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Published in:
Journal of Fundamentals of Renewable Energy and Applications

DOI:
10.4172/2090-4541.1000211

First published: 15/06/2016

Document Version
Publisher's PDF, also known as Version of record

Journal of Fundamentals of Renewable Energy and Applications

Smoucha et al., J Fundam Renewable Energy Appl 2016, 6:4
DOI: 10.4172/2090-4541.1000211

Research Article Open Access

Life Cycle Analysis of the Embodied Carbon Emissions from 14 Wind Turbines with Rated Powers between 50 Kw and 3.4 Mw

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Abstract

In order to facilitate increased renewable energy production, there continues to be a global increase in wind turbine installation. When quantifying the carbon offsets from these installations, the production emissions are rarely accounted for. This paper reports on the embodied carbon emissions from the production of 14 wind turbines, rated between 50 kW and 3.4 MW. The embodied emissions were quantified from emission factors specific to each material involved in manufacture, transport to site, and installation of the turbines. The resulting trend was that higher-rated turbines had greater embodied carbon emissions with one 3 MW turbine incorporating 1046 tCO_{2eq} compared to only 58 tCO_{2eq} for an 80 kW turbine. However, the greater electricity output of the turbines offset these emissions more quickly with a recovery in 64 days for a 3.4 MW turbine compared to 354 days for a 100 kW one. This also resulted in lower carbon emissions per kilowatt hour of electricity generated and quicker payback as a percentage of lifetime of 0.9% for a 3.4 MW turbine compared to 4.3% and 4.9% for a 50 and 100 kW turbines, respectively. The findings of this analysis indicate that a preference for installation of higher-rated, over lower-rated, turbines should be favoured for greater environmental benefits.

Keywords: Wind turbines; Embodied energy; Manufacture; Transport; Installation; Carbon

Introduction

The requirement for onshore wind turbines within the UK

The European Commission has set a target of reducing CO_2 emissions across the EU by 20% compared to 1990 levels by 2020 [1]. As part of this commitment, the UK is obligated to reduce its emissions by 16% against 1990 levels [2]. However, the UK has more ambitious goal of 80% reduction by 2050 [3] and Scotland aims to generate 100% of electricity from renewable sources by 2020 [4].

There is potential to substantially contribute to the UK's GHG emission reduction targets through expansion of onshore wind farms, to meet targets set under the European Commission's Renewable Energy Directive. During their operation, turbines release negligible carbon dioxide (CO_2) emissions and are therefore considered carbon-neutral [5]. For example, the operational turbines in 2011 generated enough electricity to offset more CO_2 emissions than that produced in the city of Leeds [6].

Windmills and their ability to capture wind and convert it to power have possibly been used by human civilisations for over two thousand years [7]. Wind turbines are an increasingly popular renewable energy generation source in the United Kingdom and throughout the world [8]. Construction of large-scale wind turbine installations began in the 1990s, and the rate of installations has been increasing ever since [9,10] due to their ability to produce electricity with minimal greenhouse gas (GHG) emissions [11]. In 2012 alone, 44,711 MW of wind turbines were added, bringing the global capacity to 282,482 MW [9]. These numbers are only expected to increase as countries, especially in the European Union, work toward their carbon reduction goals for 2020 and 2050. At the end of 2012, the UK had the sixth highest installed capacity in the world behind China, the USA, Germany, Spain, and India [8].

The UK Government is looking to expand this further by the middle of the century in order to reach its own GHG reduction targets [2,3]. The UK needs to increase the capacity of onshore wind turbines from the current level of 15.4 terawatt hours (TWh) per annum to between 24 and 32 TWh by 2020 [12,13]. The largest onshore turbines currently manufactured at 7.5 MW [14,15], have an improved energy conversion from wind to wire over the smaller available turbines [16,17]. Installation of 509 of these 7.5 MW turbines would potentially reach the established 24 TWh goal and 983 turbines would reach the 32 TWh goal. However, this is unrealistic as turbines of varying powers below 7.5 MW are installed in the UK, and a greater number of these smaller turbines will be needed to reach the target [18].

Wind turbine life cycle analysis

Carbon offsets from turbine electricity are calculated without accounting for emissions that occurred during turbine manufacture, transportation and installation [19]. Only accounting for the operational emissions misrepresents the environmental impact of a wind turbine's lifecycle [20]. Manufacturing components, transporting, installing, maintaining, and decommissioning the turbines all have energy costs and corresponding carbon footprints [21]. Once the turbine is operational, it only emits GHGs during maintenance [21], which occurs during its lifetime in the form of workers traveling to turbines and from the production and installation of any parts

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Received March 11, 2016; **Accepted** June 10, 2016; **Published** June 15, 2016

Citation: Smoucha EA, Fitzpatrick K, Buckingham S, Knox OGG (2016) Life Cycle Analysis of the Embodied Carbon Emissions from 14 Wind Turbines with Rated Powers between 50 Kw and 3.4 Mw. J Fundam Renewable Energy Appl 6: 211. doi:10.4172/20904541.1000211

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that need replacing [5]. The operation stage is therefore where wind turbines differ from traditional energy-generating sources. Therefore, to accurately assess turbine offsets, these emissions must be taken into consideration. Calculating the embodied carbon from production determines the genuine carbon offset during a turbine's operation. Different measures are used to estimate this such as life cycle analysis (LCA), Carbon intensity, Avoided Emissions and Carbon payback.

