model is illustrated by quantifying the LCA impacts of 20 offshore wind farms (OWF) operating in the UK. The results show that the impacts vary considerably with the specific characteristics of OWF, including the age, type and size of wind turbines, their capacity and distance from the shore. For example, the GWP ranges by a factor of three (6.4-19.5 g CO_2 eq./kWh) and the other impacts by a factor of 2.2-3.2. The developed model can be used by designers, developers and policy makers to customise the inputs for a specific OWF and estimate the impacts quickly and cost-efficiently, without the need for prior expertise in LCA and extensive data collection.

Keywords: Energy planning; Energy modelling; Life cycle assessment; Wind electricity; Sustainable energy

1 Introduction
Wind electricity has become an important source of renewable energy, with installations of wind farms growing rapidly worldwide. The total global installed capacity of wind turbines stands at 651 GW, with an average annual growth of 10% (Lee and Zhao, 2020). According to the same authors, this trend is expected to continue in the foreseeable future, particularly as the costs of wind electricity continue to decline with the economies of scale. Offshore wind farms (OWF) are especially attractive as they can accommodate larger and more powerful installations than the onshore equivalents. As a consequence, their number has been increasing fast, reaching a worldwide installed capacity of 29.1 GW at the end of 2019 (Lee and Zhao, 2020).

Mitigation of climate change is the main driver for the growth in wind-electricity capacity due to its relatively low global warming potential (GWP) on a life cycle basis. However, the GWP values of wind electricity vary widely, depending on a variety of factors, such as capacity, installation site, wind availability, maintenance requirements and many others. Despite this, there are very few life cycle assessment (LCA) studies that take these specific conditions into account when estimating the GWP of wind turbines, the supporting infrastructure and maintenance requirements. This can lead to inaccurate estimates of their potential to contribute to climate change mitigation. Furthermore, as discussed in the next section, few studies have considered other life cycle impacts of wind energy beyond the GWP so that these are still largely unknown, particularly for different installation, operating and maintenance conditions.

Therefore, there is a need for models and tools that would enable users to estimate the GWP as well as other environmental impacts based on their specific data, either for an existing or a proposed OWF. Aiming to address this need, this paper presents a new Model for Environmental Assessment of Offshore Wind (MEAOW) which allows the user to define their individual installations or a whole OWF based on their requirements. The model takes into account the full life cycle of an OWF, including construction, operation, maintenance and decommissioning. It is simple to use and requires a minimum input from the user, as it is accompanied by extensive LCA databases. In addition to GWP, ten other LCA impacts can also be estimated, such as resource depletion, human toxicity, eco-toxicities and other categories typically considered in LCA studies. The tool is available to download with this paper.

Following a literature review discussed next, the rest of the paper is organised as follows. Section 3 provides an overview of the model and the methodology behind it. This is followed in Section 4 by its application to 20 real OWF operating in the UK to show how the model works but also to provide for the first time estimates of the LCA impacts of OWF depending on their specific design, installation, operating, maintenance and end-of-life characteristics.

2 Literature review

A wide variability in GWP has been observed since early days of modern-age development of wind power, as attested in a number of review studies. One of the early reviews (Lenzen and Munksgaard, 2002) found 29 studies of GWP of wind electricity, with the values ranging from 7.9 to 123.7 g CO_2 eq./kWh. Excluding the latter value which was an outlier, reduces the maximum GWP to 52 g CO_2 eq./kWh, which refers to an onshore Simplon 30 kW-turbine in Switzerland (Frischknecht, 1996). This study was one of only three out of the 29 which went beyond just considering the wind turbine generator (WTG) to include the foundations and the connection to the grid in the scope. The remaining two studies were for OWF and had the GWP of 16.5 g CO_2 eq./kWh (Schleisner, 2000).

In an effort to reduce the variability and arrive at a more representative range of GWP, a subsequent review carried out ten years later (Dolan and Heath, 2012) screened approximately 240 studies of utility-scale wind installations. The authors systematically reviewed and harmonised the 49 references that met the minimum thresholds for quality, transparency and relevance, also excluding any outliers. Via this process, they narrowed the gap in the harmonised GWP values to 3-45 g CO_2 eq./kWh for onshore and to 7.2-23 g CO_2 eq./kWh for offshore installations. A more recent review of OWF (Kadiyala et al., 2017) arrived at a similar range, except that the lowest value in the range reduced to 3.2 g CO_2 eq./kWh. However, the latter was an outlier and corresponded to a deep offshore floating wind turbine (Weinzettel et al., 2009).

The latest review (Mendecka and Lombardi, 2019) widened the above ranges further to 7.8-32 g CO_2 eq./kWh as more recent studies were added. In particular, the higher maximum, which is also mentioned in another review study (Arvesen and Hertwich, 2012), was recorded for wind turbines with capacity greater than 5 MW. This suggests that higher capacity does not necessarily imply lower GWP values per unit of electricity generated because of the increased requirements for construction materials. As a result, the authors recommended that further work should focus on the correlation between the wind farm size and additional material consumption. The review also highlighted that the discrepancies in the GWP were due to the differences in assumptions for site-specific wind conditions, wind turbine sizes and design.

The LCA literature also reveals that studies based on design data usually have lower estimated GWP values, typically ranging from 3.2 to 16.8 g CO_2 eq./kWh. For example, studies of Danish OWF (Elsam Engineering A/S., 2004; Jungbluth et al., 2004; Schleisner, 2000; Vestas Wind Systems, 2006) reported the GWP in the range of 5.3-16.5 g CO_2 eq./kWh while a study of an average (fictitious) wind farm in Brazil estimated a GWP of 7.1 g CO_2 eq./kWh (Oebels and Pacca, 2013). In Germany, Weinzettel et al. (2009) considered a floating wind power plant and Reimers et al. (2014) investigated an average OWF, both based on design data, and reported the values of 12.2 and 16.8 g CO_2 eq./kWh, respectively. These values were higher in studies that assumed lower electricity generation (32 g CO_2 eq./kWh) (Wagner et al., 2011) or higher material requirements (18-47.32 g CO_2 eq./kWh) (Raadal et al., 2014; Tsai et al., 2016) compared to the design values. A scenario analysis of a wide range of capacities and site conditions (Murai and Aono, 2009) for a spar-type power station estimated the GWP of 21-76 g CO_2 eq./kWh which is the highest range found in the literature.

These significant differences in the GWP of wind electricity suggest that the impact is very sensitive to various assumptions and operating conditions, necessitating more detailed studies taking into account specific characteristics of installations and their locality. This is particularly important for OWF due to significant differences in offshore distances, ocean depths and wind speeds and the related construction and maintenance requirements. One such recent study is the site-specific LCA of a 24 MW floating OWF (Poujol et al., 2020) expected to be installed in Leucate (southern France). Taking into account geo-located wind data, the GWP at the two locations was estimated at 19.6 and 17.8 g CO_2 eq./kWh, respectively. Another recent case that used spatial (and temporal) information in order to assess the impacts of Danish OWF is the "LCA WIND DK" online interactive platform (Besseau et al., 2019). This is based on a parameterised model (Sacchi et al., 2019) which allows estimates of GWP based on site-specific characteristics. However, it is restricted to turbine capacities of up to 2 MW and one type of subsea cable (33 kV). The authors suggested that access to such parameterised models would support better informed decisions and a more accurate reporting of GHG emissions, especially at the national level. However, currently the user cannot configure their own OWF according to their desired specifications. Furthermore, the modelling is restricted to GWP only, with no possibility to estimate other LCA impacts.

3 Methods

3.1 Overview of the model

As indicated in Figure 1, the MEAOW model follows the LCA methodology defined by the ISO 14040/44 standards (ISO, 2006a, 2006b). It consists of four parts, to match the four LCA phases: goal and scope definition, inventory analysis, impact assessment and interpretation. For greater accessibility and simplicity of use, the model was developed in Excel.

3.1.1 Goal and scope definition

The main goal of the studies carried out via MEAOW is to estimate the life cycle environmental impacts of electricity generation from offshore wind electricity. As indicated in Figure 2, the model takes a cradle-to-grave approach to enable consideration of raw materials, manufacturing and transportation of wind turbine components and other supporting infrastructure, their assembly and installation, maintenance and end-of-life waste management. The components included in the model are listed in Figure 2. Onshore substations and cabling, as well as onshore transmission and distribution of electricity, are excluded as the focus is on OWF; besides, these will be common to other electricity-generating technologies.

