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Review

# Life cycle energy and carbon footprint of offshore wind energy. Comparison with onshore counterpart

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A B S T R A C T

The exploitation of wind energy worldwide comprises one of the main factors for reaching the targets towards a non-fossil fuel era set by many countries. Nowadays, onshore wind power is an established industry with significant contribution to energy production. On the other hand, offshore wind power is an emerging industry where numerous challenges should be faced. Apart from the main components such as platforms, turbines, cables, and substations, offshore installations include also the manufacturing, construction, shipping, and decommissioning phases. Additionally, the Operation & Maintenance (O&M) activities consist of employees' transportation by vessel or helicopter and occasional hardware retrofits. Therefore, various life cycle (LC) stages of offshore projects present a carbon footprint which affects their sustainable character in a more significant way than onshore ones. Concerning the environmental uncertainties arisen from the greenhouse gas (GHG) emissions of offshore wind power generation, the present work intents to provide a literature review on the LC carbon and energy footprint of offshore wind power projects compared to the onshore counterparts.



**Contents**



## 1. Introduction

Technologies used in electricity production are associated with primary energy consumption and greenhouse gas (GHG) emissions in a life cycle assessment (LCA) perspective. The investigation of upstream and downstream processes in the life cycle of an electricity production power plant is necessary in order to appraise the magnitude of its energy and carbon footprint. Upstream operations comprise extraction of fuels, transportation and processing activities of the materials used during manufacturing, along with the power station construction, while downstream includes activities concerning the operation of the plant, waste management, and decommissioning [1,2]. Most renewable electricity generating technologies involve primary energy consumption and GHG emissions in both upstream and downstream processes, provided they are based on fossil fuel exploitation. Likewise, although wind power technologies offer significant potential for achieving the goal of GHG reduction, in a life cycle analysis non-renewable sources

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**Nomenclature**

*Acronyms*

| | |
|---|---|
| CF | Capacity Factor |
| EPBP | Energy Payback Period |
| ELC | Life Cycle Primary Energy |
| GHG | Greenhouse Gases |
| IPCC | Intergovernmental Panel on Climate Change |
| LC | Life Cycle |
| LCA | Life Cycle Assessment |
| O&M | Operation and Maintenance |

*Symbols*

| | |
|---|---|
| $\Delta$ | Technical Availability |
| $\omega$ | Mean Power Coefficient |
| $E_C$ | Required Primary Energy for Wind Turbine Construction |
| $E_D$ | Required Primary Energy for Wind Turbine Decommissioning |
| $E_{O\&M}$ | Required Primary Energy for Wind Turbine O&M |
| $E_{WF}$ | Wind Farm Annual Mean Energy Production |
| $k$ | Life Stage of a Wind Farm |
| $P_{ex}$ | Power Output of the Wind Turbine |
| $P_R$ | Rated Power of the Wind Turbine |
| $R$ | Reference Unit (Generated Energy per Rated Power) |
| $V$ | Wind Speed |
| $V_C$ | Cut-in Speed of the Wind Turbine |
| $V_F$ | Cut-out Speed of the Wind Turbine |
| $z$ | Number of Wind Turbines |

associated with wind technology deployment (on the basis of the fuel mix used in each case), enhance the carbon footprint of such installations [3].

Wind power is considered nowadays as one of the most competitive and mature sustainable technologies with a cumulative capacity at the end of 2015 of 432.9 GW [4]. Up to now, installations concern mostly onshore projects with total capacity reaching 420.8 GW in 2015 [4]. However, onshore wind farms are associated with negative environmental implications (such as visual and noise impacts) and their social acceptance is often questionable [5]. This condition confines the development of new projects and induces difficulties in site selection. On the other hand, offshore wind power capacity presented considerably high increase over the last decade and reached at the end of 2015 12.1 GW, from which 11 GW were developed in Europe [4,6,7] (see Fig. 1). Supporting this trend, it is worth mentioning that 3 GW were fully connected to the grid only in the European continent during 2015, a value two times greater than that of the 2014 installations [6,7]. On top of that, during the first half of 2016, new offshore installations in Europe reached 511 MW, while at the same time 9 under construction wind farms are expected to rise cumulative capacity once completed by 3.7 GW [6].

The major markets of offshore wind industry in 2015 comprised mainly European countries, representing 90% of the new installations' share. The biggest market outside Europe was China with 360.5 MW annual installed power in 2015, followed by Japan with 3 MW. Compared to 2014 (see Fig. 2a), it is obvious that Germany and China presented a four-fold and 57% increase of new offshore projects respectively, while the UK reduced its annual installations by 30% [4].

Regarding the annual installed offshore capacity since 2009 (see Fig. 2b), the UK market was the only one with annual installations

