Environmental implications of large-scale adoption of wind power: a scenario-based life cycle assessment

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Corrigendum: Environmental implications of large-scale adoption of wind power: a scenario-based life cycle assessment

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S Online supplementary data available from stacks.iop.org/ERL/7/039501/mmedia

An error was discovered in the model used to compute results for our recent letter (Arvesen and Hertwich 2011). The error occurred in the implementation of the method described in the second to last paragraph of section 2 in the letter. Due to the error, our model used too low inputs from the input–output (IO) background system (too low numbers in A^{nf}), and hence life cycle inventory analysis results for the IO system were underestimated. The error did not influence any of the conclusions of the letter, but some of the quantitative results were significantly affected. Total climate change impacts were underestimated by 27–35%, other impacts by roughly 30–40%. Effects on contribution analysis results, including figures 1 and 2, are generally fairly minor. The IO system generates 45–61% of total greenhouse gas emissions in corrected results, as opposed to 24–40% reported in the letter. The error affected the absolute scale in figure 3 and the purple dotted line in figure 4, but conclusions drawn from the figures were not affected. Below we correct previous statements and reproduce figures 1–4 and table 5 using updated results. Modified supplementary information containing all corrected results (tables S23–S31 available at stacks.iop.org/ERL/7/039501/mmedia) is attached to this corrigendum.

In the results section, the first two sentences should read as follows. 'According to our unit-based analysis results, the delivery of 1 kWh of electricity from onshore wind energy conversion causes 22.5 g CO_2-eq climate change, 0.024 g N-eq marine eutrophication, 0.128 g NMVOC photochemical oxidant formation, and 0.123 g SO_2-eq terrestrial acidification impact potentials. The corresponding values for offshore wind power are 21.2 g CO_2-eq, 0.032 g N-eq, 0.157 g NMVOC, and 0.129 g SO_2-eq.' The fifth sentence of the abstract changes accordingly.
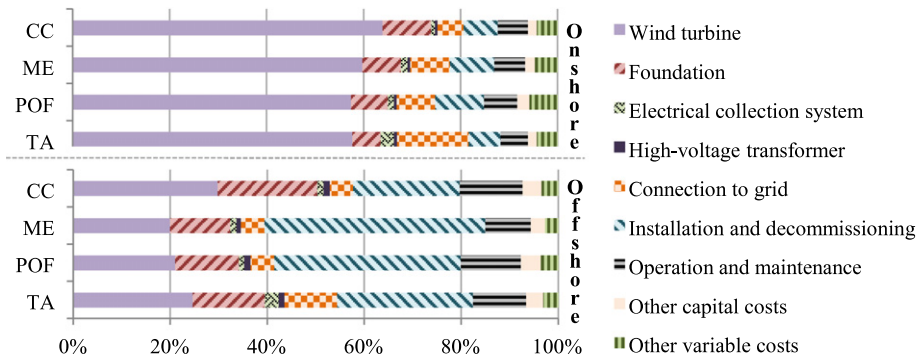
In the results section, third paragraph, the first two sentences should read as follows. 'Our scenario analysis yields cumulative greenhouse gas (GHG) emissions due to wind power development of 2.3 Gt and 3.5 Gt CO_2-eq, for the BLUE Map and BLUE hi REN scenarios respectively, in the time period 2007–50 (figure 3). Corresponding values for other impact categories are 2.9 (4.5) Mt N-eq, 16 (24) Mt NMVOC, and 13 (20) Mt SO_2-eq for the BLUE Map (BLUE hi REN) scenario'. In a subsequent sentence in the same paragraph, the text should read '... GHG emission intensity, $(\cdots)$, is reduced to less than 14 g kWh^{-1} in 2050.'

In the results section, second to last paragraph, the second to last sentence should read as follows. 'At the most, emissions of wind energy amount to 23% of gross reduced emissions (photochemical oxidant formation); at the least 5% (climate change).' The last sentence of the abstract changes accordingly.
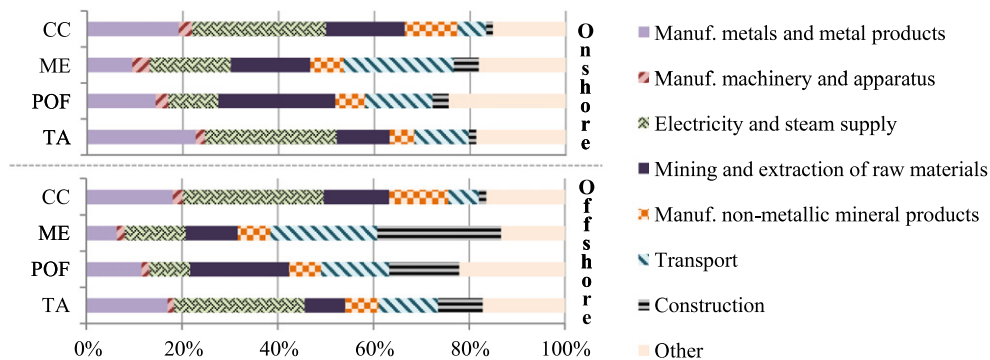
In the discussion and conclusions section, second paragraph, the second to last sentence should read as follows. 'In our analysis, which has a fairly simple physical foreground system, the IO background system generates 45% and 61% (climate change), 51% and 47% (marine eutrophication), 67% and 66% (photochemical oxidant formation), and 46% and
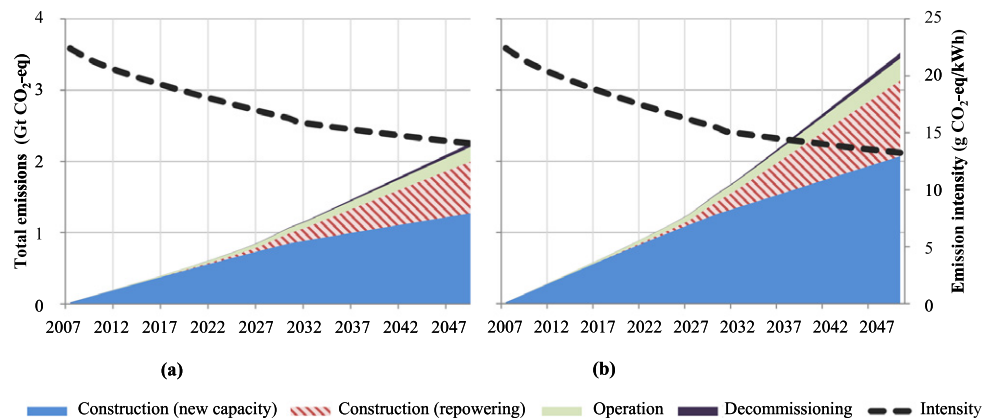
Figure 1. Life cycle emissions of onshore and offshore wind power in the reference year 2007 by main components. Impact categories: CC = climate change; ME = marine eutrophication; POF = photochemical oxidant formation; TA = terrestrial acidification.