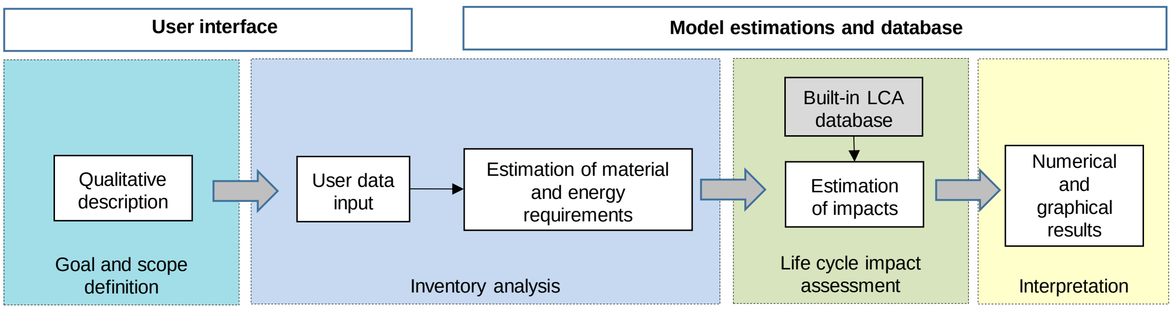

Figure 1 Overview of the MEAOW model for estimating the LCA impacts of offshore wind electricity

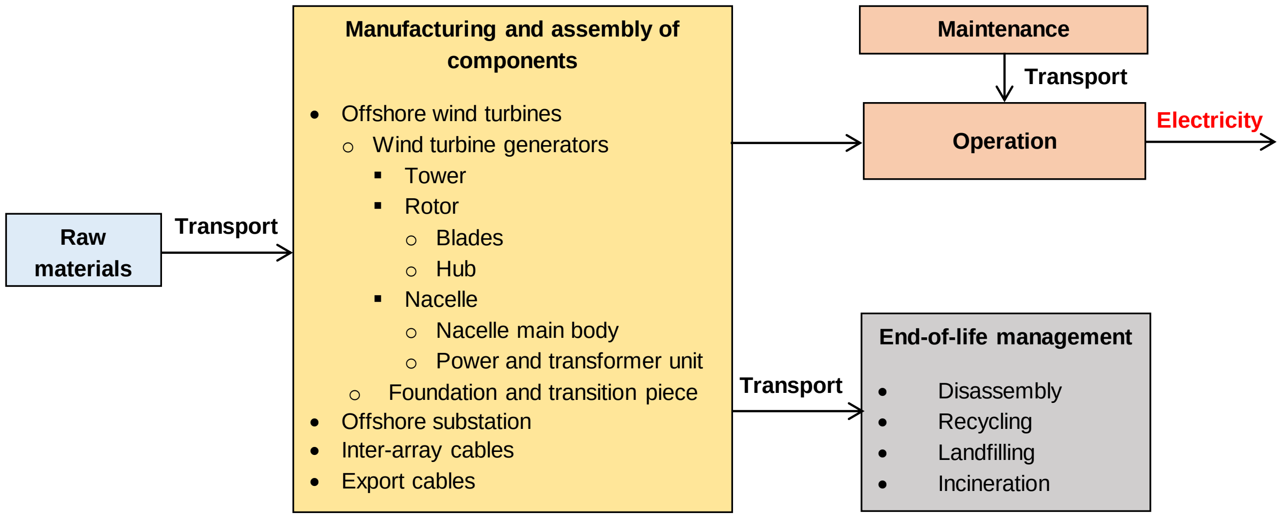

Figure 2 Life cycle of offshore wind electricity included in the MEAOW model

Two functional units are considered in the model for each OWF:
- generation of electricity over the lifetime of the OWF; and
- generation of 1 kWh of electricity by the OWF, based on its lifetime generation.

3.1.2 Inventory analysis

This part of the MEAOW model comprises both user-specific and built-in (default) inventory data listed in Table 1. These are available in the “Inventory” sheets in the model. There are 20 inventory sheets, each corresponding to a different OWF and/or type of turbine. They contain both the user and built-in data which were populated as part of this research and correspond to the UK OWF considered here. Each sheet can be modified to suit the user needs and more sheets (i.e. OWF) can be added if needed. Although the model is designed for OWF comprising a number of installations, it is also possible to consider a single wind turbine if desired.

Each inventory sheet contains the life cycle stages shown in Figure 2: manufacture and assembly of components; operation and maintenance; and end-of-life waste management. To minimise the user effort, most of the data in these sections are pre-populated, with only few further data required. These include specifying the type of wind turbine, total number of turbines, their capacity factors and the lifetime. The last two are used to estimate total electricity generated by the OWF. Alternatively, if the total electricity generation is known, the capacity factor does not need to be specified. The other user data are related to the distances from the manufacturing site to the location of the OWF, the scale of the foundations and substations, the length of the cables and information on maintenance of the turbines.

The built-in data comprise the composition and quantities of different components for each turbine type, as well as the recycling rates of metals at the end of the OWF’s life. All the default data can be changed by the user if required.

Once all the user data have been specified, they are used by the model together with the pre-defined values to estimate the total material and energy requirements in the life cycle of the OWF over its lifetime. The inventory sheets also show the specific life cycle inventory data associated with relevant data inputs. These are sourced from Ecoinvent v2.2 (Hischier et al., 2010) and are not changeable by (nor accessible to) the user.

The next sections provide further details on the inventory data available in the model for different life cycle stages. They were collected from publicly-available data from different wind turbine manufacturers (Ormiston, 2012; Siemens AG, 2015a, 2015b, 2015c; Vestas Wind Systems, 2007, 2008a, 2008b), confidential data and literature, as detailed below.

Table 1 User and pre-defined (default) data in the inventory part of the model

User input	Default data by wind turbine type[a]
Wind turbine type	Capacity
Number of wind turbines	Weight of the tower
Capacity factor	Weight of the nacelle
Distance between manufacturing and onshore point by land	Weight of the nacelle
Distance between manufacturing and onshore point by waterways	Weight of the power unit/transformer unit
Distance between the onshore point and the centre of the wind farm	Weight of the rotor
Distance between the onshore point and end-of-life-treatment facility	Weight of the blades
Lifetime	Weight of the hub
Substation total weight	Rate of metals recycling[b]
Foundation pile length and weight	Rate of recycled metals used[b]
Transition pile length and weight	Rate of metals lost during recycling[b]
Inter-array cable burial depth, nominal voltage and length	
Export cable burial depth, nominal voltage and length	
Annual lubricant requirement	
Times of travel required by barge and helicopter	
Maintenance crew and equipment weight	
Recycling, landfill and incineration rates for the oil, metal, plastic and glass materials	

[a] Most data depend on the choice of the wind turbine type, except for those specified in the footnote below. They can be changed by the user if required.
[b] These data will vary by region and can be changed as required.

3.1.2.1 Manufacture and assembly

As indicated in Figure 2, the main components of an OWF are wind turbines, offshore substations and inter-array and export cables. The turbines comprise electricity generators and foundations. The latter consist of a steel monopile (or a jacket in some cases) and a transition piece on which the generator is mounted. The inter-array cables are used to connect the turbines with the offshore substations while the export cables transmit electricity onshore. These components are discussed in turn below.

3.1.2.1.1 Wind turbines

Wind turbine generators (WTG): The key components of WTG are a tower, rotor and nacelle (Figure 2). The rotor comprises blades and a hub and the nacelle is divided here into the main body and a power/transformer unit. The inventory data in the model are available for seven types of WTG classified according to their rotor diameter (*d*) and capacity (*C*) as small ($d < 80$ m; $C = 2$ MW), medium (80 m ≤ d < 120 m; 2 MW ≤ C ≤ 3.6 MW) and large (d ≥ 120 m; 3.6 MW ≤ C ≤ 5 MW). Based on this classification, there is one small, four medium and two large WTG, here respectively referred to as S2, M2, M2.3, M3, M3.6, L3.6 and L5, where the letter denotes the size and the number the capacity of the WTG. These are listed in Table 2, together with the total weights of each component. They are based on real WTG but their actual types are concealed in the table and the model for confidentiality reasons.

The material composition of the components given in Table 3 was calculated based on the detailed (confidential) data for specific types of generator and blade provided by manufacturers. These data are used to estimate the total material requirements for each component. A cut-off criterion was applied to exclude materials with a mass contribution below 1%; the rest of the materials were scaled up equally to make up the shortfall of 1%. The model assumes the same material composition for the wind turbine components of all types of turbine for two reasons: first, more specific modelling would require data that only manufacturers have, and secondly, this reduces the complexity of the model, making it more user friendly.

The other data considered in the model are related to energy used for manufacturing of different WTG types and were sourced from manufacturers. The energy mixes correspond to the European region (utilising the Union for the Coordination of Transmission of Electricity (UCTE) dataset) because the various parts of the WTG can be manufactured in different European countries.

All the above data are available in the model as default/pre-defined values and are populated in the inventory once the user selects the type of WTG. Therefore, no other input is needed by the user, unless they wish to override the existing data and provide their own.

Table 2 Total weight of components for different types of wind turbine generator (tonnes)[a]

Component	S2	M2	M2.3	M3	M3.6	L3.6	L5
Tower	91	130	162	160	255	210	221
Rotor	23	37	60	41	95	100	125
Blades	12	19	35	22	55	58	56.5
Hub	11	18	25	19	40	42	68.5
Nacelle	57	67	82	70	125	140	315
Nacelle main body	50	59	73	62	111	124	279
Power/ transformer units	7	8	9	8	14	16	36

[a] Source: Ormiston (2012), Siemens AG (2015a, 2015b, 2015c), Vestas Wind Systems (2008a, 2008b, 2007). The actual types of WTG are concealed to preserve confidentiality. S2: d < 80 m, C = 2 MW; M2-M3.6: 80 = d < 120 m, C = 2 - 3.6 MW; L3.6: d ≥ 120 m; C= 3.6 MW; L5: d ≥ 120 m; C = 5 MW. d: rotor diameter; C: capacity.

Table 3 Material composition of different wind turbine components

Component	Contribution	Component	Contribution
Tower		Nacelle main body	
Steel (low alloyed)	98%	Cast iron	47%
Aluminium	2%	Steel (low-alloyed)	45%
Blades		Steel (chromium)	3%
Glass fibre	67%	Steel (electric)	3%
Epoxy resin	26%	Copper	2%
Wood (mix)	5%	Aluminium	1%
Polypropylene	2%	Power/transformer units	
Hub		Steel low alloyed	52%
Cast iron	46%	Steel electric	20%
Steel (chromium)	27%	Copper	19%
Steel (low alloyed)	24%	Aluminium	5%
Glass fibres	3%	High density polyethylene	4%

Foundations: These will vary across different OWF as they are dependent on site characteristics, such as water depth. Therefore, user data are required to specify the length and weight of monopoles and transition pieces. Based on manufacturer data, these consist of steel (97.2%), sand (1.5%) and cement (1.3%). This composition is used in the model to determine the total amount of the materials required to build and install the foundations.