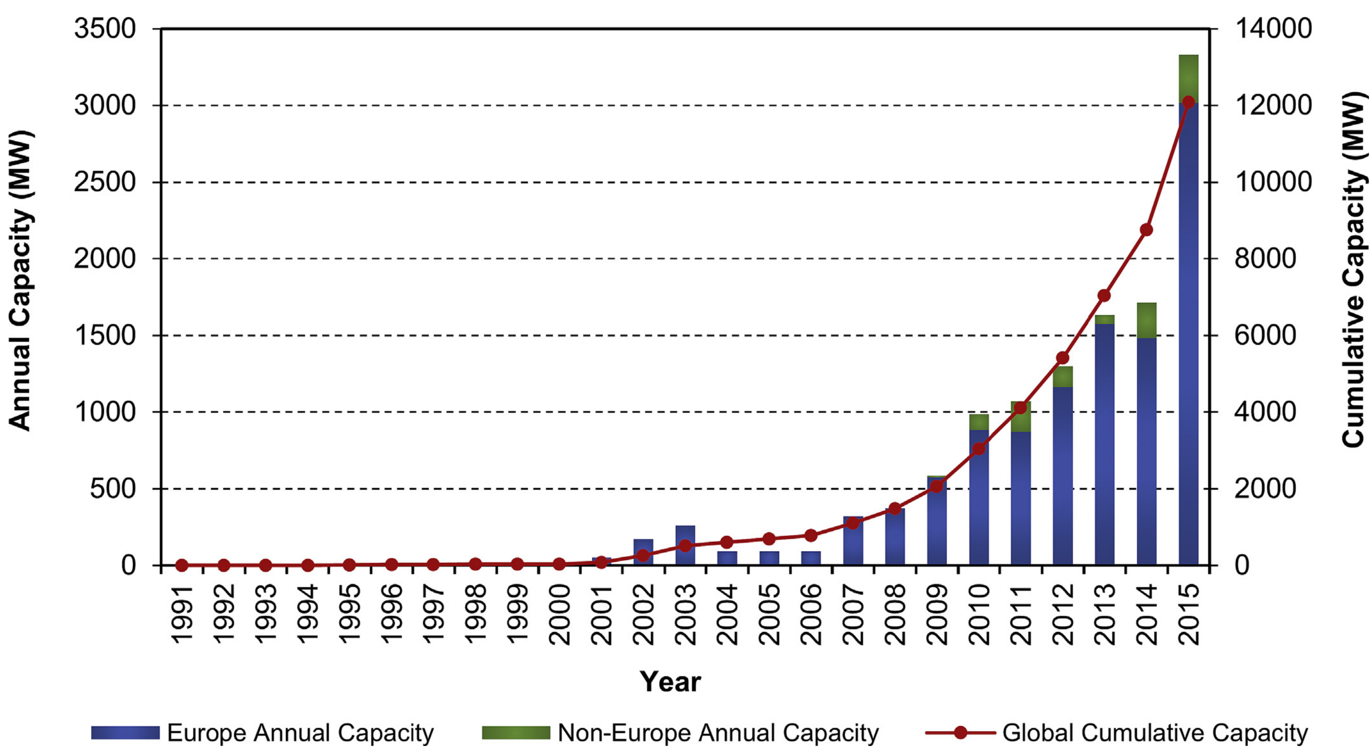



**Fig. 1.** Offshore wind capacity evolution. Based on data from Refs. [4,6–8].

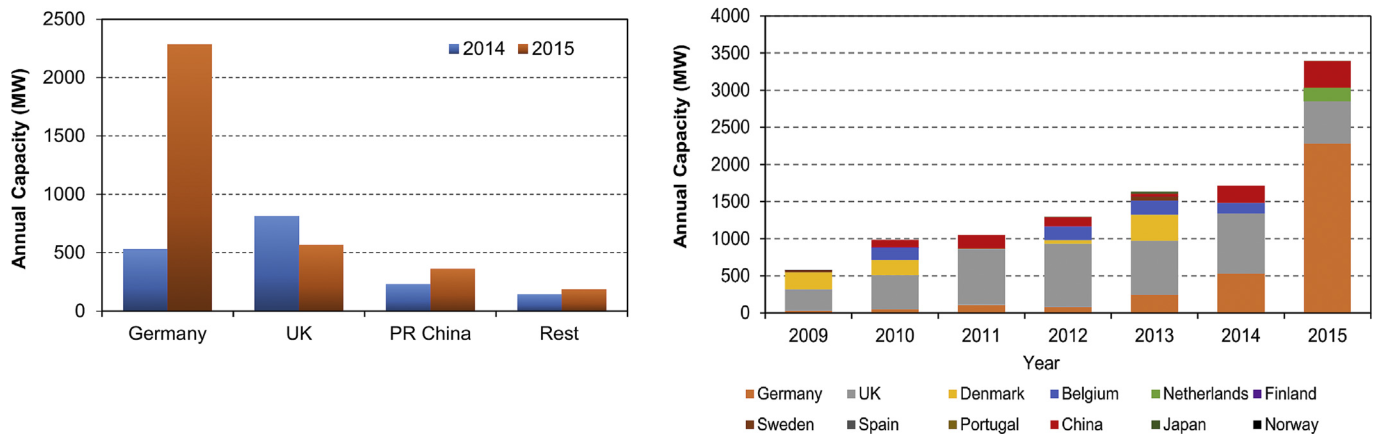



**Fig. 2.** (a) Offshore 2014–2015 annual installations by country, (b) Annual capacity by country since 2009. Based on data from Refs. [4,6].

above 300 MW, while the market in Germany presented an increasing trend until 2015, where implementation of new large projects resulted to an enormous growth of its cumulative offshore capacity to 3.3 GW. On the other hand, China's first offshore wind installation dates back to 2010, and since 2013 its annual capacity presents an increasing trend [4,6].

The annual number of installed wind turbines between 2010 and 2015 presented an increase almost similar to annual capacity (see Fig. 3). In 2015, 860 turbines were fully commissioned from which 63.5%, 18%, and 11.6% erected in Germany, the UK, and China respectively [4,9,10]. Compared to Fig. 2b, it is observed that in some countries the share of annual capacity is not consistent with the one of installed turbines (e.g. Denmark in 2010 and Netherlands in 2015). This may be explained by the relation between a wind farm's capacity and the rated power of the corresponding wind turbines of the farm. Hence, in the case of wind turbines with relative low rated power, the corresponding wind farm comprises of a larger number of wind converters.

The motivation towards offshore installations, stems firstly from the higher wind resource met in sea areas that exceeds even the 8 m/s at 50 m height and contributes to higher capacity factors (CFs) (see Fig. 4), and secondly from the lower impacts on human societies compared to the onshore counterparts [11,12]. As it is obvious from Fig. 4, mean CFs of offshore installations in the UK and Germany were much higher than onshore counterparts during the last 5 years, with an exception of CFs in 2013 and 2014 of onshore and offshore farms in Germany which were almost equal [13,14].

However, the advantages of offshore projects are counterbalanced by the higher demand on raw materials, manufacturing, construction, transportation, and decommissioning processes in a life cycle perspective.

In this regard, wind turbines installed offshore, present fundamental differences in design processes compared to onshore counterparts. These different drivers comprise of higher acceptable noise levels, higher capital cost share concerning the non-turbine components with the cost arising from turbine size scaling, and better required reliability in general. Based on the above, offshore wind converters feature larger rotors, rated power, and higher rotor tip speeds than onshore, while constraints concerning land use found in onshore installations are not applicable resulting to larger offshore wind farms [15].

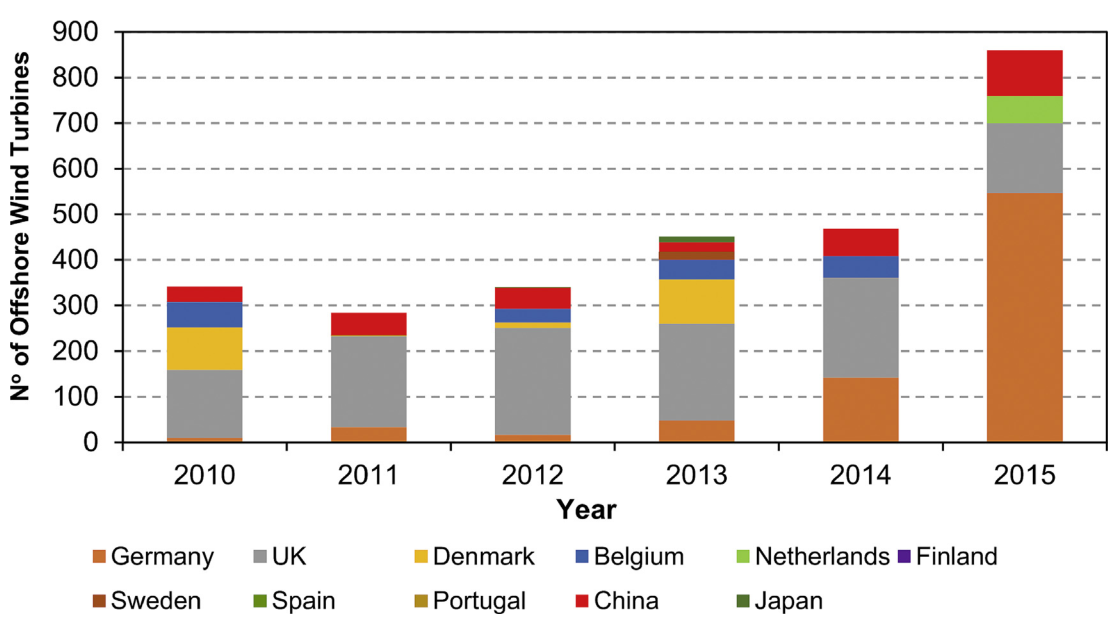
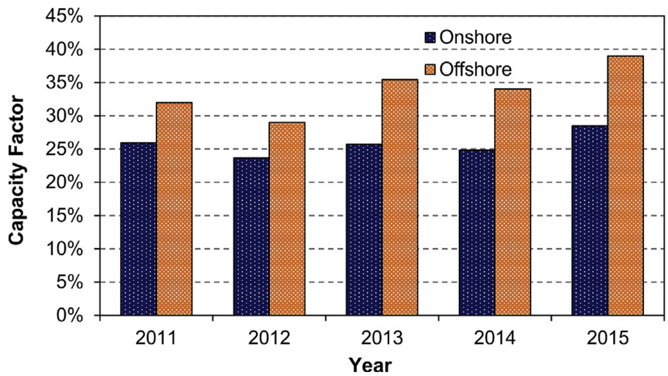



**Fig. 3.** Number of annual wind turbines installed by country. Based on data from Refs. [4,9,10].



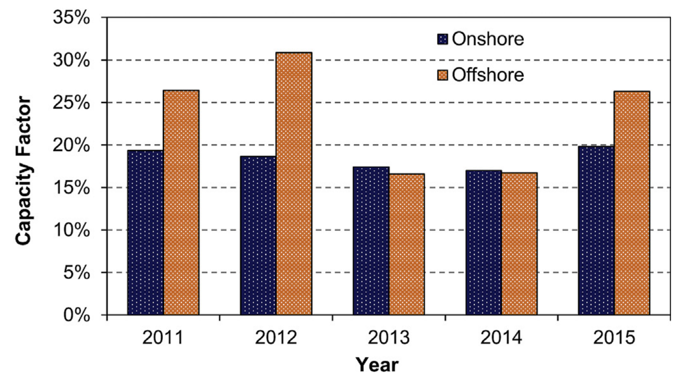




**Fig. 4.** Mean annual Capacity Factors of Onshore-Offshore wind installations in the UK (left) and Germany (right) since 2011. Based on data from Refs. [13,14].