Figure 2. Life cycle emissions of onshore and offshore wind power in the reference year 2007 by main emissions source. Impact categories: CC = climate change; ME = marine eutrophication; POF = photochemical oxidant formation; TA = terrestrial acidification. Manuf. = manufacture of.

Figure 3. Cumulative GHG emissions due to the construction, operation and demolition of wind power systems, and GHG emission intensity of current-year wind electricity (2007–50) for the BLUE Map (a) and BLUE hi REN (b) scenarios.

Table 5. Results of sensitivity analysis: total cumulative GHG emissions results for BLUE Map and BLUE hi REN scenarios in 2030 and 2050. Reference case results are consistent with results reported in section 5. Results are in units of Gt CO_2-eq. Numbers in parentheses give relative change compared with reference.

	BLUE Map		BLUE hi REN	
	2030	2050	2030	2050
Low CF	1.1 (+5.0%)	2.5 (+6.7%)	1.6 (+4.7%)	3.7 (+6.4%)
Reference	1.1	2.3	1.5	3.5
Reference + Longt LT	0.96 (−10%)	2.1 (−7.8%)	1.4 (−9.3%)	3.3 (−7.5%)
High CF	1.0 (−6.7%)	2.1 (−7.7%)	1.4 (−7.0%)	3.2 (−8.0%)
High CF + Long LT	0.90 (−16%)	2.0 (−15%)	1.3 (−16%)	3.0 (−15%)
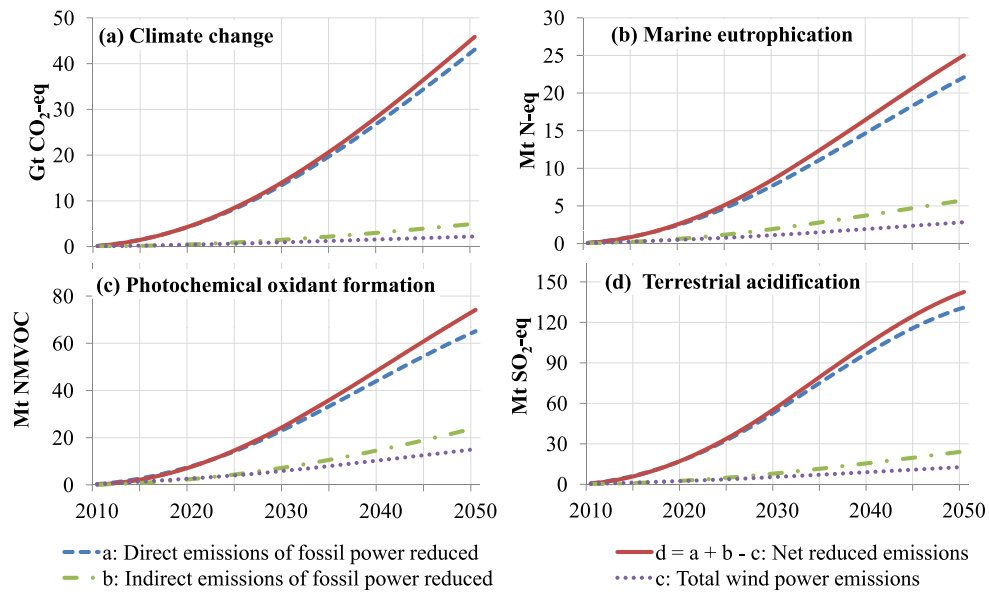
Figure 4. Cumulative gross (broken blue line) and net (solid red line) reduced emissions of wind power 2010–50 by four impact categories for the BLUE Map scenario.

55% (terrestrial acidification) of onshore and offshore total emissions, respectively.'

The discussion and conclusions section was otherwise not affected. Relative changes studied in the sensitivity analysis were not affected.

References

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Environmental implications of large-scale adoption of wind power: a scenario-based life cycle assessment

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Abstract
We investigate the potential environmental impacts of a large-scale adoption of wind power to meet up to 22% of the world's growing electricity demand. The analysis builds on life cycle assessments of generic onshore and offshore wind farms, meant to represent average conditions for global deployment of wind power. We scale unit-based findings to estimate aggregated emissions of building, operating and decommissioning wind farms toward 2050, taking into account changes in the electricity mix in manufacturing. The energy scenarios investigated are the International Energy Agency's BLUE scenarios. We estimate 1.7–2.6 Gt CO_2-eq climate change, 2.1–3.2 Mt N-eq marine eutrophication, 9.2–14 Mt NMVOC photochemical oxidant formation, and 9.5–15 Mt SO_2-eq terrestrial acidification impact category indicators due to global wind power in 2007–50. Assuming lifetimes 5 yr longer than reference, the total climate change indicator values are reduced by 8%. In the BLUE Map scenario, construction of new capacity contributes 64%, and repowering of existing capacity 38%, to total cumulative greenhouse gas emissions. The total emissions of wind electricity range between 4% and 14% of the direct emissions of the replaced fossil-fueled power plants. For all impact categories, the indirect emissions of displaced fossil power are larger than the total emissions caused by wind power.

Keywords: carbon footprint, hybrid life cycle assessment, renewable energy scenario, environmental management, climate mitigation scenario

S Online supplementary data available from stacks.iop.org/ERL/6/045102/mmedia

1. Introduction

In recent years, increasing concerns over security of energy supply and harmful climate change have fueled interest in the development of renewable energy technologies. Electric power generation by wind turbines is a fast-growing technology, with global installed capacity growing at an average annual rate of around 25% over the past ten years [1]. Furthermore, typically foreseen paths to renewable energy supply and climate stabilization imply a massive expansion of the wind power industry and its supply network in coming decades. Despite the renewable nature of wind energy conversion, non-renewable resource inputs and emissions occur in the life cycle of wind energy systems. The potential environmental impacts generated throughout a product's life cycle can be quantified and assessed by the method of life cycle assessment (LCA).

In the literature, climate change mitigation scenario analyses explore pathways leading to decarbonized energy supply at the economy-wide level, but do not take into account the greenhouse gas emissions in the production of the power plants; while conversely, conventional, unit-based

Table 1. Distribution of activities by modeling sub-system.

Activity	Sub-system	Physical/monetary
Final manufacturing and assembly of main components	Foreground	Physical
Operation and maintenance	Foreground	Physical
Installation and decommissioning	Foreground	Physical
Supply of electricity to foreground system	LCA database background	Physical
Supply of selected materials and material processing to foreground system	LCA database background	Physical
Supply of all other inputs to foreground system	IO database background	Monetary

LCAs of power generation do not address aspects of scale and time. In the broader context of climate change mitigation, an integration of the two perspectives can be valuable in establishing a more complete understanding of the environmental effects of proposed transitions away from fossil and toward lower carbon energy systems. Examining the economy-wide environmental costs and benefits of wind power, the current study represents an early research attempt in this direction.