While the default values in the model correspond to the monopile foundation, other types can also be defined by providing user-specific data. These data should be available from the developer and in some cases they can be found in online databases (4C Offshore Ltd, 2016; LORC, 2015).

3.1.2.1.2 Substations

Substations are used to convert to a higher voltage the electricity generated by WTG to minimise transmission losses. The size and number of substations will depend on the size of the OWF. The only user input required here is the total weight of offshore substations. This information is then used by the model to estimate the amounts of materials needed to construct the substations as well as the oil used in the transformers. These estimates are based on the following contributions of construction materials and oil to the total weight of substations (Arvesen et al., 2013): 82% steel, 6% aluminium, 3% copper and 9% oil. In cases where the distance from the shore is short and offshore substations may not be used, the user can set its weight to zero. In addition, the pre-defined values can be changed if specific information is available.

3.1.2.1.3 Cables

Two data inputs are required from the user for both the inter-array and export cables: the burial depth and their length. Eleven types of inter-array and export cables can be specified for each, based on their nominal voltage and conductor cross section. For the inter-array cables, these range from 11 kW/70 mm^2 to 33 kW/800 mm^2 and for the export cables from 11 kW/70 mm^2 to 150 kW/1000 mm^2. These inputs are used by the model to estimate the resources required for manufacturing the cables based on data from industry and literature (ABB, 2010; Arvesen et al., 2013), as well as authors' own estimates. The installation of the inter-array and export cables is also taken into account based on their length and burial depth. For further details on the inventory data, see Tables S1 and S2 in the Supplementary Information (SI).

3.1.2.2 Operation and maintenance

For the operation and maintenance stage, the model considers the amount of lubricant used annually by each wind turbine and transportation distances and the weight of the maintenance crew and equipment. These data are provided by the user and are used by the model to estimate the resource requirements. The equipment data, if not readily available to the user, can be obtained from the developer or from the online databases mentioned earlier (4C Offshore Ltd, 2016; LORC, 2015).

3.1.2.3 End-of-life waste management

This life cycle stage does not require any user inputs. Instead, the model uses the values for the components defined previously to estimate the total amount of materials that will need to be treated after decommissioning, taking into account pre-defined recycling and landfilling rates. These rates can be changed by the user, if desired. The following materials are considered: aluminium, cast iron, steel, chromium steel, copper, lead, lubricating oil, glass fibres, epoxy resin and plastics (high density polyethylene and polypropylene).

In addition to the recycling rates, the proportion of secondary materials used for manufacturing of the components is also considered, alongside the rate of materials lost during the recycling process for the following metals: aluminium, copper, steel, chromium steel, cast iron and lead. Based on these data, the model calculates the amount of material that actually enters the recycling process as well as how much of the virgin material can be avoided so that the system can be credited for avoiding the impacts of its production. Thus, system expansion (or the avoided burdens approach) is used for this purpose, in accordance with the ISO 14040/44 standards (ISO, 2006a, 2006b).

It should be noted that during decommissioning of an OWF, the foundation parts will typically be left in the seabed to reduce costs and minimise disruption to benthic life (Greater Gabbard Offshore Winds Ltd., 2007). For this reason, the amount of steel left in situ is excluded from the end-of-life treatment.

3.1.2.4 Transportation and other data

As indicated in Figure 2, transport is considered across the whole life cycle of the OWF. To estimate the resource requirements related to transportation, the user is required to specify transportation modes and distances of the components from their manufacturing site to the OWF and from there to treatment facilities after decommissioning. These inputs are combined by the model with the weights of the components to determine fuel requirements for different transportation means. The latter include lorry transport, shipping and helicopter transfers to the OWF (the latter for maintenance).

The final information required from the user is the lifespan of the OWF and the total amount of electricity generated annually or the capacity factor to enable estimation of the lifetime electricity generation. This simplified approach assumes that electricity generation is the same every year over the lifetime of the OWF. However, it is unlikely that this will be the case, as electricity generation will depend on the weather and other factors, such as grid management. To overcome this limitation, the user could use historical data for the previous years if available or estimate the electricity generated based on the rolling load factor (RLF). The RLF represents the average capacity (load) factor for all available rolling 12-month periods for each OWF. For example, if for a 100 MW OWF the capacity factors for three 12-month periods are 20% for April 2017-March 2018, 28% for April 2018-March 2019 and 21% for April 2019-March 2020, then the RLF will be equal to: (20%+28%+21%)/3 = 23%. The average annual electricity generation is then estimated based on the total installed capacity, the maximum annual operating hours and the RLF as follows: 100 MW x 8760 h x 23% = 201,480 MWh/y.

3.1.3 Life cycle impact assessment

This part of the MEAOW model estimates the life cycle environmental impacts based on the input data provided in the Inventory sheets and life cycle inventory (LCI) data sourced from Ecoinvent. The later were used in GaBi 7.3 (Thinkstep AG, 2016) to estimate the unit impacts for each material (e.g. per kg of steel), energy type (e.g. per kWh electricity) and activity (e.g. per t·km for road transport). The unit impacts are stored in the built-in LCA database within the model (Figure 1). The database is not accessible to the user to avoid accidental overwriting and also to preserve confidentiality.

The estimated impacts for each component and life cycle stage of the OWF are provided in the "Impacts" sheets. Like the Inventory sheets, there are also 20 Impacts sheets. The results are presented in three sets of tables: the first two show the environmental impacts for the two functional units (total generation over the lifetime of the OWF and per kWh of electricity generated) for each component and life cycle stage, while the third table presents a contribution analysis, showing their percentage contribution to the total impacts. The per-kWh impacts are estimated based on the total lifetime generation, taking into account the RLF of these OWF.

The impacts are estimated according to the CML 2001 impact assessment method, the April 2015 update (Guinée et al., 2002). All 11 impacts available in this method are considered as follows: abiotic depletion potential of elements (ADP elements) and fossil fuels (ADP fossil), acidification potential (AP), eutrophication potential (EP), freshwater aquatic ecotoxicity potential (FAETP), global warming potential (GWP), human toxicity potential (HTP), marine aquatic ecotoxicity potential (MAETP), ozone layer depletion potential (ODP), photochemical oxidant creation potential (POCP) and terrestrial ecotoxicity potential (TETP). For definitions of the impacts, see Table S4 in the SI.

3.1.4 Interpretation

To help with the interpretation of the results, the impacts in each of the three tables in the Impacts sheets are presented graphically in the "Interpretation" sheets. These graphs are created automatically once the results have been estimated. They can be edited and formatted as desired by the user, as well as further graphs added.

3.2 Model application and validation

The application of the model is demonstrated by considering the actual OWF based in the UK. In total, 20 farms are considered, using 2015 as the reference year. The main reason for choosing these OWF is the availability of data on their actual electricity generation for at least 12 months which means that they should be operational in the reference year. For this reason, the post-2015 OWF are excluded from the study. In addition, since the goal is to assess OWF with their supporting offshore infrastructure, demonstration projects are not considered.

The data for the 20 OWF are summarised in Table 4 with the detailed data available in the model in the inventory sheets. These data were sourced from RenewableUK (2017), apart from the distance from the shore which is from 4C Offshore (2016). The RLF data for estimation of the annual generation of electricity were obtained from the Renewable Energy Foundation (2016).

Table 4 Selected UK offshore wind farms and their characteristics[a]

Offshore wind farm[b]	Wind turbine type[b]	Number of wind turbines	Total OWF capacity (MW)	Rolling load factor, RLF (%)[c]	Estimated annual generation based on RLF (GWh/y)	Distance from shore (km)	Number of sub-stations	Year of commissioning
OWF1	M3	30	90	35.6	281	12.7	1	2006
OWF2	S2	2	4	11.4	4	1.1	0	2000
OWF3	M3.6	25	90	35	276	8	0	2007
OWF4	M3.6	140	504	36.4	1607	32.5	2	2012
OWF5	M3.6	48	172.8	35.5	537	7.4	1	2010
OWF6	M3	30	90	31.5	248	9.8	0	2005
OWF7	L3.6	75	270	34.2	809	9.1	1	2013
OWF8	L3.6	175	630	41.7	2301	27.6	2	2013
OWF9	M3.6	54	194.4	34.1	580	6.9	0	2009
OWF10	M2	30	60	34.1	179	9.1	0	2003
OWF11	L5	30	150	39.2	515	12.3	1	2012
OWF12	M3.6	25	90	34.2	270	10.7	0	2009
OWF13	M3	60	180	34.8	548	11.5	2	2010
OWF14	M2	30	60	30.6	161	3.5	0	2004
OWF15	M3.6	88	316.8	30.3	841	21.4	2	2012
OWF16	M2.3	27	62.1	31.4	171	2.2	0	2013
OWF17	M3	100	300	30.8	809	17.7	1	2010
OWF18	M3.6	51	183.6	40.6	653	19.3	1	2011
OWF19	L3.6	51	183.6	44.6	717	22	2	2012
OWF20	L3.6	108	388.8	41.4	1410	20.1	1	2014

[a] Source: 4C Offshore Ltd (2016); Renewable Energy Foundation (2016); RenewableUK (2017).
[b] Data refer to real OWF in the UK. Their names and turbine types are not shown to preserve confidentiality. S, M and L refer to small, medium and large turbines. See the footnote to Table 2 for further details on turbine types.
[c] Rolling load factors (RLF) sourced from (Renewable Energy Foundation, 2016).

As seen in Table 4, the OWF have moved over time from approximately 1 km from the shore to approximately 33 km, making it possible to harness higher wind speeds. Along with that, increasing the number of installed turbines from 2 to 175 and the project capacity from 4 to 630 MW resulted in increasing the generated electricity from 4 GWh to 2301 GWh. The utilisation of newer wind turbine models also contributed to this because the capacity increased from 2 to 5 MW. The newer models are also able to withstand more challenging weather conditions.