Following the above, Fig. 5 compares the cost distribution between offshore and onshore installations. It is obvious that in the case of offshore projects, wind turbine along with foundation and transmission costs exceed 90% of total expenditures, while in the case of onshore counterparts this value reaches 80% of total cost. This is caused mainly due to the high cost share of the foundation infrastructure of offshore installations.

Fig. 6 indicates the process flow chart of a wind farm's life cycle which includes the manufacturing, transport and on-site erection, operation and maintenance, and decommissioning phases. During the manufacturing phase, mining and refining of the raw materials take place along with construction of the main components of the wind turbines (e.g. rotor, nacelle, tower, foundation, connection cables). Transportation of the parts and construction activities require mainly carbon-based fuels for the operation of the machinery equipment. Additionally, fuel consumption occurs during the operation and maintenance phase which includes the transportation of the personnel and spare parts on-site, and the use of various oils and lubricants. During the decommissioning of the installation, dismantling of the turbines, and materials' transport to disposal sites or recycling areas require the operation of machinery and vehicles (e.g. vessels, trucks) and therefore energy is consumed [17]. Hence, the erection of a wind farm encloses an amount of energy which is called embodied, resulting to indirect GHG emissions.

The present study aims at delivering a detailed review concerning the carbon footprint of offshore wind developments through the presentation of the key findings in the existing international literature. In this context, the second Section of this research indicates the significance of the capacity factor parameter in the energy payback period of wind power technologies and subsequently, the third Section gives an analysis of the energy and $CO_2$ intensity values of the offshore wind power installations. Additionally, a comparison with onshore counterparts in energy requirements and GHG emissions was also performed in order to assess the subject more comprehensively.

## 2. Wind resource and technical availability impact on wind energy payback period

Although wind energy nowadays is granted as a mature power generation technology, its dependence on the stochastic nature of wind comprises one of its most significant drawbacks [18]. The intermittent operation of wind turbines contributes to reduced energy yield in a life cycle as the local wind potential of wind installations cannot be "regulated". In addition to wind resource, a parameter that affects significantly the energy performance of a wind energy converter is its technical availability. This term expresses the ability of a wind converter to operate under no technical problems resulting to decreased downtime hours and thus to higher energy production [19].

In this context, the wind resource characteristics along with the technical availability factor designate the term of capacity factor via the equation:

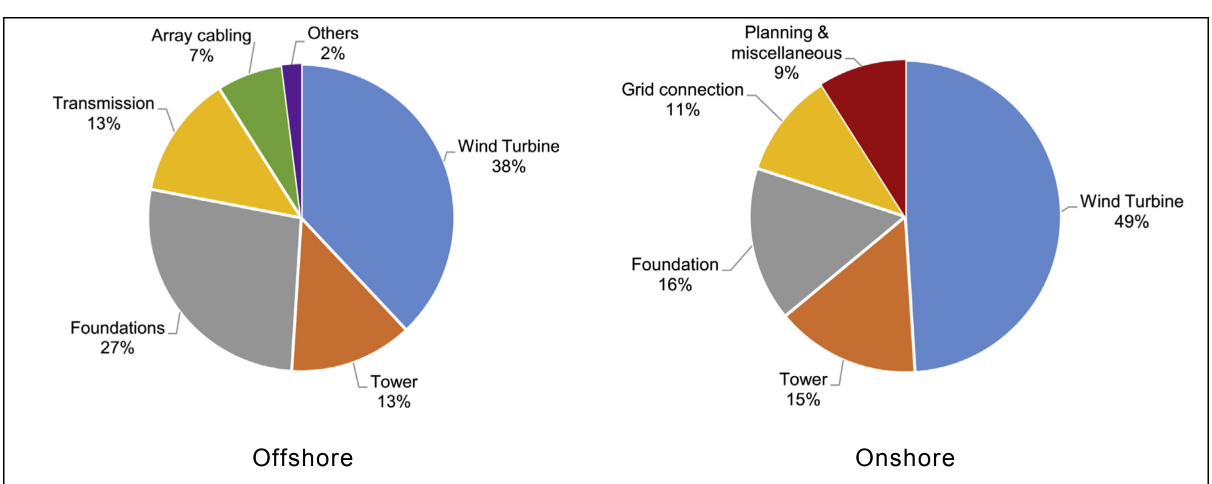



**Fig. 5.** Cost breakdown of offshore and onshore installations. Based on data from Ref. [16].

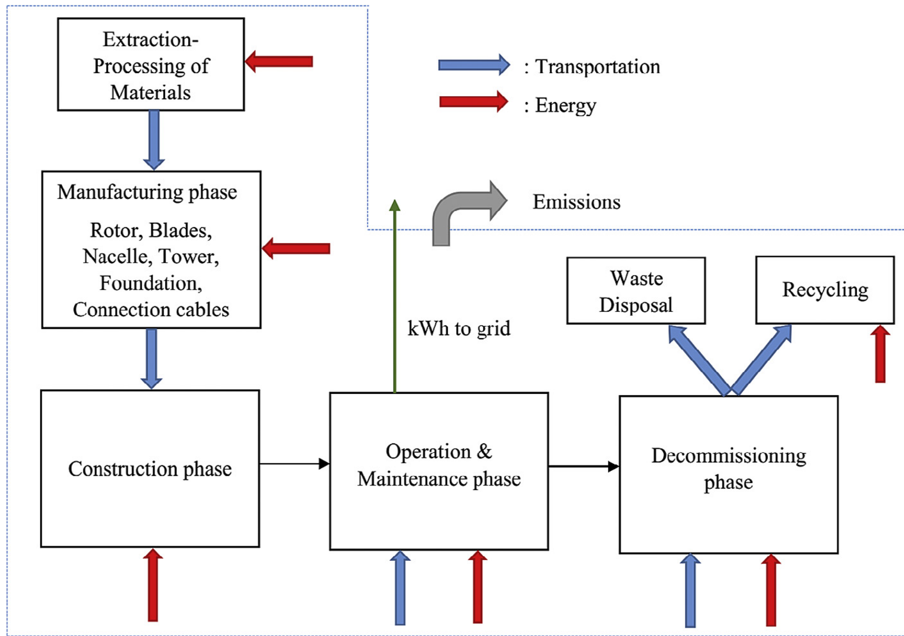



**Fig. 6.** Life cycle flowchart of a wind farm.

$$CF = \omega \cdot \Delta \tag{1}$$

where "$\Delta$" is the technical availability of the installation and "$\omega$" is the mean power coefficient which is defined as:

$$\omega = \int_{0}^{\infty} \frac{P_{ex}(V)}{P_R} f(V) dV = \int_{Vc}^{Vf} \frac{P_{ex}(V)}{P_R} f(V) dV \tag{2}$$

where "$f(V)$" represents the probability density curve of the local wind potential, "$P_{ex}(V)/P_R$" is the dimensionless power curve of the wind turbine with "$P_{ex}(V)$" being the power output of the wind converter (of "$P_R$" rated power) at different wind speeds "$V$" at hub height. "$V_c$" and "$V_f$" are the cut-in and cut-out speed of the wind turbine respectively.

Contemporary large wind turbines present technical availability of 99% which means less than 100 h per year out of operation. Fig. 7 indicates the evolution of technical availability, where it is obvious that high values of "$\Delta$" have been achieved during the last decade [19].

In this regard, mean values of CF during the last 20 years (see Fig. 8), presented an increase from around 18% to 21.5% in both European and Global projects suggesting firstly the technology upgrades of wind turbines that increased technical availability and energy capture and secondly the sophisticated assessment of the local wind potential that contributed to better locations for wind farm installations [18].