In the present study we estimate aggregated emissions caused by global wind power development toward 2050, following energy scenarios by the International Energy Agency (IEA) [2]. The analysis builds on the LCAs of generic onshore and offshore wind farms, meant to represent average conditions for global onshore and offshore wind power development. We employ a hybrid LCA methodology, that is, we combine physical, process-based inventories and monetary, input–output-based inventories. Utilizing the extensive set of life cycle inventories for fossil-based power generation technologies in the Ecoinvent database, the scenario analysis includes an integrated LCA modeling of emissions reduction due to increased global wind power employment. The scenario analysis incorporates the temporal distribution of emissions and replacement of components at their end-of-life, as well as changing electricity mix in manufacturing.

2. Hybrid LCA: methods and data

In an LCA, a systematic mapping of emissions generated throughout a network of operations allows one to evaluate potential environmental impacts associated with or necessitated by a product or service throughout its lifetime. Two approaches to LCA prevail: process-LCA, a bottom-up technique defining and describing operations in physical terms, and environmentally extended input–output analysis (EE-IOA), utilizing monetary data at the level of economic sectors. Process-LCA facilitates the use of physical data specific for the operations under consideration, but may suffer from significant cut-off errors. EE-IOA, on the other hand, has the advantage of more complete system coverage, but it comes at the expense of precision level. Hybrid methods combining process-LCA and EE-IOA can potentially exploit advantages of both approaches.

An LCA model can be expressed mathematically by

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

where the vector d represents total impact indicator values, and the vector e contains life cycle inventory analysis results, such as emissions values. C is a matrix of characterization factors, F is a matrix of stressor intensities and I is the identity matrix. In a product system, outputs of processes/sectors serve as inputs supporting the production of new outputs. Relations between physical processes and economic sectors are described by the direct requirements matrix, A, where each element in A represents the flow from one producing process/sector to a consuming process/sector. Ultimately, all activities serve to satisfy a demand given by the vector y.

The direct requirements matrix reveals the structure of the hybrid LCA model employed [3]:

$$A = \begin{bmatrix} A^{ff} & 0 & 0 \\ A^{pf} & A^{pp} & 0 \\ A^{nf} & 0 & A^{nn} \end{bmatrix}. \qquad (2)$$

We distinguish between three types of processes and sub-systems: (1) processes defined specifically for this study, together comprising the foreground system (index f); (2) processes defined in an LCA database, together comprising the LCA database background system (index p); and (3) processes represented by economic sectors in an input–output (IO) dataset, together comprising the IO background system (index n). Linkages among processes in the foreground system are described in the matrix A^{ff}. Similarly, A^{pp} and A^{nn} describe internal linkages within the LCA background and IO background systems, respectively. Inputs to the foreground system from the LCA and IO background systems are accounted for in A^{pf} and A^{nf}. Table 1 gives a summary of activities and the sub-systems in which they are modeled.

As the LCA database background system we use a matrix representation of the Ecoinvent database [4]. The IO background system is a two-region (Europe, rest of world) environmentally extended IO model for the year 2000, constructed using input–output tables from Eurostat [5] and GTAP 6 [6], and air emissions data from World Resources Institute [7] and Eurostat [8]. All inputs from the IO background system to foreground processes are made from the Europe region.

The matrix representing inputs to the foreground system from the IO background system (A^{nf}) is constructed in the following step-wise approach: (1) each foreground process is assigned to an IO sector. The foreground processes are assigned the same input distributions as their belonging IO

sectors. (2) Inputs are scaled according to the costs (with value added deducted) apportioned to the specific foreground processes. (3) Inputs from the IO background that are already covered by the LCA database background system are removed.

We alter the relative shares of power generating technologies in the LCA database and IO background systems to match the global electricity mix in 2007 (unit-based analysis). The alteration is performed consistently in the matrices A^{pf}, A^{nf}, A^{pp} and A^{nn}. In the scenario analysis, the procedure is repeated for every year, so that the electricity mix used in the entire LCA database and IO background systems is always consistent with the IEA scenarios.

3. Life cycle inventories

We model hypothetical 120 MW (onshore) and 250 MW (offshore) wind farms. The lifetime of the onshore wind power system is assumed to be 20 yr, for offshore it is 25 yr. For the unit-based analysis, we assume onshore and offshore average wind load factors of 23.6% and 37.5%, respectively, which correspond with values for the reference year 2007 in the scenario analysis (table 3). Our system of analysis comprises the wind turbines with foundations, internal electrical connections, and cabling and a high-voltage transformer for connection to the electricity grid. In addition, the analysis covers installation, operation and maintenance, and decommissioning. For the electrical connections, we utilize data gathered by Jorge *et al* [9].

Our data set covers eight air pollutants: ammonia (NH_3), carbon dioxide (CO_2), carbon monoxide (CO), methane (CH_4), mono-nitrogen oxides (NO_x), nitrous oxide (N_2O), non-methane volatile organic compounds (NMVOC) and sulfur oxides (SO_x). The relevant impact assessment categories for these stressors are: climate change, marine eutrophication, photochemical oxidant formation and terrestrial acidification. ReCiPe 1.03 characterization factors are used [10]. Emissions data for NH_3 are missing for the rest-of-the-world region of the IO background system.

In the following, we outline life cycle inventory data collection. Metal requirements for all components, as well as composites used in the rotor blades and nacelle, concrete used in the foundations, and electricity used by foreground processes, are modeled in the LCA database background system. Other inputs to the foreground are covered by inputs from the IO background system. In cases where emissions values are not known for foreground processes, we estimate them based on consumption of gas and oil. Further accounts of inventories and assumptions are provided in the supplementary information (available at stacks.iop.org/ERL/6/045102/mmedia).

3.1. Wind turbine and foundation

Total weights of rotor blades, hub and nacelle, respectively, are obtained for 2 and 3 MW wind turbines by the manufacturer Vestas [11]. We take averages for the two turbines to model a hypothetical 2.5 MW wind turbine,

which is used both onshore and offshore. The tower mass is 78 t MW^{-1} for onshore (hub height 105 m), for offshore it is 52 t MW^{-1} (hub height 80 m), consistent with tower weights used in an LCA by Vestas [12]. We model the tower as made of low-alloy steel, and the rotor blades as consisting of glass-reinforced plastics. To achieve a higher resolution for the nacelle with respect to components and material types, we utilize relative shares (by component and material type) of [13] together with our own assumptions (tables S6–S10 in supplementary information, available at stacks.iop.org/ERL/6/045102/mmedia). Wire drawing for copper content in the generator and transformer, and sheet rolling of steel content in the tower are included.

Direct energy requirements (electricity, heat, gas and oil) and emissions of CO_2 for a wind turbine manufacturer are established from Vestas reports. We take the averages of values reported for the years 2007–9 [14], and adjust to take into account that around 80% of the towers are supplied to Vestas rather than manufactured in-house. The adjustment builds on data in [15] and causes energy use to increase by 3–10% from non-adjusted values. We model onshore gravity-based foundations made of reinforced concrete (1000 t), and offshore foundations made of steel (300 t at water depth 20 m), with aluminum anodes to prevent corrosion.