However, these changes come at a cost in terms of material and energy requirements, as demonstrated in Table S3 in the SI which summarises the weights of components across all 20 OWF. This raises the question of whether the additional resource requirements would result in a considerable increase in environmental impacts. This is discussed in the Results and discussion section.

Apart from the different characteristics of the selected UK offshore wind farms, some common assumptions were made. Since the wind turbines are produced in Europe, the following assumptions on transportation distances were made: 800 km for shipping to the UK, 200 km for inland transport to the onshore point and another 200 km from there to the end-of-life treatment facility after decommissioning.

It was also assumed that the lifetime of all OWF is 20 years and that the percentages of the materials being incinerated and landfilled, as well as the recycling rates, are common across the installations. These values are summarised in Table 5.

The following section presents the environmental impacts of the 20 OWF calculated by the MEAOW model based on the inventory data discussed above. To validate the model and the results, the estimated environmental impacts were compared to literature values, as also discussed in the next section.

Table 5 End-of-life waste treatment rates [a]

Material	Landfill	Incineration	Recycling	Secondary material usage	Material losses in recycling
Glass fibres	100%	0%	0%	-	-
Epoxy resin	100%	0%	0%	-	-
Lubricating oil	100%	0%	0%	-	-
High density polyethylene	0%	100%	0%	-	-
Copper	0%	10%	90%	32%	31%
Lead	5%	5%	90%	74%	54%
Aluminium	5%	5%	90%	39%	3%
Cast iron	10%	0%	90%	42%	0
Steel	10%	0%	90%	42%	11%
Chromium steel	10%	0%	90%	42%	0

[a] Source: British Metal Recycling Association, (2016), Frischknecht et al. (2005), Vestas Wind Systems (2006).

4 Results and discussion

The focus in this section is on the impacts per kWh of electricity generated; for the impacts over the lifetime of the OWF, see the model (the Impacts sheets) and Figure S1 in the SI. This is followed by a comparison of the results with literature and then by the contribution analysis to identify the hotspots. Finally, the OWF are compared to identify factors that may potentially influence the impacts and possibly help to predict them for other existing or future OWF without the need for detailed LCA modelling.

4.1 Impacts per kWh electricity generated

The impacts estimated for each of the 20 OWF (in the Impacts sheets in MEAOW) are summarised in Figure 3. As can be seen, they vary considerably across the farms. For example, the GWP ranges by a factor of three, from 6.42-19.48 g CO_2 eq./kWh. Similar variations are found for the other impacts with the maximum values 2.2-3.2 times higher than the minimum. These results show the importance of considering the specific design and operating characteristics of each OWF to obtain a true picture of their environmental impacts and understand better how they compare to other low-carbon options. For instance, the maximum GWP (19.48 g CO_2 eq./kWh) is up to four times higher than that of nuclear power (5.5-7 g CO_2 eq./kWh) and several-fold greater than the impact of hydroelectricity (2-13 g CO_2 eq./kWh), but it is within the range for geothermal (15-53 g CO_2 eq./kWh) (Parliamentary Office of Science and Technology, 2011). However, assuming the minimum value in the GWP range (6.42 g CO_2 eq./kWh) would make offshore wind electricity similar to nuclear and hydro and better than any other renewables.

The impacts of different OWF are compared in Figure 4 via a heatmap; for the normalised values, see Table S5 in the SI. It can be seen that OWF2 has the highest impacts followed by OWF4, 10, 12, 15 and 16; OWF9 shows particularly high values for FAETP and MAETP. Their individual characteristics vary widely, including the year of installation (2000-2013), the number of substations (0-2), total amount of the materials used for construction (524-106,189 t), WTG capacity (2-3.6 MW), total installed capacity (4-504 MW) and distance from the shore (1.1-32.5 km). However, one aspect they have in common is the relatively low capacity factors (30.3-36.4%, excluding the outlier OWF2 with 11.5%) compared to the rest of the OWF considered here (Table 4) which could potentially explain their higher impacts.

However, looking at the farms with the lowest impacts, including the GWP (OWF1, 5, 6, 11, 13 and 14), the influence of the capacity factors on the impacts appears less important as they are not much higher (30.6-39.2%). Therefore, even the farms with lower capacity factors could have low impacts. On the other hand, OWF19 that has the highest capacity factor (44.6%) as well as the farms with capacity factors above 40% (OWF8, 18, 20) do not have the lowest impacts. This could be explained by the distance from the shore which is greater than the average (>19.3 km) as well as the greater amount of construction materials which is also greater than the average (> 41 kt). The latter is particularly high for OWF8 and 20 (143.1 kt and 86.5 kt respectively). This again reinforces the point that the impacts of different OWF cannot be simply averaged or linked to one particular parameter without taking into account their various other characteristics.

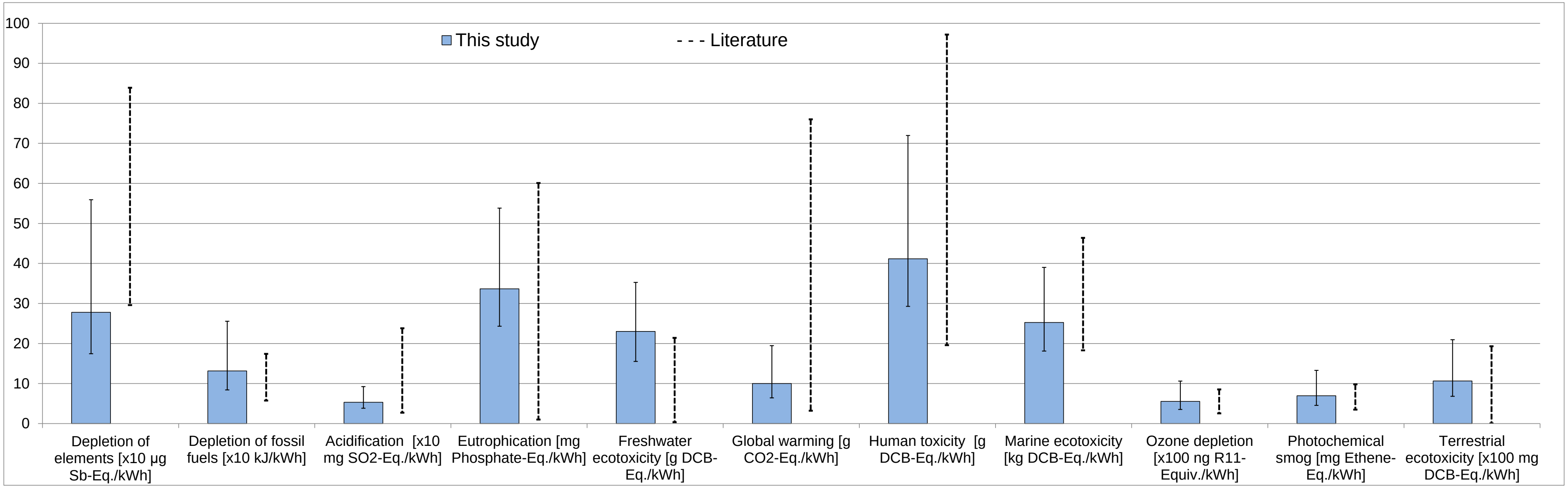

Figure 3 Life cycle environmental impacts of UK offshore wind electricity, showing a range of values across the 20 wind farms considered in comparison with literature values

[Literature values sourced globally from Arvesen et al. (2013), Mendecka and Lombardi (2019), Murai and Aono (2009), Stamford and Azapagic (2012), Wagner et al. (2011), Weinzettel et al. (2009).]

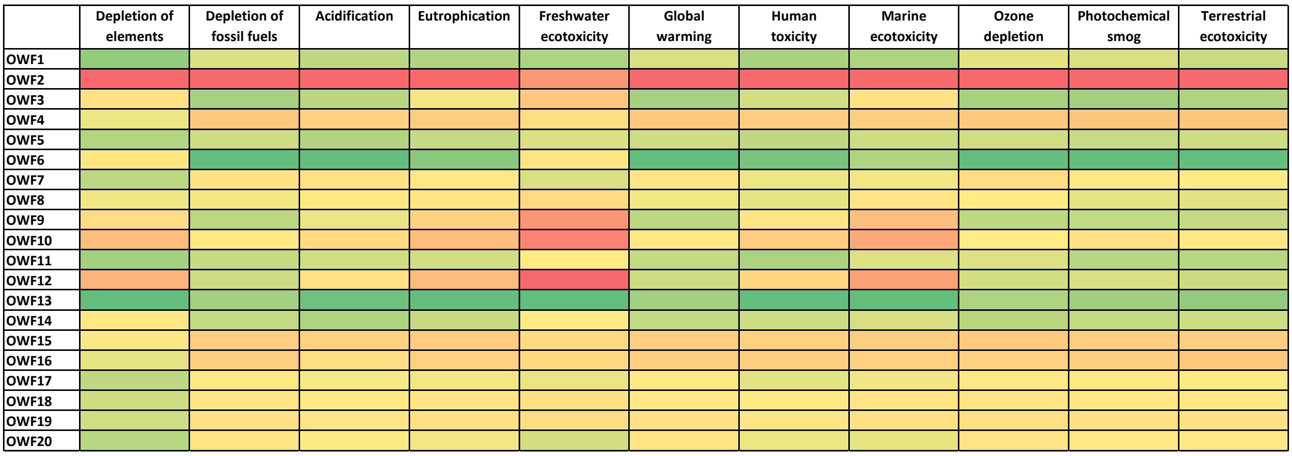

Figure 4 A heatmap comparing the impacts of different offshore wind farms
[Legend: Green represent the lowest, amber medium and red the highest impacts. The comparison of OWF for each impact is normalised relative to the OWF with the highest value for that impact.]