Life Cycle analysis (LCA) establishes the impacts the entire lifespan of a product has on the environment - from cradle to grave. It covers every aspect of the supply chain and lifecycle, from procuring and processing raw materials to use of the final product, end-of-life treatment, recycling, and disposal method of any remaining materials [22]. The results of each LCA are different depending on the goal, scope, what processes are considered and assumptions that are made in the analysis [23]. For example, not all LCAs of wind turbines include recycling of materials at the end of their lives, which can greatly impact the total carbon footprint of the turbine [11]. Due to an unavoidable amount of uncertainty that arises from modelling, the results of LCAs are not exact; rather they are best estimates of impacts based on the data used [22].

LCAs follow two main approaches, either an input-output model or a process chain analysis. Input-output models assess all inputs and outputs of the model that affect the functional unit - the product of the system that is used for comparison and for which a value can be calculated [22,24]. For wind turbine LCAs, the functional unit is often defined as the carbon emissions produced per kWh, which can then be used in calculations to compare the carbon emissions from different turbines [25]. Process chain analyses are based on detailed records of materials and processes for each step of the lifecycle [26]. It can be quite difficult to acquire necessary specific information for each step of the lifecycle for either process. When this is the case, a hybrid of the two methods works best to reduce uncertainty in the results [8].

One of the most widely used methods of comparing carbon emissions from turbines is to calculate the carbon intensity. Carbon intensity is the total emissions over the turbine's lifetime in relation to total electricity generated, giving a value in units of CO_2eq/kWh. The advantage of this method is that it allows the installer to see the trade-off between the electricity generated and GHGs produced. This will allow for CO_2eq per electricity unit generated to be compared between turbines.

Lenzen and Munksgaard [27] analyzed data from 72 turbines of various rated powers around the world. Their results showed that of the 29 turbines for which the carbon intensity could be calculated, it ranged from 7.9 to 123.7 g CO_2eq/kWh [28]. This deviates substantially from the Intergovernmental Panel on Climate Change's (IPCC) Renewable Energy Sources evaluation that says emissions from turbines are 8 to 20 g CO_2/kWh [16]. Less than half of the turbines Lenzen and Munksgaard [26] analysed fell within the IPCC's range. Kabir et al. [21] compared the carbon intensity of three 100 kW capacity wind farms, each with different turbine configurations. The farm that consisted of twenty 5 kW turbines had the highest carbon intensity at 42.7 gCO_2eq/kWh. The configuration of five 20 kW turbines had a total of 25.1 gCO_2eq/kWh. Installing a single 100 kW turbine had the lowest impact, producing 17.8 g CO_2eq/kWh [21].

Comparing the carbon intensity can help determine which configuration of turbines will have the lowest GHG emissions for the electricity returned. When compared to non-renewable sources, wind turbines have a significantly lower average carbon intensity [18,29]. When compared with other renewable sources, the ranges overlap more significantly, indicating the technologies need to be evaluated on a case-by-case basis [29]. Marimuthu and Kirubakaran [30] found that a 1.65 MW turbine had a carbon intensity 165 times lower than coal, which meant the turbine could offset 2831 tCO_2 each year it operated.

Avoided emissions and carbon payback

The carbon payback period determines how long the turbine would need to operate before the electricity it generates can be considered carbon neutral. To calculate the carbon payback period, the life cycle GHG emissions from the turbine are compared to the amount of GHGs a non-renewable source would emit to produce the same amount of electricity the turbine produces in its lifetime. This method can be used to compare what the effects would be of installing different types of electricity generation sources. Marimuthu and Kirubakaran [30] reported that a 1.65 MW turbine would generate 393,843 kg CO_2 over its 20-year lifespan. When compared to a coal-fired power plant, the turbine would only have to run for 51 days to generate carbon-neutral electricity [30]. The carbon payback period can also be calculated using the average emission content of all electricity sources for the area in which the turbines will be installed, rather than the emission content of a single technology source. Tremeac and Meunier [5] used this method to compare the emissions from turbines with those of location-specific carbon intensity values when deriving carbon payback periods.