3.2. Electrical connections

Based on a survey of wind power projects, we assume 0.4 km of internal cabling and 0.3 km cabling for connection to grid is required per MW wind farm capacity. Submarine cables are steel armored. Material and energy requirements are derived from manufacturer data and previous LCAs [16–19]. Because data on energy use in manufacturing of infield cables is missing, we assume equal energy per weight ratios for internal and external cables. Each wind farm is connected to a high-voltage transformer, for which material composition and direct energy inputs during manufacturing we derive from reports by manufacturers [20, 21]. The offshore transformer platform is modeled as one wind turbine foundation.

3.3. Installation and decommissioning

The installation phase includes transportation to site and on-site construction activities. Diesel consumption for on-site activities for an onshore wind farm comes from reported measurements [22]. We convert reported life cycle energy to direct energy equivalent. When shifting to offshore sites, it is assumed that on-site diesel consumption scales proportionally to the installation costs. Transportation of one wind turbine is modeled as 10 lorries (32 t capacity) with pilot cars traveling 600 km; and onshore and offshore foundations, respectively, as 40 and 10 lorries traveling 50 and 200 km. Electrical connections travel 200 km by lorry. For the offshore case, transportation with barge (30 km) comes in addition.

Demolition is modeled as identical to installation. Composite materials in the rotor blades and nacelle are assumed to be 50% incinerated and 50% recycled. Apart from

Table 2. Selected characteristics of IEA's Baseline, BLUE Map and BLUE hi REN energy scenarios [2].

	2007	Baseline 2050	BLUE Map 2050	BLUE hi REN
Global electricity production from wind (TWh)	173	2149	4916	8193
Share of renewables in electricity production (%)	18	22	48	75
Share of wind in electricity production (%)	0.9	4.7	12.2	21.8
Average generation cost increase from baseline (2050) (%)			19	31
Total energy-related CO_2 emissions (Gt/yr)	28.9	57.0	14.0	12.9

this, waste disposal is not taken into consideration, as it is assumed that most other materials contained in the system will be returned to the technosphere for recycling or remain *in situ* without causing further environmental burdens.

3.4. Operation and maintenance

A case study [22] indicates that around 50 kg of diesel will be consumed per year per MW for inspections. Helicopter operation (100 h/wind turbine) is added for the offshore wind farm. Based on the presumption that the gearbox is the component most vulnerable to failure, we assume 50% (onshore) and 70% (offshore) of gearboxes will have to be replaced during the lifetime. Replacement parts are transported by lorry (600 km) and barge (offshore).

3.5. Level and distribution of costs

To determine the inputs from the IO background system to the foreground (that is, to establish A^{nf}), cost numbers must be assigned to each of the processes in the foreground. We assume total capital cost is 1250 Euro kW^{-1} (onshore) and 2200 Euro kW^{-1} (offshore), and that variable costs amount to 1.2 Eurocent kWh^{-1} (onshore) [23]. Figures for the variable costs of offshore wind farms are scarce in the public domain, though they are known to substantially exceed the variable costs of onshore wind projects [23]. We set variable costs of offshore wind power to 1.6 Eurocent kWh^{-1}. Cost numbers are converted from 2007 to 2000 prices using average annual inflation rate.

A breakdown of costs by foreground processes is established by synthesizing data from different sources. For the capital costs of the onshore wind farm, as a starting point we take the cost distribution of a wind project in Europe, as estimated by [23]. Then, we disaggregate the costs of the actual wind turbine into main wind turbine components [23]. The cost breakdown for the offshore wind turbine is identical to that of the onshore unit, except for the wind turbine tower, which is assigned a lower cost offshore to reflect lower height (we scale costs for the offshore tower in proportion to the tower mass). For capital expenditures other than wind turbine costs, we use the cost breakdown of [24] for the offshore wind farm. Further disaggregations are based on [25] and our own assumptions. We add costs for decommissioning (equal to costs of installation). Service and spare parts constitute 26% of the variable costs for an onshore wind farm [26], for an offshore wind farm 60% (own assumption).

Table 3. Global wind power development by BLUE Map and BLUE hi REN scenarios [2]. Numbers without superscripts are obtained from [2, 27].

	2007	2030	2050
BLUE Map scenario			
Annual electricity production (TWh)	173	2933	4916
Cumulative capacity at end of year (GW)	96.3	1134	1737
Of which offshore (GW)	1.6	214	444
Average load onshore (%)	23.6[a]	27.4[b]	29.0[b]
Average load offshore (%)	37.5[c]	41.7[b]	43.2[b]
Average load (%)	23.8[d]	30.1[d]	32.6[d]
BLUE hi REN scenario			
Annual electricity production (TWh)	173	4463[e]	8193
Cumulative capacity at end of year (GW)	96.3	1691[f]	2869[f]
Of which offshore (GW)	1.6	320[f]	733[f]

[a] Calculated by the authors based on an annual onshore production of 173.1 TWh in 2007 [2, 27], and by assuming mid-year onshore capacity was (94.7 + 73.2)/2, where 94.7 GW is the onshore capacity at the end of 2007 according to [2, 27] and 73.2 GW the onshore capacity at the end of 2006 according to [1].
[b] Calculated by the authors from production and capacity numbers in [2, 27].
[c] Assumed by the authors.
[d] Calculated based on onshore and offshore load factors and capacity numbers.
[e] Based on linear interpolation.
[f] Assuming equal average load, and equal onshore and offshore shares, in BLUE hi REN as in BLUE Map.

4. Scenario modeling

The IEA has produced a series of scenarios describing ways in which global energy-related CO_2 emissions can be reduced by 50% by 2050, relative to 2005. Of these, the BLUE Map scenario represents the least-cost alternative. The BLUE hi REN scenario has an additional assumption of 75% renewable electricity supply by 2050 (table 2) [2].

In essence, our scenario analysis consists of scaling onshore and offshore unit-based findings to match future developments given in the BLUE Map and BLUE hi REN scenarios, using time series modeling. Table 3 summarizes future wind power developments toward 2050. For the BLUE hi REN scenario, only 2007 and 2050 values are given; therefore, linear interpolation is used to establish intermediate

values. For both scenarios, we use linear interpolation to determine intermediate data points not reported in table 3.

We incorporate changes in electricity mix by altering the relative shares of power generation technologies in the direct requirements matrix, A, consistent with the IEA scenarios (see table S21 in the supplementary information (available at stacks.iop.org/ERL/6/045102/mmedia) for electricity mix toward 2050). Simplifying assumptions are necessary to deal with incomplete coverage of futuristic power generation technologies in the LCA and IO data sets. We assume fossil power with carbon capture and storage eliminates 90% of in-plant CO_2 emissions. Non-fossil energy technologies accounting for small percentages of total generation in 2007–50 are only partly modeled (biomass, waste) or not modeled (geothermal, ocean). As the IO background system lacks a proper representation of solar power, solar power in the IO background (Europe region) is moved to the LCA database system.