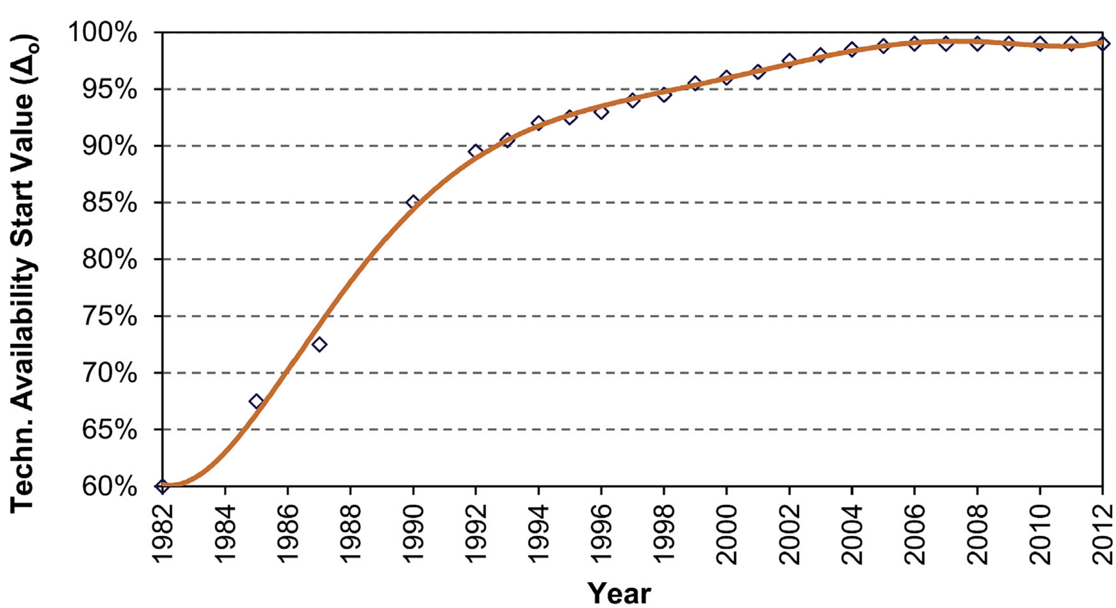



**Fig. 7.** Time variation of wind turbines' technical availability due to technology evolution. Based on data from Ref. [19].

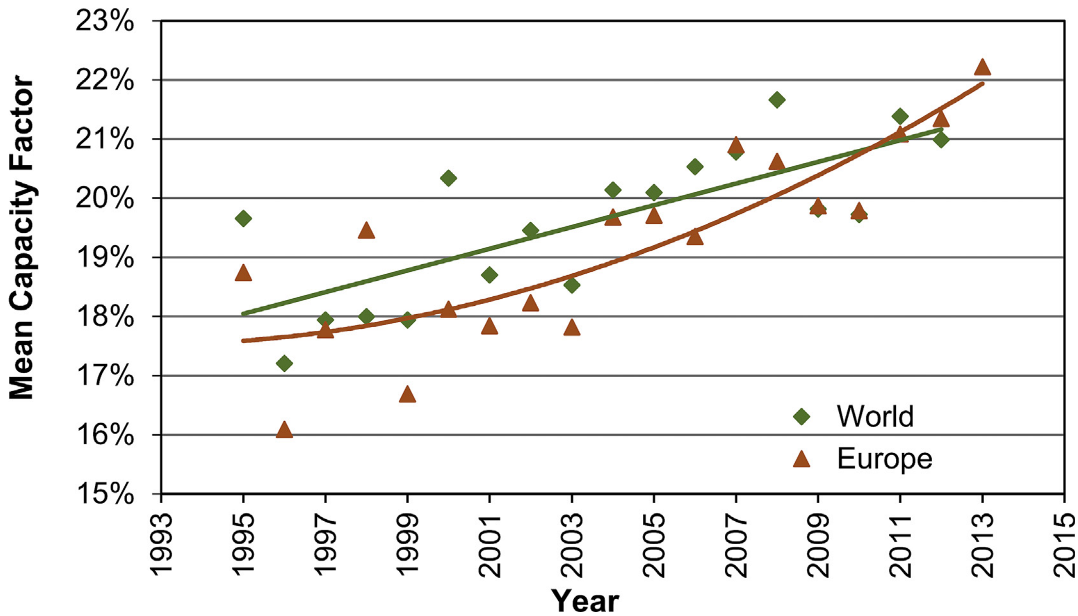



**Fig. 8.** Evolution of mean capacity factor. Based on data from Refs. [20,21].

Acknowledging the above, it should be noted that the annual energy yield of a wind farm is proportional with the capacity factor during its operation. Hence, according to Equation (3), the produced (annual mean) energy from a wind installation equals to:

$$E_{WF} = CF \cdot (z \cdot P_R) \cdot 8760 \tag{3}$$

where "$z$" is the number of the wind turbines of the park.

In this context, one may calculate the energy payback period (EPBP) of a wind farm project, which expresses the period that the installation should operate to offset the amount of energy that is consumed during its lifetime operation (see Equation (4)) [22].

$$EPBP = \sum_{k=1}^{n} E_k / E_{WF} \tag{4}$$

where "$E_k$" is the energy required for a life cycle stage "$k$".

Based on Equations (1), (3) and (4), the EPBP is highly dependent on the CF of a wind installation. Hence, high values of technical availability and mean power coefficient result to low EPBP and thus promote the sustainable character of wind power technology.

## 3. Energy and $CO_2$ intensity of wind energy technologies

Both onshore and offshore wind power systems are known as low-emission energy production technologies, with the sole use of wind as the main energy source for generating electricity. However, seen from a sustainable point of view and a life cycle (LC) perspective, wind turbines require primary LC embodied energy amount (ELC) in the order of about 1 to 7MWh$_{pr}$/kW that is usually offset by the renewable energy produced within the first 12 months of operation. On the other hand, LC GHG emissions equals to around 1.84–2.07tons $CO_{2\text{-}eq}$/kW of installed electric capacity [22–33].

### 3.1. Embodied energy

As previously mentioned, the embodied energy of a wind turbine includes the energy consumed during the stages of raw material extraction, manufacturing, operation and final disposal at the end of its lifetime. When considering turbines as part of a wind farm project, this embodied energy may also include during the construction phase the energy required for other materials and components manufacture, including electrical connections (internal cables within the wind farm, external cabling), transformers, substations and access roads.

To this end, infrastructure differences between offshore and onshore installations can be seen in Fig. 9, where it is obvious that for a V80-2 MW turbine although the materials used are almost the same, the required quantities for offshore projects concerning steel and lead are significantly higher. This mainly arises from the fact that manufacturing of offshore foundations, internal cables and transformer stations present high demand for these materials. Specifically, steel reinforced concrete is used for onshore foundation while steel monopiles are mainly used offshore. The steel quality used for monopiles is based on experience from offshore projects, while the procedure followed comprise of "shotblasting". For the coating of the steel to avoid corrosion, a two-component thick (epoxy) film is usually used. Additionally, in order to minimise corrosion, foundation piles are supplied with cathodic protection inside and outside [27,28].

Most studies also consider an end-of-life recycling credit for some components as well as the energy consumed during the operation and maintenance (infrastructure/reinvestment) of the wind turbine/project, transportation activities (fuel consumption) and the phase of decommission. Thus, one may estimate the primary LC embodied energy amount (ELC) (see Equation (5)) as a function of the total primary energy required or gained (recycling) during the three main life cycle phases, i.e. construction ($E_C$), operation and maintenance ($E_{O\&M}$) and decommission ($E_D$) of a wind farm project, divided by a reference unit ($R$) (generated kWh of electricity throughout lifetime (kWh$_{pr}$/kWh$_e$) or rated power of the project (kWh$_{pr}$/kW)).

$$ELC = \frac{E_C + E_{O\&M} + E_D}{R} \tag{5}$$

A remarkable number of LC assessments (LCAs) have been conducted for onshore and offshore wind power plants concerning large, medium and small-scale installations as well as stand-alone