Different location-specific carbon intensities indicate that the carbon intensity value chosen has important implications for LCA results, suggesting two important points. Firstly, where electricity is used, will impact its ability to reduce emissions. Tremeac and Meunier [5] showed this by comparing the different payback periods that resulted from replacing French electricity (66 gCO_2/kWh) and European electricity (450 gCO_2/kWh) with electricity from wind turbines. When calculated the payback time assuming the electricity was generated and used in France, i.e. using the French carbon intensity of 66 g CO_2/kWh, the turbines generated emission free electricity for 15.2 years (4.5 MW turbine) and 6 years (250 W turbine). However, if the electricity was generated in France, but exported to Europe (i.e. all other factors of the study were kept the same except the carbon intensity was 450 g CO_2/kWh), the turbines operated emission free for 19.3 years (4.5 MW) and 18 years (250 W) [5]. Secondly, as countries reduce the carbon content of their electricity grid, the addition of each new renewable source will have a smaller impact on reducing emissions. The relatively low carbon electricity grid already in place in France means that installing turbines there has less of an impact than installing them in other countries in Europe. This may impact where turbines should be installed in order to maximize return, with the focus on installing more turbines in countries with high-carbon electricity grids.

Most turbines have an estimated lifespan of 20 years, while a few offer 25 or 30 years [16,27]. It is stipulated as a condition in the planning permission how the site and turbine is to be treated after it has reached the end of its lifespan. Few wind farms in the UK have reached this stage due to the longevity of turbine lifespans, but it is an issue that will be coming more into focus over the next decade [31]. The exact decommissioning process is a site-specific process, but ideally includes removing the turbine and the foundation in order to restore the site to its pre-turbine conditions [31]. Decommissioning requires GHG-emitting machinery, which is brought on site to deconstruct the tower and possibly the foundation [11]. However, the foundation may sometimes be left after the turbine is removed or the company may apply to repower the site by replacing the turbines [10].

Extraction and processing of turbine materials, consistently account for the largest contribution of energy and GHG emissions in turbine LCAs [5,20,21]. Recycling these materials greatly impacts the total GHG emissions from the turbines because these materials have some of the highest embodied carbon levels [20,23]. If the decommissioning process includes recycling, the total emissions from a turbine's lifespan undergoing these processes have the potential to be lowered significantly [28].

Current technology allows for about 80% of the total turbine to be recycled, with the potential for further developments in composite recycling [11]. The decommissioning and recycling of a 4.5 MW turbine were estimated to save 969.5 tCO_2eq over its lifetime, a saving of 20.8% [5].

As part of the turbine LCAs, Kabir et al. [21] assumed recycling rates of 90% for steel and 95% for copper and aluminium. Recycling saved 3 to 11 gCO_2eq/kWh, with the largest savings for the twenty 5 kW turbine wind farm [21]. Guezuraga et al. [11] lowered the recycling rates for steel, cast iron, and copper to 90% based on specific manufacturer's recycling estimates. Only concrete was sent to landfill with epoxy, plastic, and fiberglass incinerated. Additionally, 2% of the electricity generated during the turbine's lifetime was allocated to the decommissioning stage, making it unavailable to count toward the offsets [11]. Thus, the total CO_2eq emissions resulting from a 2 MW turbine were 907.4 t, which results in 7.59 gCO_2eq/kWh [11]. However, if the simulation were altered so that none of the materials are recycled, the total CO_2eq more than doubles to 2074 t, resulting in 17.35 gCO_2eq/kWh.

Each study outlines different parameters for each stage of its LCA. Recycling is not always considered in LCAs and those that include recycling do not always quantify the difference in emissions to that of no-recycling. When calculating a turbine's LCA, whether these materials will be recycled should be included in order to improve the accuracy of the embodied CO_2eq value. In order to offset the largest amount of GHG emissions with onshore wind farms, the components that can be recycled at the end of their lives should be recycled.

Other factors influencing turbine LCA

Winds are variable, so the speed acting on the turbine is not always constant, which means a turbine produces a lower amount of electricity than its rated capacity. To allow for this a capacity factor is applied to the rated power, which relates to the actual amount of energy produced in a year expressed as a percent of the rated power [9] reflecting the true efficiency of the system. Wind turbines are classified according to their rated power, which is the amount of electricity the turbine would generate if it constantly produced electricity at full capacity.

In the UK, the average capacity factor for onshore wind turbines was 25.8% in 2012 [32]. The capacity factor has the ability to influence the corresponding carbon emissions from wind turbines [20]. The lower the capacity factor, the lower the energy return from the turbine. If the energy output of the turbine is lower, the greater the emissions there will be per kWh of electricity produced.

Nayak et al. [33] determined capacity factors can substantially affect the carbon emissions from turbine production. In their analysis, the average capacity factor for the turbines was 30%, which resulted in a carbon payback time of 27 months. Altering the capacity factor resulted in a three-month change in payback time [33]. Sensitivity analysis by Nayak et al. [33] showed increasing the capacity factor to 45% had a greater impact on decreasing the carbon payback time. White [20] analyzed three operational wind farms in the Midwestern United States for several years of operation and found that the capacity factors were much lower than the manufacturer's projections; capacity factors dropped from 33% to 25.6%, 35% to 28.6% and 31% to 19.9% [19]. Ardente et al. [28] found similar results when comparing the load factor of an Italian wind farm where the theoretical value was 30%, but the turbine only produced at 19% [28]. Therefore using the most precise capacity factor values for the installation site, rather than manufacturer values, will result in more accurate payback assessments due to its considerable ability to influence carbon payback.