To allow for the temporal distribution of emissions to be taken into account, the demand vector y for the wind power system is broken down into three components:

$$y = y_{start} + y_{oper}\tau + y_{end} \qquad (3)$$

where y_{start} represents direct requirements prior to operation (construction; $t' = 0$), y_{oper} annual average operation and maintenance direct requirements, and y_{end} direct requirements at the end-of-life (decommissioning; $t' = \tau$). The elements of y_{start} and y_{end} are measured on a per added capacity basis (e.g., t MW^{-1}), while y_{oper} is measured per capacity per year (e.g., t MW^{-1} yr^{-1}). τ is the lifetime, and $t' = \{1, \ldots \tau\}$ the age of a wind power system.

Denote by $K_{new}(t)$ and $K_{repow}(t)$ added capacities and repowering of existing capacities, respectively, in year t, and by $K_{oper}(t)$ average total capacity in operation over year t. With end-of-year onshore and offshore operating capacity values for the years 2007, 2030 and 2050 (table 3) together with end-of-year capacity values for 2006 [1], and assuming linear growth in cumulative capacity in 2007–30 and 2030–50, we establish K_{new} and K_{oper} for 2007–50. We assume constant lifetimes (τ) of 20 yr (onshore) and 25 yr (offshore); longer lifetimes are considered in the sensitivity analysis. Statistics on annual added capacities from 1996 and onwards (onshore) and for 2006 (offshore) [1] are used to determine K_{repow} values for 2017–27 (onshore) and 2032 (offshore); for succeeding years K_{repow} equals K_{new} with a time lag of τ. Implicit in K_{new}, K_{repow} and K_{oper} are changes in load factors (table 3). Time series data for K_{new}, K_{repow} and K_{oper} values used in the scenario analysis are provided in the supplementary information (table S22 available at stacks.iop. org/ERL/6/045102/mmedia).

While equation (3) separates requirements occurring prior to, during and after the operating lifetime, it does not incorporate time as a variable; nor does it reflect scale or the need for repowering. We express the economy-wide direct requirements of building, operating and decommissioning wind power systems in year t as

$$\tilde{y}(t) = y_{start}K_{new}(t) + y_{start}K_{repow}(t)$$
$$+ y_{oper}K_{oper}(t) + y_{end}K_{repow}(t) \qquad (4)$$

where the first term on the right-hand side represents construction of new capacity and the second term construction of replaced capacity. The third and fourth terms express, respectively, direct requirements associated with operating and decommissioning wind farms. Absolute emissions $\tilde{e}(t)$ are then calculated year-by-year as

$$\tilde{e}(t) = F(I - A(t))^{-1}\tilde{y}(t),$$
$$\text{for } t = \{2007, \ldots, 2050\}. \qquad (5)$$

Because we take into account changes in the electricity mix, A is a function of time. The calculation is performed separately for onshore and offshore wind power.

Finally, utilizing the set of life cycle inventories for coal, natural gas and oil-fired power stations in the Ecoinvent database, a life cycle approach is taken to evaluate economy-wide emissions savings from wind power. The evaluation is performed on the assumption that additional wind electricity (measured in TWh) in the BLUE Map scenario, compared with IEA's baseline scenario, replaces fossil-based power. The quantifications of direct and indirect reduced emissions are done year-by-year in the scenario analysis, taking into account temporal evolutions in additional wind electricity in BLUE Map compared with the baseline, relative shares of onshore and offshore wind power, and relative shares of energy carriers (coal, natural gas, oil) in fossil power generation toward 2050. Only conventional fossil power is replaced; wind power is not assumed to displace power plants with carbon capture.

5. Results

According to our unit-based analysis results, the delivery of 1 kWh of electricity from onshore wind energy conversion causes 16.4 g CO_2-eq climate change, 0.016 g N-eq marine eutrophication, 0.075 g NMVOC photochemical oxidant formation, and 0.085 g SO_2-eq terrestrial acidification impact potentials. The corresponding values for offshore wind power are 13.7 g CO_2-eq, 0.023 g N-eq, 0.095 g NMVOC and 0.084 g SO_2-eq. For the onshore case, the wind turbine is the most important single component, contributing 60–69% to total emissions (figure 1). Of this, the tower holds shares of 35–42%, the nacelle 25–37% and the rotor (including hub) 20–25%. The wind turbine is a much less dominant contributor to the emissions of ocean-based systems (19–35%), for which installation and decommissioning become more important (18–52%). The foundation contributes 6–11% (onshore) and 13–25% (offshore).