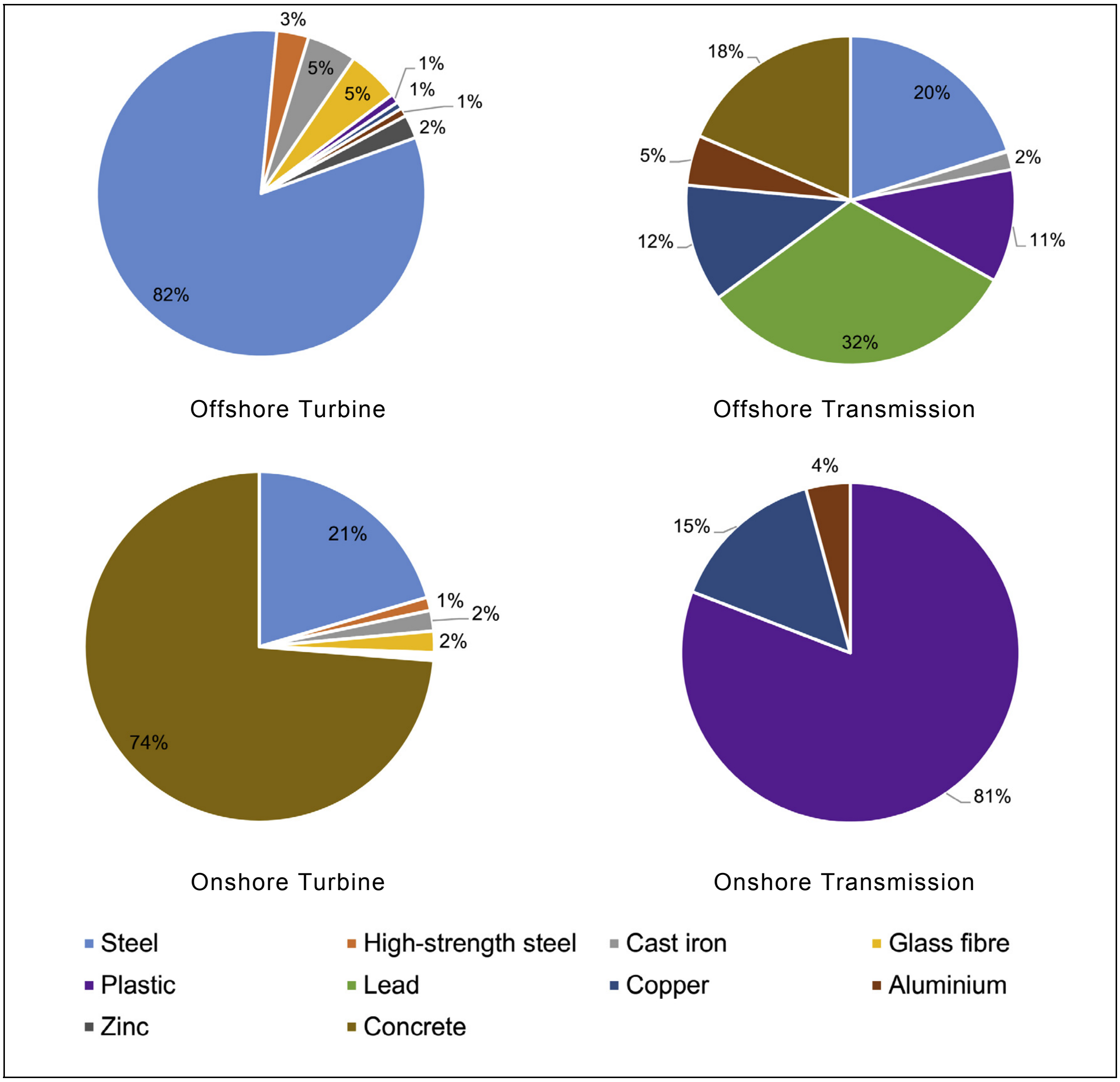



**Fig. 9.** Share of materials for offshore and onshore installations. Based on data from Ref. [28].

systems for remote consumers [23,24] (Fig. 10).

However, regarding offshore wind, LCAs are limited to bottom-fixed foundations employed mainly in shallow water depths (<30 m). Few studies focus on floating installations, analysing hypothetical wind farm installations comprised by floating units [22,34], and a specific study concerns a non-floating operational wind farm (Alpha Ventus) which is one of the deepest large-scale pilot offshore developments employed at an average water depth of 30 m and about 60 km away from shore [35].

As seen from Fig. 10, reported LC embodied energy amount per kW across all wind power system categories forms an interval of about 1 to 7MWh$_{pr}$. However, if wind turbine capacity ratings below 0.5 MW are excluded, the interval narrows to 1-5MWh$_{pr}$, suggesting that the highest embodied energy is observed for small wind turbine sizes which are only met in land-based environments. In fact, acknowledging the set of data previously analyzed, the primary energy requirements can be adequately represented by a “U-shape curve”, showing evidence that energy use is downward sloping with growing wind turbine capacity (strong presence of economies of scale).

Nevertheless, this trend reverses when moving into the multi-MW spectrum, and increases again due to existing technological barriers (e.g. technical feasibility and availability, immaturity of technology etc.). Another observation which may be made from the results depicted in Fig. 10 is that offshore systems show slightly higher primary energy requirements as they present higher energy-demand during the construction stage [18,22,25–29,35–41].

### 3.1.1. Energy payback period

As mentioned in the previous Section, the EPBP comprises one of the factors that are investigated throughout an LCA in order to appraise the impacts associated with the development of a wind power project. Since 2000, many studies concerning the estimation of EPBP have been performed for both onshore and offshore wind turbines indicating that for the majority of the cases EPBP is less than 1 year. Specifically, by taking these 17 studies into account, the EPBP for onshore turbines ranges between 3.1 and 12 months (average value equals to 6.8 months), while for offshore the EPBP ranges between 4.7 and 11.1 months (average value equals to 7.8 months) (see Fig. 11) [17,22,24–27,29,35,42,44,46,47].

Based on the above estimated values, one may comprehend that offshore wind installations present higher EPBP (although average values are at the same order with onshore farms) which mainly

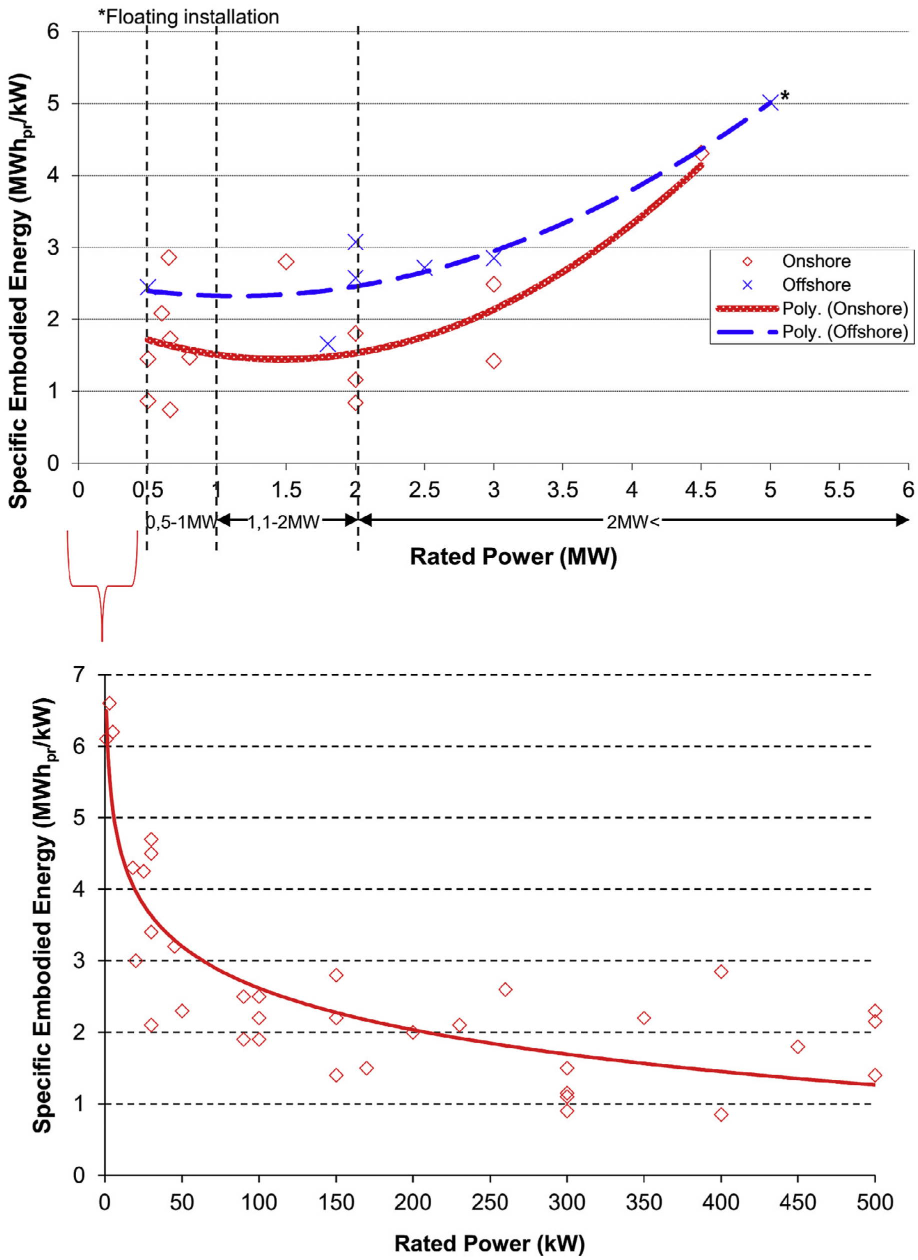



**Fig. 10.** Specific energy content of commercial wind turbines as a function of increasing wind turbine nameplate capacity. Estimated based on data from Refs. [22–33,40–45].