Emissions derived from soil and vegetation disruption during turbine construction can greatly impact the total lifecycle emissions of a turbine, yet are rarely included in LCAs. Turbines built on peat soil are of particular concern in the UK due to the potential for large carbon emissions if disrupted [33]. Removing peat and vegetation results in an estimated loss of 0.12 and 0.31 tC/ha/yr [34,35] that would have accumulated each year had the peat not been disturbed. Removing peat also results in the loss of carbon already accumulated. Peatland soils are often drained as a result of construction processes, increasing the rate of decomposition in the soil and contributing additional carbon emissions [33]. Combined this disruption can account for 51% of the carbon losses from installing a wind farm on peat soil [33]. If developed on a poorly suited site and improperly managed, the payback time could be as high as 19 years, even before accounting for the emissions from the turbine's manufacture [33]. The Scottish Government now requires wind farms to undergo carbon assessments when applying for permission [36] to factor this potential carbon loss in. This is to ensure that the construction of new wind turbines has significant positive outcomes rather than offsetting the benefits of renewable electricity generation.

To accurately quantify the carbon savings from wind turbines, the emissions that result from the production of turbines must be deducted from the offset. The LCAs of previous studies contain extensive details on the emissions from aspects of the lifecycle, but in this study we have attempted to capture the emissions from component manufacture, road transportation to site, and on-site installation for a range of turbines being used within the United Kingdom, because these are the areas of the LCA previous shown to contribute most to overall emissions. The prevailing Government incentives, in the form of feed in tariffs, were also considered within the assessment in order to determine if financial incentives could be overriding potential for more rapid carbon offsets.

Materials and Methods

A total of 14 different turbines were analyzed that ranged from 50 kW to 3.4 MW. Data was obtained for two turbines with a power rating of 100 kW and two at 2.05MW and are referred is to as 100 kW_A and 100 kW_B and 2.05 MW_A and 2.05 MW_B, respectively. When referencing the 20-year lifespan of a turbine, it is referred to by its rated power and the subscript "20 years," (i.e. 900 $kW_{20\ years}$) and the subscript "25 years" is used for turbines that operate for an additional 5 years beyond the expected 20 years.

For the lifecycle emissions the LCA was broken down into three sections: manufacture, transportation, and installation. Generating the emissions profile of the individual turbines required specific data concerning the weights of materials and transportation methods. This was obtained from both manufacturers and estimations made from data available in previous studies [21].

Manufacturing emissions

Manufacturing emissions were calculated based on the weights of

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different materials used in the production of different components. Due to the proprietary nature of turbine material composition, proportions of individual components were not always provided by manufacturers and therefore extrapolated from literature values of the distribution of materials [21,37,38]. To determine production emissions, the total mass of each material (steel, copper, aluminum, etc.) was multiplied by its emission factor (Table 1). Emissions from each material were summed to give a total production emission value, which was repeated for each turbine. Emissions factors for methane and nitrous oxide, when given, were converted into CO_2 equivalents.

In instances where only the weight of a component was available, but the materials were not, an estimate of the material composition was determined based on the average material percentage reported in previous studies; this was often the case for the turbine generator. Previous studies that did list the materials and weights for the components showed that, on average, the generator was made of 79.67% steel and 20.33% copper. A list of material estimates based on previous studies was established (Table 2).

Known values for certain turbines were scaled and applied between turbines of the same manufacturer, making the assumption that the weight of each component would be proportional across different power rated turbines. This assumption was not used for tower height, because tower height is not based solely on the rated power of the generator. In order to scale tower height, the weight was calculated in tonnes per meter for the known turbines of that company, and the average weight per meter was then applied to the heights of other turbines from the same company.

Transport emissions

Transport emissions were calculated based on company data for hauling methods. Companies that provide diagrams for the loading of components onto heavy goods vehicles (HGVs) indicated that components were transported separately to the site of the wind farm. Unless otherwise specified, this was assumed for all turbines. The CO_2 emissions of HGVs depend on the weight of the vehicles. Component weights were used to determine which vehicles would be used to transport the turbines. Emissions are determined based on fuel efficiency of each different sized HGV. To calculate a value for the transportation, a distance of 200 miles was used as standard.

Installation emissions

Production of concrete foundation and steel reinforcement were included in installation emissions estimates. Concrete emissions were calculated based on the volume of concrete used. If the concrete values were unknown, estimates of concrete volume were based on the concrete volume per meter of tower height used in construction of other turbines by the same company. Tower height rather than tower weight was used to determine the volume because tower heights were known values for all turbines whereas weights were sometimes extrapolated from the data of other turbines. Steel reinforcement was calculated using the same method.

In addition to the foundation materials, emissions from excavators and cranes were included in the installation portion of the LCA based on operational hours. Where this was unknown, it was calculated based on the amount of concrete required for the foundation. This was justified as the excavator removed the soil for the concrete, and thus the volume removed is directly related to the amount of concrete poured.