Figure 2 shows the breakdown of the contribution of electricity, materials and manufacturing processes to the total emissions of components of the wind park. For climate change and terrestrial acidification category indicators, significant portions (20–29%) of total emissions are caused by fossil-fuel burning in the power sector, reflecting the need to use fossil-based electricity of today to develop the renewable energy systems of tomorrow. Manufacturing of metals and metal products is responsible for 9–33% of total emissions.
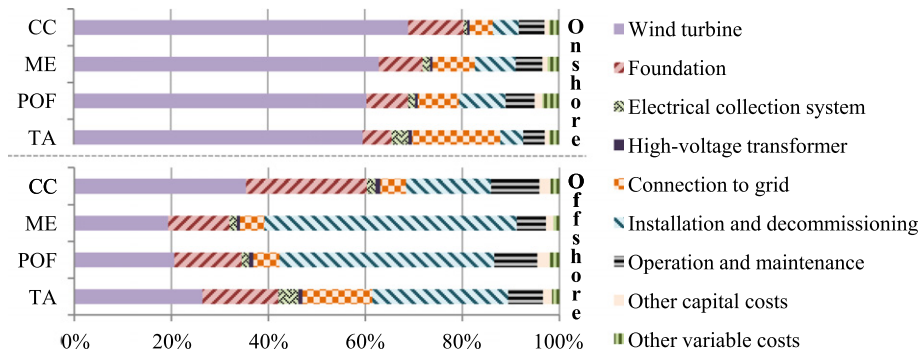
Figure 1. Life cycle emissions of onshore and offshore wind power in the reference year 2007 by main components. Impact categories: CC = climate change; ME = marine eutrophication; POF = photochemical oxidant formation; TA = terrestrial acidification.
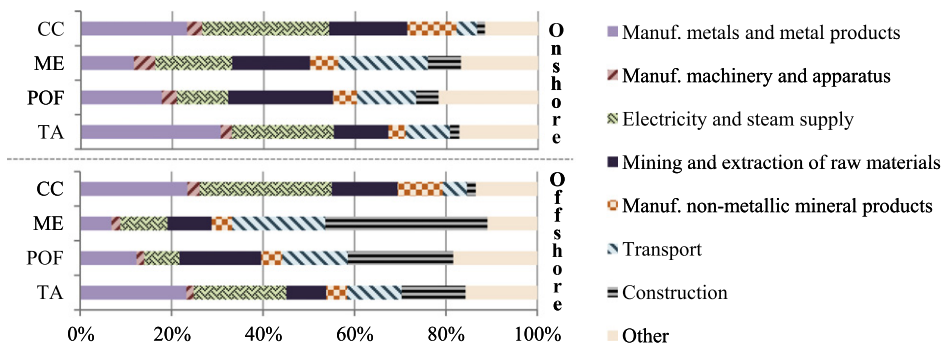
Figure 2. Life cycle emissions of onshore and offshore wind power in the reference year 2007 by main emissions source. Impact categories: CC = climate change; ME = marine eutrophication; POF = photochemical oxidant formation; TA = terrestrial acidification. Manuf. = manufacture of.
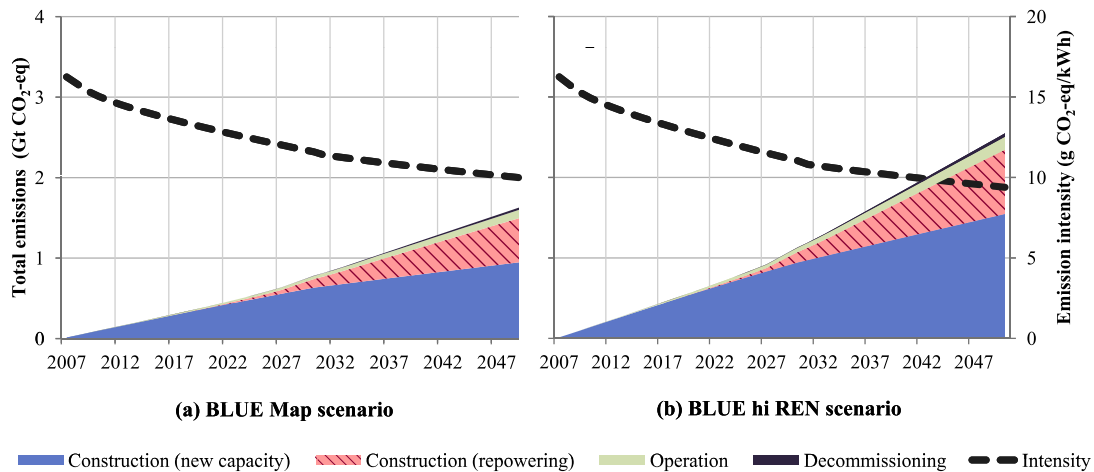

Figure 3. Cumulative GHG emissions due to the construction, operation and demolitions of wind power systems, and GHG emission intensity of current-year wind electricity (2007–50) for the BLUE Map (a) and BLUE hi REN (b) scenarios.

Transportation causes 20% of eutrophication, but only 5% of climate change impact potential.

Our scenario analysis yields cumulative greenhouse gas (GHG) emissions due to wind power development of 1.7 Gt and 2.6 Gt CO_2-eq, for the BLUE Map and BLUE hi REN scenarios respectively, in the time period 2007–50 (figure 3). Corresponding values for other impact categories are 2.1 (3.2) Mt N-eq, 9.2 (14) Mt NMVOC and 9.5 (15) Mt SO_2-eq for the BLUE Map (BLUE hi REN) scenario.

Looking at GHG emissions, construction of new capacity dominates (64% of cumulative emissions in 2050 in BLUE Map scenario), although repowering becomes increasingly important (38% in 2050). Due to the combined effects of increased load factor, shift from land to ocean sites and cleaner electricity mix in manufacturing, the GHG emission intensity, as calculated with the unit-based analysis with current-year technologies, is reduced to less than 10 g kWh^{-1} in 2050 (figure 3). Assumed lifetimes and future capacity factors are
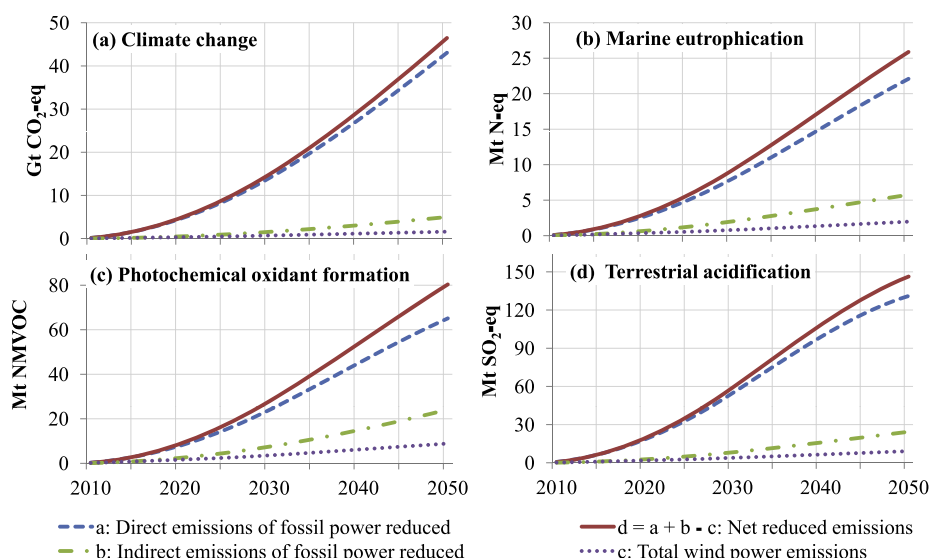
Figure 4. Cumulative gross (broken blue line) and net (solid red line) reduced emissions of wind power 2010–50 by four impact categories for the BLUE Map scenario.

Table 4. Combinations of total capacity factor value (%) and lifetime (years) assumptions used in sensitivity analysis for the years 2007, 2030 and 2050. Lifetime is constant over the modeling period. CF = capacity factor. LT = lifetime. Reference case assumptions are consistent with results reported in section 5.

	Capacity factor (%)			
Scenario	2007	2030	2050	Lifetime (years)
Low CF	23.8	28.3	30.0	20 (onshore), 25 (offshore)
Reference	23.8	30.1	32.6	20 (onshore), 25 (offshore)
Reference + Long LT	23.8	30.1	32.6	25 (onshore), 30 (offshore)
High CF	23.8	31.9	35.2	20 (onshore), 25 (offshore)
HighCF + Long LT	23.8	31.9	35.2	25 (onshore), 30 (offshore)

two important sources of uncertainty and are addressed in the sensitivity analysis (section 6).

Figure 4 compares the cumulative emissions from wind power to the reduction of emissions from fossil power plants replaced by the additional wind power capacity (2010–50). Gross reduced emissions is the direct emissions of fossil-fueled power plants replaced by the additional wind electricity in the BLUE Map scenario, compared with IEA's baseline scenario. Net reduced emissions is the difference of the life cycle emissions of the replaced fossil-fuel power stations (assuming a mix of fossil energy carriers as modeled year-by-year in the scenario analysis) and the total life cycle emissions caused by wind power. Indirect emissions are the part of the life cycle emissions not occurring directly at the power plant. At the most, emissions of wind energy amount to 14% of gross reduced emissions (photochemical oxidant formation); at the least 4% (climate change). For all impact categories investigated, our measure of net reduced emissions exceeds gross reduced emissions because the fuel-chain emissions of displaced fossil power are larger than the total life cycle emissions of wind power.