Like the above-mentioned worst installations, OWF1, 5, 6, 11, 13 and 14 also differ widely in the year of construction (2004-2012), the number of substations (0-2), total amount of construction materials (7632-37,644 t), WTG capacity (2-5 MW) and total OWF capacity (60-180 MW). It is not immediately obvious which of these parameters or their combinations may be influencing the impacts. This is explored further in Section 4.4. Prior to that, the next section compares the results obtained here with those reported in the literature for offshore wind installations around the world.

4.2 Comparison with literature

It can be observed in Figure 3 that the majority of the impacts of the UK OWF either fall within or are close to the literature ranges. The greatest discrepancies are noted for the depletion of elements, for which some OWF have values lower than the literature range, and freshwater ecotoxicity, where certain OWF show a higher impact than in the literature. It is not possible to speculate on the reasons for these differences due to the lack of detailed information in the literature and also due to the fact that many factors influence the total impacts, as discussed above, in addition to different background data in different countries.

4.3 Contribution analysis

The aim of this contribution analysis is to identify the hotspots in the life cycle of OWF to be able to explore in the next section if and how they may affect the impacts of different OWF. First, the average contributions of different life cycle stages across the 20 OWF are discussed. The full contribution ranges can be found in Table S6 in the SI and the contributions for each OWF are available in the model (Impacts sheets); they are also discussed briefly further below.

On average, manufacturing of the construction components accounts for the vast majority (90-100%) of the impacts (Figure 5). The only exception to this is freshwater ecotoxicity, where the main contributor is incineration of end-of-life waste (38%) (Hischier et al., 2010). The main reason for the high contribution of the construction components to the impacts is the high quantity of metals required for their production. Among these, the main contributors are the WTG and the foundations. The former contributes the most to elements depletion (34%), acidification (39%), eutrophication (34%), human toxicity (41%) and marine ecotoxicity (35%). The foundations are the hotspot for fossil fuel depletion (47%), freshwater ecotoxicity (26%), GWP (47%), ozone depletion (44%), photochemical smog (47%) and terrestrial ecotoxicity (50%). It is also worth noting that the combined contribution of the cables (inter-array and export) to elements depletion exceeds 46%. However, their average contribution to most other categories is relatively small (4.8-10.8%), except for human toxicity, acidification, marine ecotoxicity and eutrophication (18.1-26.2%). The substations, although they may require up to 5860 t of material per OWF, still have a relatively low contribution (0.7- 3.3%).

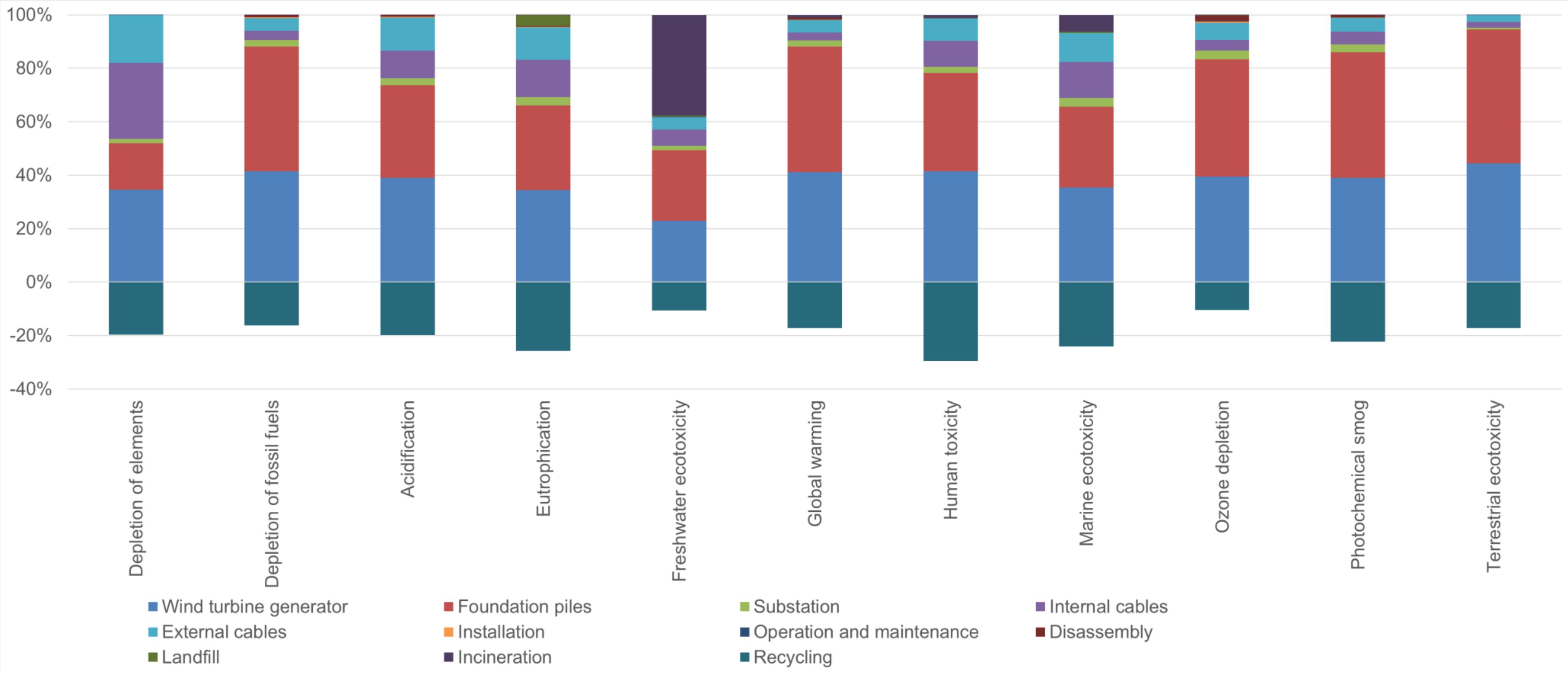

Figure 5 Average contribution of different life cycle stages to the impacts of the 20 UK offshore wind farms

The minimum and maximum values in Table S6 suggest that WTG and the foundations have the highest contributions, following the same trend as for the average values discussed above. One exception is depletion of elements, where the external cables show the highest maximum contribution of 49%. The contribution of the substations is also in some cases more important than their average would suggest, with a maximum of up to 11% and the majority of the categories with over 7%. The minimum contributions of the substations and inter-array cables are very low (approaching 0%) in cases where an OWF is very close to the shore and the external cable is the only ancillary component added to the WTG and the foundations.

The rest of the life cycle stages, as seen in Table S6, have low contributions, with installation, operation and maintenance, and disassembly contributing in total <1.2% across the impacts, except for ozone depletion (2.8%). Incineration shows a similarly small contribution (<1%), except for marine ecotoxicity (6.3%) and freshwater ecotoxicity (38%). The contribution of landfilling is negligible (<0.6%) but slightly higher for eutrophication (4%). Recycling can reduce the impacts on average by at least 10% and human toxicity by 30%.

4.4 Influence of different OWF characteristics

As discussed in section 4.1, the impacts differ significantly between the individual installations. Thus, this section aims to identify any trends in the impacts related to the differences in the OWF installations that could potentially be used to predict the impacts without the need for detailed LCA modelling. The following characteristics are selected for the analysis: the year of commencing operation, capacity of wind turbines, capacity of the whole OWF, capacity factor, amount of construction materials and distance from the shore. The motivation for choosing each of these parameters is given in the respective sections below.

4.4.1 Year of installation

Typically, as a technology matures, it becomes more efficient, due to improved design and the economies of scale. Therefore, the age of installation could influence the impacts. To test this hypothesis, the impacts of each OWF are plotted in Figure 6. against their respective year of commencing operation. Applying the best-fit correlation (polynomial), most of the impact categories have an R^2 in the range of 0.63-0.66, suggesting that the age of technology has some influence on the impacts. Human toxicity (R^2=0.57) and eutrophication (R^2=0.47) show a weak correlation, while freshwater and marine ecotoxicity are not affected by the age of installation (R^2=0.18 and 0.3, respectively). Note that the last four impacts are not shown in the figure for greater clarity.

According to the best-fit correlation, the impacts gradually declined from 2000 to 2008, after which a gradual upward trend can be noticed for installations commencing operation after 2008 (Figure 6). The reason for this could be observed in Figure 7 which shows that, as the technology evolved over time, the individual WTG capacity and the total OWF capacity increased, along with the distance from the shore and the total mass of construction materials. Most of these parameters increased more rapidly after 2008, with the greatest increase found for construction materials. An exception is the capacity factor which appears to have plateaued off after that year. The combined effect of these trends could explain the gradual apparent increase in the impacts of OWF from 2008 onwards, as discussed further in the next sections for each of the OWF characteristics.