arises from two factors. Firstly, as it is obvious from Fig. 10, the specific embodied energy of offshore turbines is higher than the onshore counterparts, and secondly, the technical availability factor may be in some cases reduced due to the harsh weather conditions found at open seas which hinder repair and maintenance activities in the case of operational faults. Hence, although the wind potential found at open seas is in general higher than onshore locations, the CF, via the technical availability parameter, combined with the LC embodied energy of offshore installations result to an increased EPBP compared to onshore counterparts.

### 3.2. Carbon footprint

Apart from the life cycle energy resource indicators, this considerable body of literature also reflects the sustainable character of the respective installations through the investigation of GHG emissions (in g/kWh$_e$), mainly those of $CO_2$ (see for example Fig. 13), and the application of the energy pay-back period (EPBP) criterion, i.e. the ratio of LC energy requirements to the system annual energy production, or alternatively the time required for the system to compensate for its primary LC energy requirements through the production of useful energy (actual electricity) amounts.

Fig. 12 compares breakdowns of life cycle primary energy use and greenhouse gas emissions during the main three life cycle phases [17,35–37,44]. Looking at the relative contribution of each phase, it is obvious that in both cases (onshore and offshore) construction of components dominates, reaching between 80% and 90% (for offshore and onshore projects, respectively) of the total ELC or GHG indicator values. The construction phase is then followed by the operation phase (approx. 5–20%), with offshore installations having higher shares mainly due to maritime

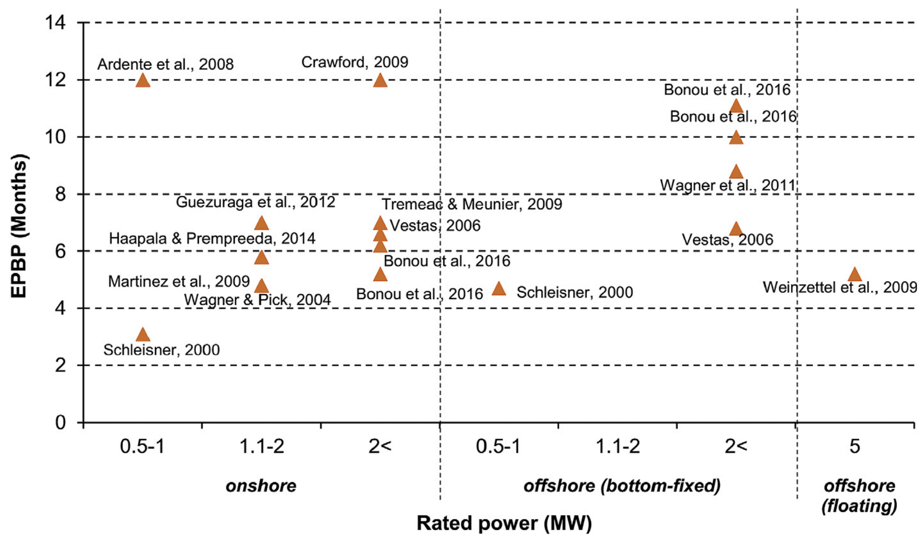



**Fig. 11.** Energy payback period as a function of wind turbine capacity for both onshore and offshore installations.

transportation (by ship or helicopter) from the shore to the site for undertaking maintenance activities. The disposal or deconstruction phase of a wind farm project, where included, seems to have a minor influence to the total ELC or GHG indicator values, especially in the case of onshore power plants. Furthermore, as illustrated in the same Figure, the turbine of onshore wind power systems is clearly the most important single component (~70%) regarding the ELC or the GHG emission indicator, followed by the substructure (~10%), while the opposite occurs for offshore counterparts where the wind turbine holds a quite lower share in the order of 25–40% and the foundation 25–45%. Moreover, one should note the remarkable contribution of electrical connections in the case of offshore projects due to the necessity of submarine cables and offshore substations [12].

The high variation in indicator shares mainly arises due to additional components and increased input of materials which are required to build an offshore wind farm, like offshore substations, submarine cables as well as complex foundations of the wind turbines requiring large amounts of concrete and steel. For example, as regarding the latter, gravity-based foundations require large weights of concrete (e.g. 1930t for a 2 MW turbine [32], 3000t for a 2.5 MW turbine [37]), monopiles are made of steel (e.g. 203t for a 3 MW turbine [27], 415t for a 2.5 MW turbine [37]) [48], while it is stated that the 5 MW floating wind turbine investigated in Weinzettel et al. [22] requires 1000t of steel in an extended 200 m tower and 3000t of gravel for ballast and mooring.

As resulting from the above, offshore projects seem to be more energy demanding than onshore ones throughout their entire life cycle. However, it should be noted that the majority of projects located offshore, demonstrates higher capacity factors (or higher energy performance) [11] because of the better wind conditions met in marine environments, a factor that almost outweighs the increased resource requirements (normalized energy intensity) and makes the two plants comparable (see also Equation (5)). In fact, by reviewing studies published between 2000 and 2009, Arvesen et al., 2009 [48] have found that energy intensity fluctuates from 0.014 to 0.082$kWh_{pr}/kWh_e$ (average value obtained from 28 studies investigated, equals to 0.037$kWh_{pr}/kWh_e$) and 0.029 to 0.054$kWh_{pr}/kWh_e$ (with average value being equal to 0.041$kWh_{pr}/kWh_e$) for onshore and offshore wind power projects, respectively. Similar conclusions may be drawn regarding the global warming potential (normalized carbon intensity) for onshore and offshore wind energy (Figs. 13 and 14). As seen, the carbon footprint of offshore versus onshore wind energy generation is marginally greater, with the average value calculations based on data published in Refs. [22,25–29,35,37–39,45,47,49–51] being equal to 15.6 and 9.0$gCO_2/kWh_e$, respectively (Fig. 13).

The highest value is reported for the offshore pilot project Alpha Ventus (Fig. 13) in Wagner et al. [35] (32$gCO_2$-eq/$kWh_e$), with offshore foundations (12 × 5MW wind converters installed on tripods and jackets at an average water depth of 30 m and 60 km away from the shore) and submarine cables being the main energy intensive components. On the other hand, the lowest value among the studies analyzed was found in Vestas [27] where the presented LCA shows that 1 kWh of electricity generated by a 3 MW offshore turbine (erected on monopile at a water depth of 10 m and 14 km away from shore) has an impact of 5.2 g of $CO_2$ during its life cycle (Fig. 13), which is slightly higher than the corresponding value (4.6$gCO_2/kWh_e$) caused by an onshore wind turbine of the same rating, due to the higher (almost double) performance of the former, i.e. real calculations indicate energy yield equal to 14.2$GWh_e$/year and 7.9$GWh_e$/year for the offshore and onshore wind turbine model, respectively. Table 1 synopsises the data that were used during the energy and carbon intensities research based on the reviewed literature.