Numerical results in tabulated form are available in the supplementary information (available at stacks.iop.org/ERL/6/045102/mmedia).

6. Sensitivity analysis

The sensitivity analysis investigates the influence of capacity factors and lifetimes on estimated cumulative GHG emissions of wind power. In addition to the reference case, four scenarios are constructed to represent more pessimistic and optimistic assumptions, respectively, as summarized in table 4. As shown in table 5, the alternative capacity factor scenario assumptions yield changes of 5–8% in cumulative emissions, compared with the reference case. Table 5 illustrates that prolongation of system lifetimes can potentially reduce emissions significantly. Returning to the emissions trends depicted in figure 3, it can be noted that assuming longer lifetimes effectively reduces the contribution from repowering (red striped area in figure 3), but does not affect emissions that are caused by new capacity additions (blue solid area); an elimination of emissions caused by repowering thus determines an upper limit of the reductions that can be achieved through lifetime extensions.

7. Discussion and conclusions

The climate change impact indicator value of 16.4 g CO_2-eq kWh^{-1} for an onshore wind farm is comparatively

Table 5. Results of sensitivity analysis: total cumulative GHG emissions results for BLUE Map and BLUE hi REN scenarios in 2030 and 2050. Reference case results are consistent with results reported in section 5. Results are in units of Gt CO_2-eq. Numbers in parentheses give relative change compared with reference.

	BLUE Map		BLUE hi REN	
	2030	2050	2030	2050
Low CF	0.82 (+5.0%)	1.8 (+6.7%)	1.2 (+4.7%)	2.7 (+6.4%)
Reference	0.78	1.7	1.1	2.6
Reference + Longt LT	0.70 (−10%)	1.5 (−7.9%)	1.0 (−10%)	2.4 (−7.6%)
High CF	0.73 (−6.8%)	1.5 (−7.7%)	1.1 (−7.1%)	2.3 (−8.0%)
High CF + Long LT	0.65 (−17%)	1.4 (−15%)	1.0 (−16%)	2.2 (−15%)

high; other recent estimates for onshore wind farms consisting of multi-megawatt turbines are in the range of 5–16 g CO_2-eq kWh^{-1} [12, 13, 28, 29]. The estimated GHG intensity of 13.7 g CO_2-eq kWh^{-1} for offshore wind electricity (with assumed lifetime of 25 yr) compares with 5 g CO_2 kWh^{-1} in [12], 12 g CO_2-eq kWh^{-1} in [30], 22 g kWh^{-1} in [31], and 32–33 g kWh^{-1} in [32, 33] (generally assuming lifetimes of 20 yr). Differences in results across studies may stem from differences in the types of wind power systems that are studied (e.g., offshore wind farms in either shallow [12] or deep [32, 33] waters), assumed values of key parameters (capacity factor and lifetime), background system characteristics (e.g., relatively dirty or clean manufacturing), and scope and methodologies (e.g., process-LCA or hybrid LCA) [33, 34].

We identify four factors that are of relevance when comparing the emission intensity estimates of this study with that of previous research. Firstly, we assumed a relatively low average load of 23.6% for the onshore wind farm. Correspondingly, [12, 13, 28, 29] assume 30%, 23%, 33% and 30%, respectively, for onshore wind electricity. Realized values during 2003–07 have been estimated to average at 20.8% for Europe and 25.7% for the US [35]. Secondly, the lifetime of the offshore wind farm is set to 25 yr in the present study, as opposed to the 20 yr typically chosen in previous LCAs. Thirdly, unlike most previous studies we employ a hybrid LCA methodology, thereby achieving a more complete system definition. In our analysis, which has a fairly simple physical foreground system, the IO background system generates 24% and 40% (climate change), 27% and 26% (marine eutrophication), 42% and 44% (photochemical oxidant formation), and 22% and 30% (terrestrial acidification) of onshore and offshore total emissions, respectively. Finally, in the current study the benefits of recycling are incorporated by having a mix of primary and secondary materials as inputs into materials production, instead of crediting the system with emissions that are perceived to be avoided through future recycling of materials contained in the system.

Considerable uncertainty exists in the results of the scenario analysis, among other reasons, because of the long time frame considered. Hence, results of the scenario analysis should be interpreted with care. Some uncertainties relate to assumed values of input parameters—notably, capacity factors and lifetimes (cf the sensitivity analysis). Uncertainties also arise from simplifications that were necessary for the scenario analysis. Two simplifications may be replaced by

more sophisticated modeling in the future. One, technological improvements were captured only through a shift toward development in ocean waters, and an improved capacity factor. Technology foresight and evolutions studies based on current research and design work or learning curves studies may provide a better basis for modeling design changes. Two, the background economy modeled here changes only in terms of the energy mix it uses. Improvements in efficiency or increased effort to extract ever-more scarce resources are not taken into account. Also, for reasons of data availability, our model is skewed toward European technology, not fully mirroring a globalized production network.

Evaluating emission penalties due to intermittency is outside the scope of this letter, but is nevertheless an important concern for wind power. High wind power penetration requires an upgrade in electricity infrastructure, may need to be supplemented by energy storage technologies, and may lead to altered operation of thermal and hydro power plants. Ideally, environmental implications of such effects are included in LCAs of wind power, yet this is not done in the extant literature. The exception is [31], whose results suggest additional CO_2 emissions from fossil-fired power stations of 18–70 g kWh^{-1} electricity from wind (assuming a wind electricity penetration of 12% in Germany in 2020) [31]. However, such results are inherently region-specific and sensitive to characteristics of the electricity systems.

Our quantification of emissions reductions due to increased use of wind power should be interpreted in light of the assumption that additional wind power in the BLUE Map scenario substitutes fossil power. The reason for making this assumption is to achieve consistency and comparability with IEA's own reported reductions from their baseline emission trend. Essentially, the quantifications of reduced emissions presented here are means to enhance understanding; they are not attempts to establish 'true' values for emissions savings from wind power as such. On average over the modeled time period, 725 g direct fossil CO_2 is reduced per additional kWh generated from wind energy, consistent with IEA's [2] reported contributions by wind power to CO_2 reductions in the BLUE Map scenario, relative to the baseline.

By one account [36], global CO_2 from fossil-fuel burning, cement production and land use in 2000–49 should not exceed 1000 Gt, if we are to limit global warming to 2 °C above pre-industrial levels. With 320 Gt already emitted in 2000–9 [37] the remaining budget for 2010–49 is 680 Gt. In this perspective, emissions caused by wind power expansion

may seem not insignificant, considering that they represent life cycle emissions of one technology only. Besides, the BLUE scenarios are unlikely to be consistent with the 2 °C target; thus even more wind electricity may be needed.