Finally crane emissions, like those from the excavator, were based on operational hours. The given value for the duration of crane operation (16 hours) was applied across all turbines rather than in relation to the size of the turbines as components required crane use regardless of their size. Larger cranes or additional cranes were accounted for in the installation of heavier turbines.

Material	Total emissions
Steel	2.49 tCO_{2eq}/t
Copper	6.60 tCO_{2eq}/t
Aluminum	3.47 tCO_{2eq}/t
Glass	0.57 tCO_{2eq}/t
Epoxy	3.98 tCO_{2eq}/t
Polyester	3.98 tCO_{2eq}/t
Fiberglass	1.39 tCO_{2eq}/t
GRP	2.68 tCO_{2eq}/t
Iron	1.35 tCO_{2eq}/t
Concrete	0.31 tCO_{2eq}/m^3
Diesel	0.01 tCO_2/G
Crane	0.09 tCO_2/h
Excavator	0.05 tCO_2/h

Table 1: CO_2 emissions from materials and machinery used to calculate the total emissions of each turbine [21,39-42].

Payback calculations

Emissions from manufacture, transport, and installation were calculated and combined to obtain total emissions from the lifecycle of each turbine. Equations for payback methods were based on methods of previous studies [5,9,30]. The total output of the turbine (O) in MWh was calculated (Equation 1) followed by the carbon intensity (I) in tCO_2eq/MWh using Equation 2. The carbon intensity (609 $kgCO_2/MWh$) of fossil fuels used in UK electricity production [6] was used to estimate time required for production emissions to be offset. Using lifecycle emissions and fossil fuel carbon intensity, the number of megawatt hours taken to generate the turbine's lifecycle emissions can be derived. Subsequently from this, the carbon payback period (P), measured in days, can be calculated for each turbine (Equation 3).

Equation 1: Determination of total turbine output (O in MWh) where R is the rated power of the turbine in MW, 8760 is the number of hours in a year, 0.258 is the average load factor for UK onshore wind turbines in 2012 [13], and L is the lifespan of the turbine in years.

$$\mathrm{O\ MWh} = \mathrm{R\ MW} \times 8,760\,\frac{\mathrm{hr}}{\mathrm{yr}} \times 0.258 \times \mathrm{L\ yr} \tag{1}$$

Equation 2: Determination of Carbon Intensity (I) where E is the total carbon emissions from manufacture, transportation, and installation in $kgCO_{2eq}$. O is the total output of the turbine in MWh as determined using equation 1

$$I\ kgCO_2eq\,/\,MWh = \mathrm{E\ kgCO_2eq} \div O\,\mathrm{MWh} \tag{2}$$

Equation 3: Carbon payback period (P), measured in days, where M is the number of MW hours it took to generate the emissions from the turbine's lifecycle when using the fossil fuel electricity mix. R is the rated power of the turbine; 0.258 is the capacity factor, and 24 is the number of hours in a day.

$$\mathrm{P\ days} = \frac{\left(M\,\mathrm{MWh}\right) \div \left(R\,\mathrm{MWh} \times 0.258\right)}{24\,\frac{\mathrm{hr}}{\mathrm{day}}} \tag{3}$$

Equation 4: Carbon payback ratio (R) can be calculated for each

	Study	Kabir et al. [21]			Crawford [9]		Martinez et al. [25]	Average distribution of materials
	Rated power of turbine	5 kW	20 kW	100 kW	850 kW	3 MW	2 MW	
Nacelle	Total weight	0.276	0.84	5.7	22.002	68.002	46.1	
	Weight of steel (t)	0.234	0.706	4.39	20.194	61	21.69	0.79
	Weight of copper (t)	0.030	0.034	0.91	1.029	3.991	3.5	0.08
	Weight of aluminum (t)	0.009	0.026	0.26	0.599	2.311	0	0.03
	Weight of glass (t)	0.003	0.008	0.08	0	0	0	0.01
	Weight of polyester (t)	0.002	0.006	0.06	0	0	0	0.00
	Weight of plastic (t)	0	0	0	0.18	0.7	0	0.00
	Weight of iron (t)	0	0	0	0	0	18.5	0.07
	Weight of silica (t)	0	0	0	0	0	0.344	0.00
	Weight of fiberglass (t)	0	0	0	0	0	0.8	0.00
	Weight of epoxy resin (t)	0	0	0	0	0	1.2	0.00
Generator	Total weight of component (t)	0.092	0.28	2.85	1.84	7.14		
	Weight of steel (t)	0.074	0.22	2.28	1.47	5.71		0.80
	Weight of copper (t)	0.019	0.06	0.57	0.37	1.43		0.20
Blades	Total weight of component	0.025	0.068		5.02	20.07		
	Weight of fiberglass (t)	0.015	0.04		3.01	12.04		0.60
	Weight of epoxy resin (t)	0.01	0.028		2.01	8.03		0.40

Table 2: Breakdown of the material distribution for nacelle, generator and blades from previous studies. Silica was not included in the CO_2 calculations due to the inability to find an emission value for the material and its extremely low average content in the nacelle.

turbine where P is the payback period in days (derived from equation 3), and L is the lifespan of the turbine in years.