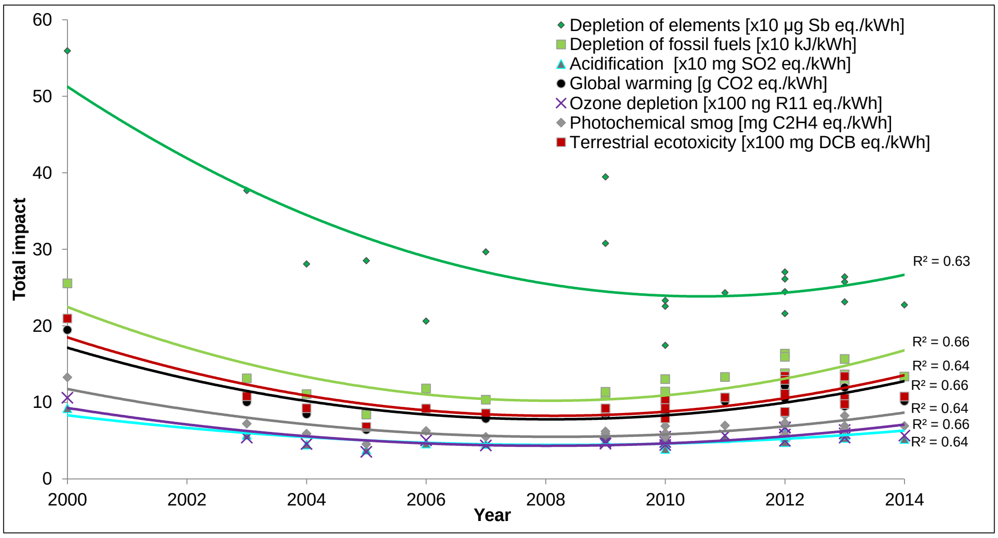

Figure 6 The effect on the environmental impacts of the year of commencing operation

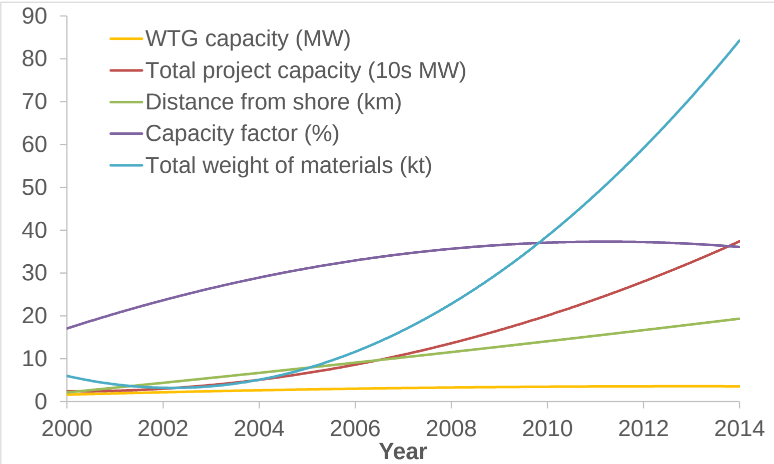

Figure 7 Trends in the characteristics of UK offshore wind farms over time

4.4.2 Wind turbine capacity

Higher capacities of WTG would be expected to reduce the impacts due to the economies of scale. However, using the best-fit correlation suggests that the capacity has no influence on the impacts, with the R^2 value ranging from 0.07-0.27 across the categories (see Figure S2 in the SI). This finding is in agreement with the study by Bhandari et al. (2020) which focused on GWP and reported no correlation between the GWP and the turbine capacity. One explanation could be that, although increasing the WTG capacity and electricity generation lead to lower impacts per kWh, the material requirements for the larger turbines increase as well. For example, the capacity of a 5 MW WTG is 1.7 times greater than that of a 3 MW unit, but its total weight is 2.8 times higher (see the Inventory sheets in the model).

4.4.3 Total OWF capacity

It might also be expected that an increase in the total capacity of OWF would lower the impacts due to the economies of scale, since more turbines share common supporting infrastructure. However, as for the WTG capacity, this parameter shows no apparent influence on the impacts (R^2=0.07-0.21), possibly for the same reasons as discussed for the capacity of the individual turbines.

4.4.4 Capacity factor

A higher capacity factor would be expected to have a positive effect on the impacts as more electricity is generated, leading to lower impacts per kWh. This general trend can be noticed in Figure 8, with R^2 ranging from 0.63-0.70 for most impacts. However, the trend changes slightly for the capacity factors above 40%. This applies to the OWF with bigger WTG (>3.6 MW) and more distant from the shore (>19 km), thus requiring higher amounts of construction materials and energy for cables, substations and maintenance. Similar to the age of the installation (Section 4.4.1), the exceptions to the trends are eutrophication and freshwater and marine ecotoxicity, which exhibit little or no dependency on the capacity factor (R^2=0.11-0.45; not shown in the figure for clarity).

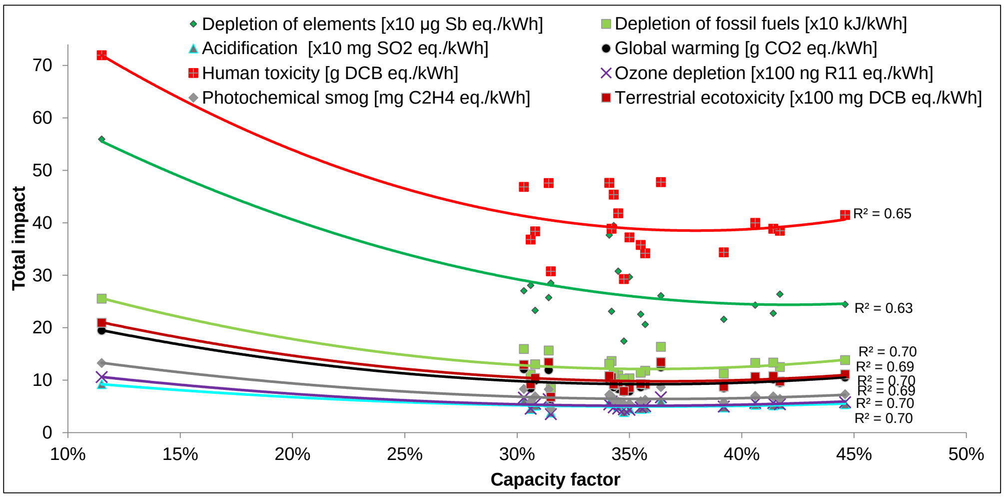

Figure 8 The effect on the environmental impacts of the capacity factor

4.4.5 Construction materials

Based on the contribution analysis, the construction materials were identified as the main environmental hotspot. As their total amount varies across the OWF, it is interesting to explore how the variation in this parameter may affect the impacts. A higher requirement for materials for larger installations would be expected to increase the life cycle impacts. However, surprisingly, there is no correlation between the total amount of materials and the impacts (R^2=0.02-0.33). This could be due to the fact that larger installations generate more electricity, hence countering the negative effect of higher material requirements.

4.4.6 Distance from the shore

This parameter would be expected to have opposing effects on the impacts as going further away from the shore allows the OWF to harness more wind and produce more electricity but it also increases the infrastructure and maintenance requirements. This may be the reason that the best-fit correlation is very weak (R^2=0.10-0.37), thus suggesting that distance from the shore has no influence on the impacts.

5 Conclusions

This paper presented a new model for estimating life cycle environmental impacts of offshore wind electricity. Two main reasons guided the development of the model. First, the intention was to provide a simplified tool aimed at non-experts to help determine the impacts quickly and easily without the need for collecting an enormous amount of data, typically required in LCA studies. Secondly, the aim was to determine how the impacts of OWF may differ depending on their specific characteristics and whether relationships could be derived between different parameters and the impacts that could potentially be used to avoid detailed LCA studies.

The application and validity of the model were demonstrated by estimating the life cycle impacts of 20 OWF in the UK. The results showed that the impacts differ significantly between different installations, ranging by a factor for 2.2-3.2 depending on many factors, including their age, capacity, capacity factors and distance from the shore. This demonstrates clearly that using average values for the impacts of OWF leads to inaccurate results. And yet, such values are used routinely to support new OWF development as well as energy and climate change policies.

The results also revealed that there was no correlation between most characteristics of the OWF and the impacts. An exception was the OWF age which showed some influence on most impacts, apart from freshwater and marine ecotoxicity. There also appeared to be a trend in impact reductions in earlier installations as the distance from the shore and the technology efficiency increased, despite the simultaneous increase in the total amount of materials required for the construction of OWF. However, in more recent years the efficiency seems to have plateaued, making the ‘building bigger and further’ counterproductive as the increase in the generated electricity does not compensate for the impacts from the additional material requirements. These results suggest that it cannot be assumed that the age, capacity and location of the installation alone can be used as proxies to predict the impacts of offshore wind electricity. Instead, each installation has to be evaluated in its own right, considering its characteristics, including all the above and many other parameters. The MEAOW model developed as part of this work can support such evaluations, helping designers, developers, policy makers as well as the general public determine the environmental impacts of offshore wind electricity quickly and easily, without prior expertise in LCA. The model can also be used for OWF in different countries and world regions by specifying the site-specific parameters, such as the sea depth, capacity factors, component weights, offshore distances and frequency of maintenance. However, some background life cycle inventory data may need to be changed to reflect the region, including the electricity mix and different end-of-life recycling rates. It should also be noted that future changes in the background system will affect the environmental impacts of OWF in general due to the increasing use of renewable energy and increased recycling rates in the production of iron, steel and other metals.

With some modification, the model could also be used for onshore wind electricity, which could be carried out as part of future work. Equivalent models could also be developed for other types of renewables to help bring LCA closer to non-expert users and so support a more informed dialogue on the environmental impacts of different energy options.

Further developments of the model could include incorporation of the latest inventory data (Ecoinvent or other) and, depending on the interests of the users, other impacts assessment methods (e.g. ReCiPE and PEF).