The present work advances current state of knowledge by aggregating unit-based findings to study economy-wide environmental costs and benefits of large-scale adoptions of wind power. Despite the real-world load factors and hybrid LCA methodology, and despite incorporating repowering of wind electricity systems as well as the temporal distribution of emissions in a scenario-based assessment, we find that emissions of wind power are low when contrasted with the emissions of fossil-based power. For climate change in particular, reduced emissions grossly exceed the emissions caused by wind power expansion. For the assessed impact categories, it appears that the true environmental benefits of wind power largely depend on the extent to which electricity from wind actually leads to a phase-out of fossil-based electricity without carbon capture.

Acknowledgment

References

[1] Global Wind Energy Council 2010 *Global Wind 2009 Report* (available at www.gwec.net)

[2] International Energy Agency 2010 *Energy Technology Perspectives 2010* (Paris: IEA)

[3] Strømman A H, Solli C and Hertwich E G 2006 Hybrid life-cycle assessment of natural gas based fuel chains for transportation *Environ. Sci. Technol.* **40** 2797–804

[4] Ecoinvent *2007 Life Cycle Inventory Database v2.1* (Swiss Centre for Life Cycle Inventories) (http://www.ecoinvent.ch/)

[5] Eurostat 2011 *National Accounts Database* (available at http://epp.eurostat.ec.europa.eu)

[6] Dimaranan B V 2006 *Global Trade, Assistance, and Production: The GTAP 6 Data Base* (West Lafayette, IN: Center for Global Trade Analysis, Purdue University)

[7] Wourld Resources Institute 2009 *Earth Trends: The Environmental Information Portal—Climate and Atmosphere Variables* (http://earthtrends.wri.org/text/climate-atmosphere/variables.html, accessed 20 March 2009)

[8] Eurostat 2011 *NAMEA Air Emissions by Industry—Datasets* (available at http://epp.eurostat.ec.europa.eu)

[9] Jorge R S, Hawkins T R and Hertwich E G, Life cycle assessment of electricity transmission and distribution—part 1: power lines and cables *Int. J. Life Cycle Assess* at press (doi:10.1007/s11367-011-0335-1)

[10] *ReCiPe, Midpoint Method, Hierarchist Version. Version 1.03* (www.lcia-recipe.net/)

[11] Vestas Wind Systems *Product Brochures* (available at www.vestas.com)

[12] Vestas Wind Systems 2006 *Life Cycle Assessment of Offshore and Onshore Sited Wind Power Plants Based on Vestas V90-3.0 MW Turbines* (Aarhus: Vestas Wind Systems) (available at www.vestas.com)

[13] Martínez E, Sanz F, Pellegrini S, Jiménez E and Blanco J 2009 Life-cycle assessment of a 2-MW rated power wind turbine: CML method *Int. J. Life Cycle Assess.* **14** 52–63

[14] Vestas Wind Systems 2010 *Vestas Annual Report 2009* (available at www.vestas.com)

[15] Vestas Wind Systems 2010 *Vestas Towers, Rudkøbing, Denmark: Environmental and Occupational Health & Safety Statement 2009—site description* (Aarhus: Vestas Wind Systems) (available at www.vestas.com)

[16] Parker Scanrope AS 2008 Technical specifications of 5 MW, 22 kV, 70 mm² copper conductor (personal communication) (www.scanrope.no)

[17] ABB 2008 *Miljörapport för år 2007 [Environmental Report 2007]* (Sweden: ABB, High Voltage Cables)

[18] Eltra 1999 *Ressourceoppgørelse for 132/150 kV oliekabel [Resource account for 132/150 kV oil-filled cable]* (Doc no. 50810) (Denmark: Eltra)

[19] New Energy Externalities Development for Sustainability Consortium 2008 *Life Cycle Approaches to Assess Emerging Energy Technologies. Final Report on Offshore Wind Technology* (available at www.needs-project.org)

[20] ABB 2003 *Environmental Product Declaration. Power Transformer 250 MVA* (available from www.abb.com)

[21] ABB 2006 *LCA Technical Report for Oil Filled Large Distribution Transformer* ABB, Transmissione & Distribuzione (Italy: S.p.A)

[22] Ardente F, Beccali M, Cellura M and Lo Brano V 2008 Energy performances and life cycle assessment of an Italian wind farm *Renew. Sust. Energy Rev.* **12** 200–17

[23] Blanco M I 2009 The economics of wind energy *Renew. Sust. Energy Rev.* **13** 1372–82

[24] Offshore Design Engineering 2007 *Study on the Costs of Offshore Wind Generation. A Report to the Renewables Advisory Board (RAB) & DTI* (*URN Number 07/779*)

[25] European Wind Energy Association 2009 *The Economics of Wind Energy* (available from www.ewea.org)

[26] Deutsches Windenergie Institut 2002 *Studie zur aktuellen Kostensituation 2002 der Windenergienutzung in Deutschland [Study of the costs of wind energy in 2002 in Germany]* (available from www.wind-energie-de)

[27] Remme U 2011 Energy Technology Policy Division, International Energy Agency (personal communcation)

[28] Crawford R H 2009 Life cycle energy and greenhouse emissions analysis of wind turbines and the effect of size on energy yield *Renew. Sust. Energy Rev.* **13** 2653–60

[29] Tremeac B and Meunier F 2009 Life cycle analysis of 4.5 MW and 250 W wind turbines *Renew. Sust. Energy Rev.* **13** 2104–10

[30] Weinzettel J, Reenaas M, Solli C and Hertwich E G 2009 Life cycle assessment of a floating offshore wind turbine *Renew. Energy* **34** 742–7

[31] Pehnt M, Oeser M and Swider D J 2008 Consequential environmental system analysis of expected offshore wind electricity production in Germany *Energy* **33** 747–59

[32] Wagner H-J, Baack C, Eickelkamp T, Epe A, Lohmann J and Troy S 2011 Life cycle assessment of the offshore wind farm alpha ventus *Energy* **36** 2459–64

[33] Wiedmann T O, Suh S, Feng K, Lenzen M, Acquaye A, Scott K and Barrett J R 2011 Application of hybrid life cycle approaches to emerging energy technologies—the case of wind power in the UK *Environ. Sci. Technol.* **45** 5900–7

[34] Lenzen M and Munksgaard J 2002 Energy and CO_2 life-cycle analyses of wind turbines— review and appliations *Renew. Energy* **26** 339–62

[35] Boccard N 2009 Capacity factor of wind power realized values vs. estimates *Energy Policy* **37** 2679–88

[36] Meinshausen M, Meinshausen N, Hare W, Raper S C B, Frieler K, Knutti R, Frame D J and Allen M R 2009 Greenhouse-gas emission targets for limiting global warming to 2 °C *Nature* **458** 1158–62

[37] Global Carbon Project Website (www.globalcarbonproject.org)