$$R = \frac{P\,\text{days}}{L\,\text{yrs} \times 365\,\text{days}} \quad (4)$$

From the carbon payback period, the carbon payback ratio (R) was calculated for each turbine (Equation 4). Some turbines had a guaranteed lifespan of 20 years, but have potential for 25 years. When this was considered, the carbon payback period as a ratio of turbine lifespan was calculated for both potential lifespans in order to determine how increasing the lifespan by 25% affected the payback period. The final payback calculation was for the offset emissions (S). Offset emissions is defined as the amount of emissions that would be produced from fossil fuels generating the same amount of electricity as is produced during the duration of the turbine's lifespan after it has already operated long enough to offset its production emissions. This was derived using the number of MWh of electricity produced during the carbon payback period and the carbon intensity of fossil fuels (Equation 5).

Equation 5: Carbon savings in offset emissions (S) where 609 $kgCO_2$/MWh is the carbon intensity of fossil fuels used to produce electricity in the UK, O is the total output of the turbine in MWh (determined using equation 1), and H is the number of MWh of electricity the turbine produces during the carbon payback period.

$$S\,\text{tonnes} = \frac{609\,\text{kgCO2 / MWh}\left(O\,\text{MWh} - H\,\text{MWh}\right)}{1000} \quad (5)$$

Sensitivity analysis calculations

A sensitivity analysis of the different parameters on carbon intensity was calculated for each turbine to determine the impact of altering each by 25%, both positively and negatively. The major parameters were defined as all those from transport and installation as well as the manufacturing materials that made up 99% or more of the turbine's weight and therefore included; steel, copper, GRP (fiberglass reinforced plastic), iron, fiberglass, epoxy, transport distance, steel reinforcement, concrete, duration of excavator use, and duration of crane use. The difference in carbon intensity (D) from altering each parameter was calculated (Equation 6).

Equation 6: Carbon intensity (D) established from altering each major parameter by either an increase or decrease of 25%. *I* is the original carbon intensity of the turbine (calculated in equation 2), and I_2 is the carbon intensity of the turbine with the parameter changed.

$$D\frac{\text{kgCO2eq}}{\text{MWh}} = I\frac{\text{kgCO2eq}}{\text{MWh}} - I2\frac{\text{kgCO2eq}}{\text{MWh}} \quad (6)$$

Feed-in tariffs

The UK Government has an incentive scheme that pays producers to generate electricity from renewable sources, the Feed-in Tariff (FiT) scheme. The amount of money the FiT scheme pays back depends on the amount of energy that is generated. The incentives for wind turbine production as of December 2012 were: 21 p/kWh for turbines ≤ 100

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kW, 17.5 p/kWh for 100 kW < turbines ≤ 500 kW, 9.5 p/kWh for 500 kW < turbines ≤ 1.5 MW and 4.48 p/kWh for 1.5 MW < turbines ≤ 5MW [37]. These values are subject to yearly reductions. The digression is set at a 5% baseline, but can range from 2.5 to 20%, depending on the number of turbines installed each year [36] and apply only to the wind turbine produced electricity, so any unused electricity sold back to the grid is unaffected.

Results

Life cycle emissions

The lifecycle emissions of each turbine were calculated as the sum of the manufacture, transportation, and installation emissions as set out by the parameters listed in the methodology. As well as total lifecycle emissions, the carbon intensity, carbon payback period, carbon payback period as a percentage of lifespan and the total offset emissions of each turbine were calculated (Table 3). Additionally, the emissions of each turbine were broken down by sector to determine what percentage manufacture, transportation, and installation contributed to the total emissions.

The general trend showed that lifecycle emissions increase as the rated power of the turbine increases (Table 3). However, there were some exceptions to this trend. The smallest turbine examined, a 50 kW turbine had lifecycle emissions of 58.9 tCO_{2eq}, which were slightly higher than an 80 kW turbine with 57.9 $tCO_{2eq.}$ Turbines of similar size did not always result in the same lifecycle emissions. For 100 kW generator turbines, 100 kW_B had over twice the lifecycle emissions of turbine 100 kW_A with 60.5 tCO_{2eq} and 133.5 tCO_{2eq}, respectively. Similarly, the 2 MW turbine had nearly 50% more emissions than the 2.05 MW_A turbine and 25% more emissions than 2.05 MW_B turbine, which emitted 640 and 750 tCO_{2eq}, respectively, during their lifecycles. The highest CO_{2eq} emissions resulted from the production of a 3 MW turbine, which emitted 221.5 $tCO_{2eq,}$ and not from the production of the largest turbine (3.4 MW).