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A model for estimating life cycle environmental impacts of offshore wind electricity considering specific characteristics of wind farms

Victor Kouloumpis and Adisa Azapagic

Supplementary information

Table S1 Resource requirements for different inter-array cables

Nominal voltage (kV)/ diameter (mm^2)	Cable weight (kg/m)	Steel (kg/m)	Copper (kg/m)	Lead (kg/m)	Poly-ethylene (kg/m)	Poly-propylene (kg/m)	Zinc-plating process (m^2/m)	Electricity (kWh/m)	Heat (MJ/m)
11/70	15.0	8.4	0.0	4.8	1.0	0.9	0.3	17.1	116.5
33/95	19.5	9.7	2.1	5.4	1.3	1.0	0.4	22.2	151.5
33/120	20.7	10.0	2.7	5.6	1.4	1.0	0.4	23.5	160.8
33/150	22.1	10.4	3.3	5.8	1.5	1.1	0.4	25.1	171.7
33/185	23.6	10.7	4.1	6.1	1.6	1.1	0.4	26.8	183.3
33/240	25.9	11.0	5.4	6.7	1.7	1.1	0.4	29.5	201.2
33/300	28.2	10.9	6.6	7.9	1.7	1.1	0.4	32.1	219.1
33/400	32.0	10.6	8.7	10.0	1.7	1.1	0.4	36.4	248.6
33/500	36.0	11.7	12.0	9.2	2.0	1.2	0.4	40.9	279.7
33/630	40.9	13.1	16.0	8.2	2.3	1.3	0.5	46.5	317.7
33/800	47.2	16.4	25.4	5.9	3.0	1.6	0.6	53.7	366.7

Table S2 Resource requirements for export cables

Nominal voltage (kV)/ diameter (mm^2)	Cable weight (kg/m)	Steel (kg/m)	Copper (kg/m)	Lead (kg/m)	Poly-ethylene (kg/m)	Poly-propylene (kg/m)	Zinc-plating process (m^2/m)	Electricity (kWh/m)	Heat (MJ/m)
11/70	15	8.40	0.04	4.79	0.99	0.86	0.32	17.06	116.53
33/300	28.2	10.87	6.63	7.91	1.70	1.10	0.41	32.07	219.08
33/500	36	11.74	11.97	9.17	1.95	1.17	0.45	40.95	279.68
33/630	40.9	13.13	16.00	8.20	2.26	1.31	0.50	46.52	317.75
132/300	48	12.93	1.14	0.06	0.01	0.00	2.99	54.25	370.54
132/630	65.2	17.56	1.55	0.08	0.02	0.01	4.06	73.69	503.31
132/800	74	19.94	1.75	0.09	0.02	0.01	4.60	83.63	571.24
132/1000	85.4	23.01	2.02	0.10	0.02	0.01	5.31	96.52	659.24
150/630	69.7	18.78	1.65	0.08	0.02	0.01	4.34	78.77	538.05
150/800	79.8	21.50	1.89	0.09	0.02	0.01	4.97	90.19	616.01
150/1000	90.5	24.38	2.15	0.11	0.03	0.01	5.63	102.28	698.61

Table S3 Estimated weights of components for different offshore wind farms

Offshore wind farm (OWF)	Cables (t)	Substation (t)	Wind turbine (t)	Foundation & transition pieces (t)
OWF1	1094	1266	8130	14,780
OWF2	45	-	342	450
OWF3	1448	-	11,875	9314
OWF4	5472	5860	66,500	126,840
OWF5	1514	1929	22,800	21,878
OWF6	1506	-	8130	6836
OWF7	3564	3420	33,750	41,600
OWF8	12,413	4308	78,750	121,275
OWF9	3312	-	25,650	21,300
OWF10	1406	-	7020	9658
OWF11	1910	1620	19,830	22,500
OWF12	2209	-	11,875	9880
OWF13	1494	3199	16,260	23,478
OWF14	798	-	7020	6000
OWF15	3001	3763	41,800	55,877
OWF16	447	-	8208	12,949
OWF17	3363	2480	27,100	48,052
OWF18	2554	2224	24,225	38,680
OWF19	2712	2224	22,950	47,970
OWF20	5204	3020	48,600	88,128

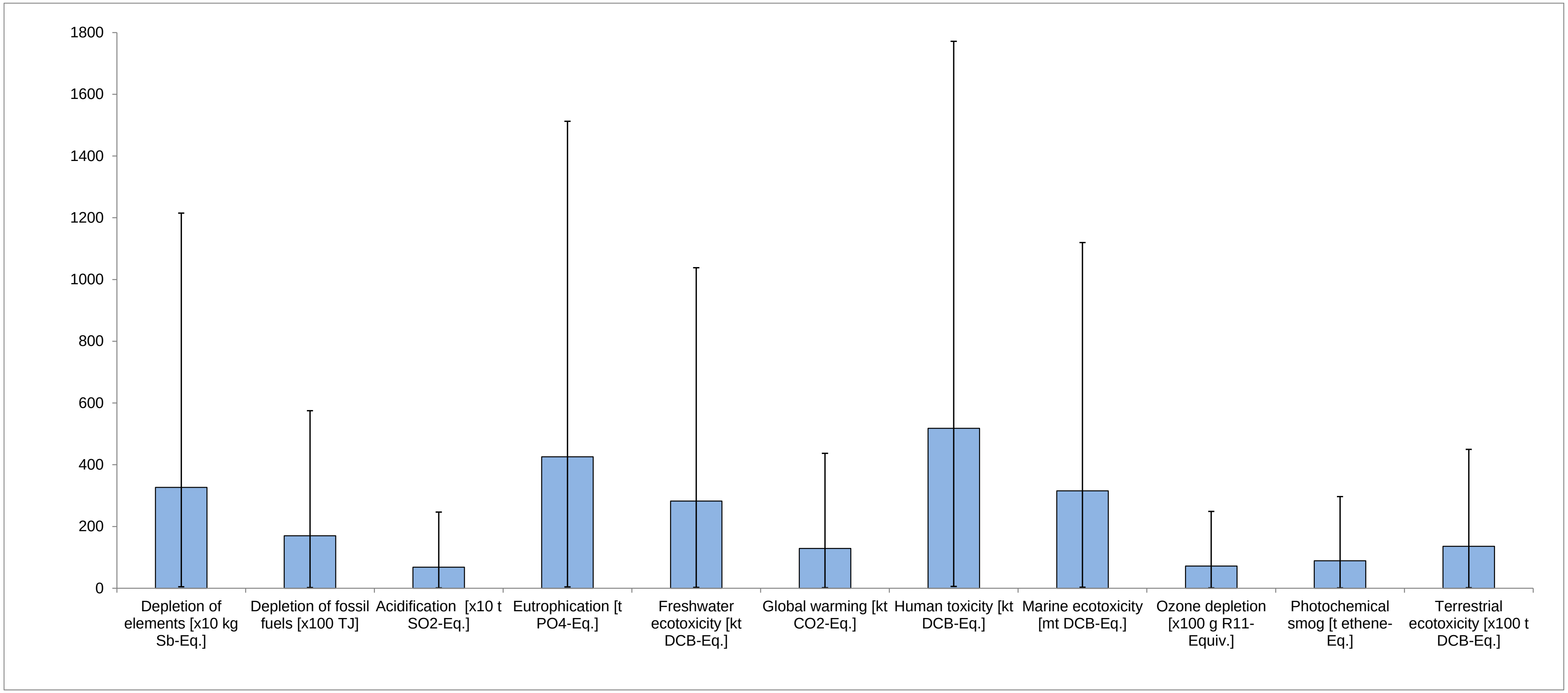

Figure S1 Life cycle environmental impacts of electricity generated by 20 UK offshore wind farms over their lifetime of 20 years
[The graph bars represent the average and the error bars the minimum and maximum values across the farms.]

Table S4 Definition of environmental impacts included in the CML 2001 method[a] and considered in the study

Impact	Definition	Default unit (per functional unit)[b]
Abiotic depletion potential of elements	Depletion of world reserves of metals and minerals	kg Sb eq.
Abiotic depletion potential of fossil fuels	Depletion of world reserves of fossil fuels	MJ
Acidification potential	The potential of acid gases, such as sulphur dioxide, nitrogen oxides and ammonia, to cause acidification of waterways and soil	kg SO_2 eq.
Eutrophication potential	The potential of nutrients to cause over-fertilisation of waterways and soil, which can result in increased growth of algae	kg PO_4 eq.
Freshwater aquatic ecotoxicity potential	The potential of toxic substances to affect freshwater organisms	kg 1,4-DB eq.
Global warming potential	The potential of greenhouse gases to cause global warming and related climate change	kg CO_2 eq.
Human toxicity potential	The potential of toxic substances to affect human health	kg 1,4-DB eq.
Marine aquatic ecotoxicity potential	The potential of toxic substances to affect marine organisms	kg 1,4-DB eq.
Ozone layer depletion potential	The potential of chlorofluorohydrocarbons (CFCs) and other halogenated hydrocarbons to deplete the ozone layer	kg CFC-11 eq.
Photochemical oxidant creation potential	The potential of volatile organic compounds and nitrogen oxides to cause photochemical (summer) smog.	kg ethylene eq.
Terrestrial ecotoxicity potential	The potential of toxic substances to affect terrestrial organisms	kg 1,4-DB eq.

[a] For further details, see: Guinée, J.B., Gorrée, M., Heijungs, R., Huppes, G., Kleijn, R., Koning, A.D., Oers, L.V., Wegener Sleeswijk, A., Suh, S., Udo de Haes, H.A., Bruijn, H. d., Duin, R.V., Huijbregts, M.A.J., 2002. Handbook on Life Cycle Assessment: Operational Guide to the ISO Standards. Kluwer Academic Publishers, Dordrecht.

[b] Note that the units presented in the study may have been scaled, depending on the actual results.