Recapitulating the above, despite the differences between studies concerning energy and carbon intensity indicators (which are influenced by turbine size, capacity factor, manufacturing materials, floating/bottom-fixed/gravitation, recycling or overhaul of components after the service life, fuel mix of countries for $CO_2$ intensity estimation etc.), even the most pessimistic figures lead to the conclusion that both onshore and offshore technologies demonstrate low (on average) energy and global warming impact in comparison to other electricity generation options (see Fig. 14). More specifically, the corresponding ranges for competing technologies are 15–40$gCO_2/kWh_e$ (mean value 28) for hydroelectric plants, 15-50$gCO_2/kWh_e$ (mean value 33) for nuclear plants and 50-100$gCO_2/kWh_e$ (mean value 75) for photovoltaics. Life cycle GHG emissions of electricity from natural gas, oil and coal range between 400 and 500$gCO_2/kWh_e$ (mean value 450), 780-900$gCO_2/kWh_e$ (mean value 840) and 900-1200$gCO_2/kWh_e$ (mean value 1050), respectively [18,26].

Judging from the values above, the carbon footprint of wind power is significantly lower than that of fossil fuel power stations

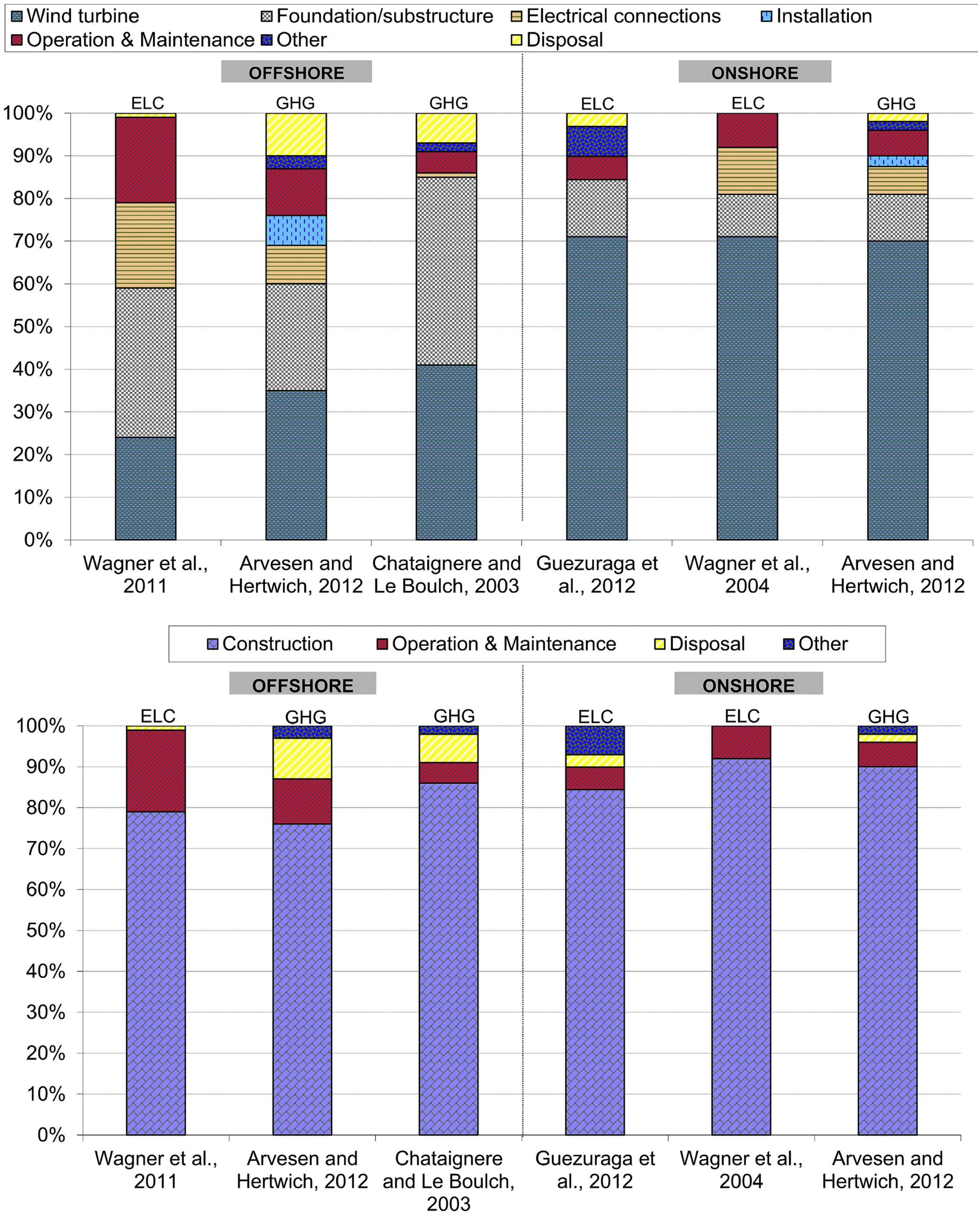



**Fig. 12.** Breakdown of life cycle primary energy requirement and greenhouse gas emissions. Based on data found from Refs. [17,35–37,44].

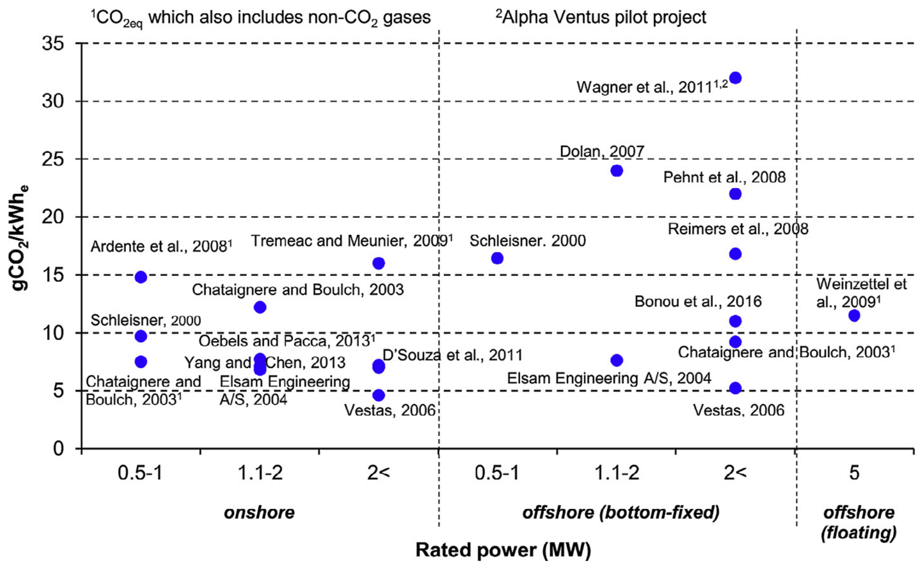



**Fig. 13.** Life cycle carbon footprint of onshore and offshore wind energy as a function of increasing wind turbine nameplate capacity.

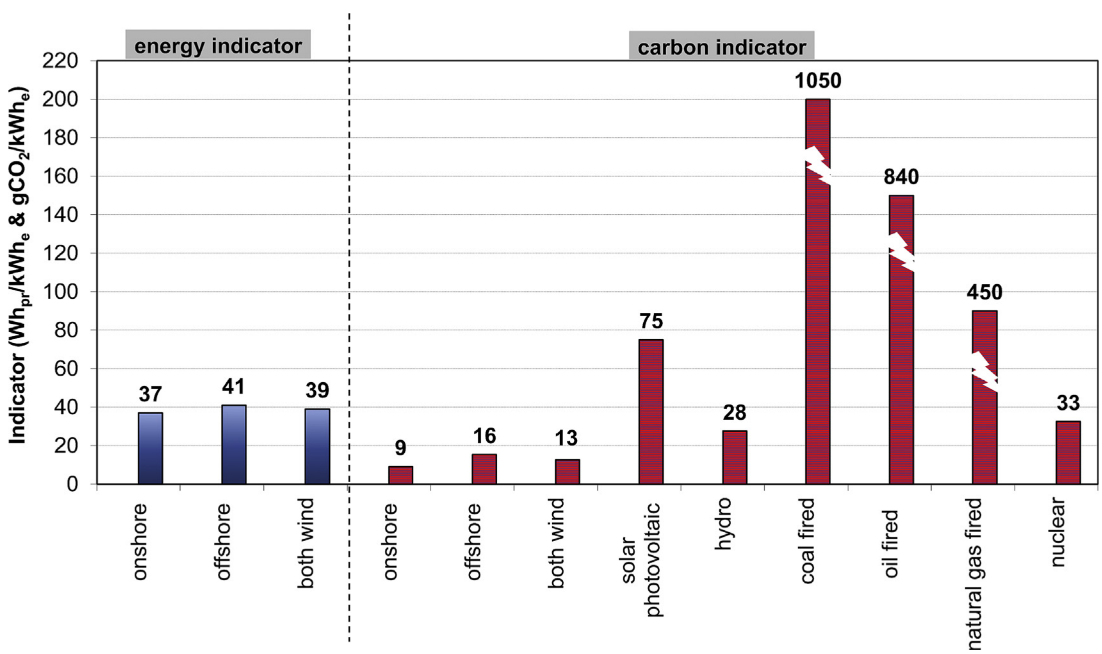



**Fig. 14.** Average values of energy and $CO_2$ emission intensity. Calculations based on data found from Refs. [18,22,25–29,35,37–39,45,47–51].