Carbon intensity

Results indicate that carbon intensity was highest among the lower power rated turbines (Table 3). For turbines rated 500 kW and under, the carbon intensity was greater than 12.1 $kgCO_{2eq}$/MWh, and by comparison, no turbines over 500 kW had a carbon intensity greater than 10.4 $kgCO_{2eq}$/MWh. Due to their differences in total carbon emissions, the carbon intensities of the 100 kW turbines were different with 29.5 $kgCO_{2eq}$/MWh for 100 kW_B, compared to 13.4 $kgCO_{2eq}$/MWh for 100 kW_A. 100 kW_B also had the greatest carbon intensity (29.5 $kgCO_{2eq}$/MWh), and, by comparison, the lowest carbon intensity was that of the 3.4 MW turbine, with only 5.4 $kgCO_{2eq}$/MWh. Despite a 3,400% greater power rating, the carbon intensity of the 3.4 MW turbine was only 18% that of the 100 kW_B turbine.

Due to its greater total emissions, the 2 MW turbine had nearly 50% greater carbon intensity than the 2.05 MW_A and nearly 30% greater than the 2.05 MW_B (Table 3).

Carbon payback period

The carbon payback period for each turbine showed the number of days that must be spent generating electricity to offset emissions generated during manufacture, transport, and installation of the turbine (Table 3). The longest payback period was for the 100 kW_B turbine, with 354 days to offset its production emissions.

All turbines less than 500 kW took over 145 days to offset their emissions, and no turbine with a power rating above 500 kW took more than 125 days to payback its emissions.

The two 100 kW turbines had drastically different payback periods. The 100 kW_A turbine, with carbon emissions only 45% of those from the 100 kW_B turbine, had a payback period under 161 days, compared to 354 for 100 kW_B.

The 3.4 MW turbine, which had the highest production potential rating, had the shortest payback period, with 65.5 days. It took the 3.4 MW turbine only 21% of the time it took the 50 kW turbine to pay back its emissions.

The 2.05 MW_B turbine emitted 106.3 tonnes of CO_{2eq} more than the 2.05 MW_A turbine over its lifetime, but added only 14 days to offset the emissions. Despite their nearly 1 MW range in powers and 300 tCO_{2eq} emissions over their lifespans, the 2.05 $MW_{20\ years}$, 2.3 MW, and 3 MW turbines all offset their emissions within a week of one another.

Carbon payback period as a percentage of lifetime

The carbon payback period was calculated to determine what amount of the turbine's operational life is dedicated to offsetting its production emissions. As all the turbines had a minimum expected lifespan of 20 years, the trend for payback percentage was the same as for the payback period; when the payback period increased, so did the percentage of the lifetime. The 100 kW_B turbine had the highest percentage of its lifetime spent offsetting its production emissions with a value of 4.9% (Table 3).

All turbines under 500 kW required 2% or more of their lifetime to offset their production emissions. When the turbines were larger than 500 kW, the carbon payback period was 1.4% or lower. The 3.4 MW turbine only required 0.88% of its 20 year lifespan to offset its emissions.

Three turbines were listed as having extendable lives from 20 years to 25 years. Increasing the lifespan by 25% did not affect the payback period itself, but it did reduce the percent of the lifetime that was spent offsetting production emissions. Increasing the lifespan of each turbine resulted in reductions in the payback percentage by approximately 20% each.

Offset emissions

Offset emissions depend on the rated power of the turbine and the lifecycle production emissions. Offset emissions increased as the rated power of the turbine increased, thus the 50 kW turbine had the lowest offset emissions at 1,317 tCO_{2eq} whereas the 3.4MW turbine was more than 70 times that at 92,770 tCO_{2eq}.

Despite their different carbon intensities and payback periods, the two 100 kW turbines had similar total offset emissions, with 2,692 tCO_{2eq} and 2,619 tCO_{2eq} for the100 kW_A and 100 kW_B turbine, respectively.

The amount of CO_2 saved over 20 years by installing either of the 2.05 kW turbines was greater than the amount of CO_2 that could be saved by installing the 2 MW turbine combined with the 50 kW turbine.

Increasing the lifespan of the 900 kW, 2 MW, and 2.3 MW turbines, from 20 to 25 years, drastically increased the amount of emissions each could offset over their lifetimes (Table 3). The five-year increase in lifespan increased the total emissions the 900 kW, 2 MW and 2.3 MW turbine could offset by 25%, which equated to an additional 15,828 tCO_{2eq} for the 2.3 MW turbine.

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Rated Power	Electricity generated over lifetime (MWh)	Total emissions (tCO_{2eq})	Carbon intensity (kg/MWh)	Payback period (days)	Payback period as percentage of lifetime (%)	Offset emissions (tCO_{2eq})
50 kW	2260	59	26.1	312	4.3	1317
80 kW	3616	58	16	192	2.6	2144
100 kW_A	4520	61	13.4	160	2.2	2692
100 kW_B	4520	134	29.5	354	4.9	2619
250 kW	11300	148	13.1	157	2.1	6734
500 kW	22601	274	12.1	145	2.0	13490
900 $kW_{20\ years}$	40681	289	7.1	85	1.2	24486
900 $kW_{25\ years}$	50852	289	5.7	85	0.9	30680
2 MW $kW_{20\ years}$	90403	937	10.4	124	1.7	54119
2 MW $kW_{25\ years}$	113004	937	8.3	124	1.4	67883
2.05 MW_A	92663	641	6.9	83	1.1	55791
2.05 MW_B	92663	747	8.1	97	1.3	55685
2.3 $MW_{20\ years}$	103964	859	8.3	99	1.4	62455
2.3 $MW_{25\ years}$	129955	859	6.6	99	1.1	78283
3. MW	135605	1046	7.7	92	1.3	81538
3.2 MW	144645	957	6.6	79	1.1	87132
3.4 MW	153685	824	5.4	64	0.9	92770

Table 3: Results of lifecycle analyses for each turbine. Subscripts "A" and "B" differentiate turbines of the same rated power. Subscript "20 years" details the emissions information calculated based on a turbine lifespan of 20 years, while subscript "25 years" represents a lifespan of 25 years.