Table S5 Normalised impact values of different offshore wind farms (OWF)

OWF	Depletion of elements	Depletion of fossil fuel	Acidification	Eutrophication	Freshwater ecotoxicity	Global warming	Human toxicity	Marine ecotoxicity	Ozone depletion	Photochemical smog	Terrestrial ecotoxicity
OWF1	0.08	0.20	0.15	0.13	0.12	0.20	0.12	0.12	0.21	0.20	0.17
OWF2	1.00	1.00	1.00	1.00	0.74	1.00	1.00	1.00	1.00	1.00	1.00
OWF3	0.32	0.11	0.14	0.24	0.47	0.11	0.19	0.30	0.12	0.11	0.12
OWF4	0.23	0.46	0.40	0.44	0.35	0.46	0.43	0.43	0.45	0.47	0.47
OWF5	0.13	0.18	0.13	0.16	0.20	0.17	0.15	0.17	0.18	0.17	0.18
OWF6	0.29	0.00	0.00	0.06	0.30	0.00	0.03	0.13	0.00	0.00	0.00
OWF7	0.15	0.31	0.32	0.28	0.20	0.30	0.22	0.24	0.34	0.27	0.26
OWF8	0.23	0.24	0.28	0.29	0.36	0.24	0.22	0.30	0.26	0.22	0.21
OWF9	0.35	0.15	0.22	0.40	0.74	0.15	0.29	0.50	0.15	0.16	0.16
OWF10	0.53	0.28	0.36	0.52	0.85	0.28	0.43	0.64	0.26	0.31	0.28
OWF11	0.11	0.16	0.18	0.18	0.26	0.16	0.12	0.20	0.20	0.14	0.14
OWF12	0.57	0.17	0.32	0.54	1.00	0.17	0.38	0.68	0.18	0.19	0.17
OWF13	0.00	0.11	0.02	0.00	0.00	0.10	0.00	0.00	0.13	0.10	0.08
OWF14	0.28	0.16	0.12	0.16	0.25	0.16	0.18	0.19	0.14	0.16	0.17
OWF15	0.25	0.44	0.41	0.44	0.36	0.44	0.41	0.43	0.45	0.43	0.43
OWF16	0.22	0.42	0.35	0.41	0.36	0.42	0.43	0.42	0.40	0.43	0.47
OWF17	0.15	0.27	0.24	0.23	0.22	0.27	0.21	0.23	0.28	0.27	0.25
OWF18	0.18	0.29	0.27	0.29	0.31	0.28	0.25	0.30	0.30	0.28	0.27
OWF19	0.18	0.32	0.29	0.32	0.33	0.31	0.29	0.32	0.32	0.32	0.31
OWF20	0.14	0.29	0.26	0.24	0.19	0.29	0.22	0.22	0.30	0.27	0.28

Table S6 Contribution of different life cycle stages to the total impacts from the offshore wind farms considered in the study

Life cycle stage	Value	Element depletion	Fossil fuel depletion	Acidification	Eutrophication	Freshwater Ecotoxicity	Global warming	Human toxicity	Marine ecotoxicity	Ozone depletion	Photo-chemical smog	Terrestrial ecotoxicity
Wind turbine generator	Max	45.2%	52.9%	47.5%	46.8%	35.5%	52.5%	49.3%	49.7%	50.8%	48.4%	55.2%
	Average	34.4%	40.9%	38.7%	34.2%	22.8%	40.6%	41.1%	35.1%	39.0%	38.5%	43.8%
	Min	22.0%	31.5%	30.6%	26.6%	15.2%	31.2%	33.4%	26.1%	29.5%	29.5%	33.7%
Foundation piles	Max	26.8%	57.5%	47.2%	44.5%	40.5%	57.8%	49.4%	43.3%	54.7%	58.3%	61.7%
	Average	17.8%	47.4%	35.3%	32.4%	27.0%	47.6%	37.5%	31.0%	44.5%	47.7%	50.7%
	Min	7.8%	36.7%	21.8%	16.9%	11.4%	36.8%	21.5%	15.2%	34.4%	34.8%	38.4%
Substation	Max	5.7%	8.3%	8.8%	10.0%	5.3%	7.4%	7.2%	10.6%	10.6%	9.5%	2.3%
	Average	1.6%	2.5%	2.6%	2.9%	1.5%	2.2%	2.1%	3.1%	3.2%	2.9%	0.7%
	Min	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Inter-array cables	Max	42.4%	5.2%	17.9%	24.8%	10.1%	4.8%	18.5%	23.2%	6.3%	8.5%	4.0%
	Average	28.18%	3.3%	10.2%	13.8%	6.0%	3.0%	9.7%	13.3%	3.8%	4.7%	2.2%
	Min	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Export cables	Max	49.2%	8.4%	26.8%	36.3%	13.9%	7.8%	26.6%	33.8%	10.5%	12.9%	6.0%
	Average	17.92%	4.8%	12.3%	12.2%	4.7%	4.5%	8.2%	10.7%	6.4%	5.0%	2.6%
	Min	1.6%	1.2%	2.9%	1.8%	0.6%	1.2%	0.9%	1.3%	1.6%	0.9%	0.5%
Installation	Max	0.0%	0.5%	0.6%	0.3%	0.0%	0.5%	0.1%	0.0%	1.1%	0.7%	0.0%
	Average	0.0%	0.2%	0.3%	0.1%	0.0%	0.2%	0.0%	0.0%	0.4%	0.3%	0.0%
	Min	0.0%	0.1%	0.1%	0.0%	0.0%	0.1%	0.0%	0.0%	0.1%	0.1%	0.0%
Operation and maintenance	Max	0.0%	0.2%	0.1%	0.1%	0.0%	0.1%	0.0%	0.0%	0.4%	0.2%	0.0%
	Average	0.0%	0.1%	0.0%	0.0%	0.0%	0.1%	0.0%	0.0%	0.2%	0.1%	0.0%
	Min	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%	0.1%	0.0%
Disassembly	Max	0.1%	1.0%	0.8%	0.4%	0.0%	0.9%	0.0%	0.1%	2.6%	1.0%	0.0%
	Average	0.1%	0.8%	0.6%	0.3%	0.0%	0.7%	0.0%	0.1%	2.1%	0.8%	0.0%
	Min	0.0%	0.6%	0.5%	0.2%	0.0%	0.6%	0.0%	0.0%	1.8%	0.6%	0.0%
Landfilling	Max	0.0%	0.1%	0.1%	5.2%	0.8%	0.1%	0.1%	0.6%	0.2%	0.1%	0.0%
	Average	0.0%	0.1%	0.1%	4.0%	0.6%	0.1%	0.1%	0.4%	0.2%	0.1%	0.0%
	Min	0.0%	0.0%	0.0%	2.7%	0.3%	0.1%	0.1%	0.3%	0.1%	0.1%	0.0%
Incineration	Max	0.0%	0.0%	0.0%	0.2%	54.0%	1.4%	2.3%	10.1%	0.1%	0.1%	0.0%
	Average	0.0%	0.0%	0.0%	0.1%	37.3%	1.0%	1.2%	6.3%	0.0%	0.0%	0.0%
	Min	0.0%	0.0%	0.0%	0.1%	20.2%	0.5%	0.8%	3.1%	0.0%	0.0%	0.0%
Recycling	Max	-15.1%	-12.8%	-15.9%	-19.6%	-9.4%	-13.4%	-23.3%	-18.8%	-8.6%	-17.7%	-13.7%
	Average	-19.8%	-16.4%	-19.9%	-25.8%	-10.8%	-17.4%	-29.8%	-24.1%	-10.6%	-22.6%	-17.5%
	Min	-24.3%	-21.9%	-26.4%	-35.9%	-12.5%	-23.2%	-38.2%	-31.7%	-13.1%	-30.1%	-23.4%

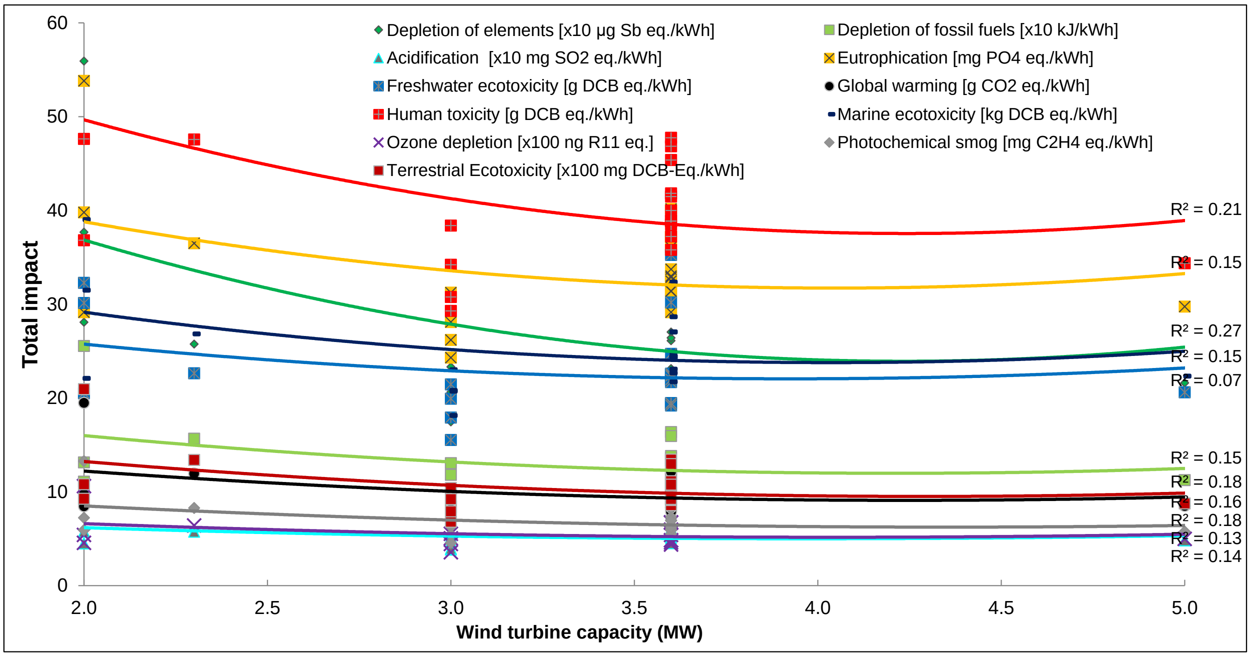

Figure S2 The effect on the environmental impacts of wind turbine capacity