and is comparable or lower than that of other non-fossil power generation technologies [36]. Likewise, the comparison of life cycle emissions concerning air pollutants, such as $NO_x$, $SO_2$ and particles, of multiple power generation technologies, presented in Intergovernmental Panel on Climate Change (IPCC) special report for climate change mitigation [52], indicates a good environmental performance for wind power.

## 4. Research for technology improvement

Although the carbon footprint and the primary embodied energy amount of wind energy developments in a life cycle perspective is insignificant compared to other sources of electricity generation, it should be mentioned that the lack of knowledge in the field of novel concepts, such as floating units, lattice towers, tripod pile foundations etc., comprises a major drawback. For instance, as mentioned in the previous section, only a limited number of studies published so far concern deep water concepts. One would expect that the limited LC energy requirements of the land-based or bottom-fixed projects apply also for a floating plant. There are, however, substantial differences between floating wind power plants and bottom-fixed, i.e. more steel and potentially more concrete are required for the construction of a floating unit, while the use of both special boats and helicopters (due to large distances and bad weather conditions) are required for installation and maintenance. Based on the above, an area which would be advantageous to investigate, is the research on new tower concepts given their high contribution to the overall embodied energy and indirect emissions during the erection of a wind farm. For example, according to Raadal et al. [1], total steel mass requirements of a

**Table 1**
Onshore and Offshore wind embodied energy and $CO_2$ intensities based on data from literature.

| Literature Sources | Onshore | | | Offshore | | |
|---|---|---|---|---|---|---|
| | Power Rating (MW) | Specific Embodied Energy (MWh/kW) | Carbon Intensity (g/kWh$_e$) | Power Rating (MW) | Specific Embodied Energy (MWh/kW) | Carbon Intensity (g/kWh$_e$) |
| Ardente et al., 2008 [26] | 0.66 | 1.73 | 14.8 | – | – | – |
| Chataignere and Boulch, 2003 [37] | 0.60 | – | 7.5 | – | – | – |
| Chataignere and Boulch, 2003 [37] | 1.50 | – | 12.2 | 2.50 | – | 9.2 |
| Crawford, 2009 [24] | 3.00 | 2.48 | – | – | – | – |
| Crawford, 2009 [24] | 0.65 | 2.85 | – | – | – | – |
| D'Souza et al., 2011 [39] | 3.00 | – | 7.0 | – | – | – |
| Ecoinvent, 2007 [32] | 0.80 | 1.47 | | 2.00 | 2.57 | |
| Elsam Engineering A/S, 2004 [28] | 2.00 | 1.80 | 6.8 | 2.00 | 3.07 | 7.6 |
| Lee and Tzeng, 2008 [31] | 0.66 | 0.74 | – | – | – | – |
| Martinez et al., 2009 [30] | 2.00 | 0.84 | – | – | – | – |
| Martinez et al., 2009 [42] | 2.00 | 1.15 | – | – | – | – |
| Oebels and Pacca, 2013 [38] | 1.50 | – | 7.1 | – | – | – |
| Yang and Chen, 2013 [41] | 1.5 | 2.8 | 7.2 | – | – | – |
| Pehnt et al., 2008 [49] | – | – | – | 5.00 | – | 22.0 |
| Pehnt, 2006 [33] | – | – | – | 2.50 | 2.71 | |
| Schleisner, 2000 [29] | 0.50 | 1.45 | 9.7 | 0.50 | 2.45 | 16.5 |
| Tremeac and Meunier, 2009 [25] | 4.50 | 4.31 | 16.0 | – | – | – |
| Vestas, 2006 [27] | 3.00 | 2.48 | 4.6 | 3.00 | 2.85 | 5.2 |
| Voorspools et al., 2000 [43] | 0.60 | 2.08 | – | – | – | – |
| Wagner and Pick, 2004 [44] | 1.50 | 0.86 | – | – | – | – |
| Wagner et al., 2011 [35] | – | – | – | 5.00 | – | 32.0 |
| Weinzettel et al., 2009 [22] (floating) | – | – | – | 5.00 | 5.01 | 11.5 |
| Bonou et al., 2016 [47] | 2.30–3.20 | – | 7.0 | 4.00–6.00 | – | 11.0 |
| Garrett and Rønde, 2013 [50] | 2.0 | | 7.7 | – | – | – |
| Dolan, 2007 [45] | – | – | – | 1.80 | 1.66 | 24.0 |
| Reimers et al., 2014 [51] | – | – | – | 5.00 | – | 16.8 |

5 MW offshore wind turbine equal to 490 tons from which 234 are used for the construction of the tower structure. In this context, the use of lattice towers and the replacement of steel with concrete as the basic tower material, may lower the energy and carbon content during the manufacturing phase (see Figs. 12 and 14) [48].

However, at this time, the differences between floating and bottom-fixed technology suggest a possible increase in the LC embodied energy amount, a situation which may not be counter-balanced by the higher wind speeds found in the open seas. On the other hand, one may argue that recycling of metals and rotor blade material can deliver significant emission savings and waste reduction compared to landfilling and incineration that comprise the most common routes for dismantling wind turbine blades and result to landfill mass increase and formation of polluting inorganic ash particles respectively [48,53]. In this context, contrary to the established procedure of recycling basic metals, recycling composite blade materials represents an engineering challenge. According to a study carried out by Vestas [27], increase of the metals recycling share from 90 to 100% lowers the total global warming impact by 8% and contributes to a decreased life cycle energy footprint.

## 5. Conclusions

This study presented a literature review concerning the carbon footprint of wind energy technologies in order to provide a comparative evaluation between offshore and onshore wind installations. The research focussed on presenting reports from life cycle assessment research on the embodied energy, energy payback period and greenhouse gas emissions of offshore projects. The study took also into account the availability of LCA research for onshore counterparts, aiming to compare the published results with the ones of offshore installations. Additionally, presentation of $CO_2$ intensity of other energy production systems indicated substantial differences with wind energy projects in favour of the latter.

In conclusion, it is obvious that although offshore wind projects present larger carbon footprint compared to the onshore counterparts, this variation is often counterbalanced from the better wind resource that leads to an increased yield of renewable electricity and consequently to an almost similar EPBP. It should be also noted that based on the data presented in Fig. 14, the avoided GHG emissions from the operation of an offshore wind farm instead of a conventional carbon-based power plant, equals from 435 to 1035g$CO_2$-eq/kWh of produced electrical energy. Moreover, new developments in the field of offshore technology, such as increase of turbine size and novel concepts (e.g. floating plants) that will contribute to the exploitation of wind resources at higher distances from shore and further reduce the GHG and energy intensity, should be monitored and taken into account in order to reassess the benefits of moving from onshore to offshore locations.

All the above suggest the great contribution that offshore concept may offer to the global efforts for fulfilling the target of GHG reduction. Nevertheless, while energy and $CO_2$ indicators are important factors during the assessment of the wind installations impacts, other parameters (e.g. visual, noise impact, impacts on avian species, etc.) should also be considered in order to appraise a broader perspective of the environmental performance of offshore wind electricity generation.

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