Emissions by production stage

Across all power ratings, transportation accounted for the smallest percentage of emissions, never reaching more than 2% of the total emissions (Figure 1). The percent of emissions from transportation was at its largest for the smaller rated turbines; for those with power ratings greater than 250 kW, transportation did not produce enough emissions to account for any percentage of the total.

Manufacturing stage of the production process accounted for the largest proportion of the production emissions in most cases. Manufacturing emissions ranged from 52% to 84% for turbines rated 500 kW and greater. The manufacturing stage of the 2 MW turbine had the largest contribution of all, accounting for 84% of total emissions for that turbine.

Exceptions to manufacturing dominated emission occurred for the 80 kW and 100 kW_B turbines, both produced the most emissions from installation. The 100 kW_B turbine had the largest proportion of emissions from installation of any turbine at 59%, whilst installation of the 80 kW turbine accounted for 50% of the emitted CO_2.

Despite identical power ratings, the two 100 kW turbines had different breakdowns in production emissions. Turbine 100 kW_A produced the majority of its emissions from manufacture, 30.6 tCO_{2eq} (51%) and 28.7 tCO_{2eq} (47%) from installation; transportation accounted for 1.18 tCO_{2eq} (2%). For the 100 kW_B turbine, installation made up the majority of emissions, 79.1 tCO_{2eq} (59%); manufacturing accounted for 54 tCO_{2eq} (41%), and transportation accounted for 0.4 tCO_{2eq} (0%).

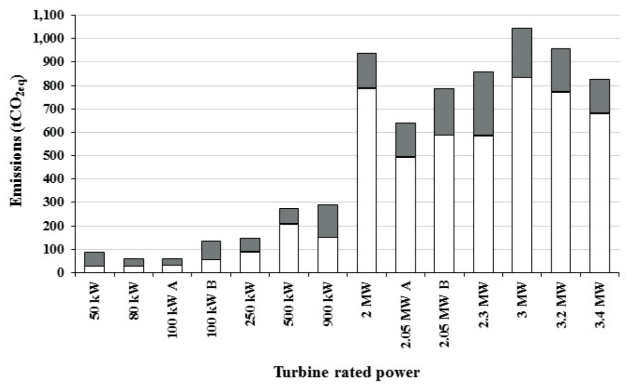

Figure 1: Breakdown of the total CO_{2eq} lifecycle emissions from the cumulative installation (dark grey), transportation (black) and manufacture (white) stages of production for 14 wind turbines. The letters "A" and "B" are used to differentiate turbines of the same rated power.

Feed-in tariff scheme

Accounting for a set 5% digression each year over a 20-year lifespan, installing a single 100 kW turbine would result in a payback of £608,947, a single 500 kW turbine £2,537,278, a single 1.5 MW turbine £4,132,138 and a single 3 MW turbine a payback of £3,897,259. However, the higher financial payback per kWh for the lower rated power turbines results in a greater total financial incentive offered by the FiTs for installing multiple small turbines to equal the same power as a single larger turbine.

Installing five 100 kW turbines, instead of one 500 kW turbine, would net the installer an additional £507,456 in payback, but would result an additional 393.66 tCO_{2eq}. Installing three 500 kW turbines net the installer an additional £3,479,696 or installing fifteen 100 kW turbines instead of one 1.5 MW turbine would net the installer an additional £5,002,062. As a final example, installing six 500 kW turbines, instead of one 3 MW turbine, would net the installer an additional £11,326,409, but would incur an additional 597.5 tCO_{2eq}.

Sensitivity analysis

Sensitivity analysis was conducted to determine which parameters had the greatest impact on carbon intensity. Steel used in the components of the turbine (manufacturing) was calculated separately from the steel reinforcement in the foundation (installation). When the sensitivity was calculated, either the steel in the turbine or the steel reinforcement in the foundation had the greatest impact on the carbon intensity (Figure 2). The second largest contributing factor was either the other steel component or the concrete foundation of each turbine.

Discussion

Total emissions of production generally increased with an increase in the rated power of the turbines (Table 1). This was due to the increased amount of materials necessary to construct larger turbines. The greater the rated power of the turbine, the larger the generator, requiring increased amounts of copper and steal, which contributed to higher total emissions levels. Previous studies generally indicated a similar trend of increasing total emissions with turbine power. Crawford [9] based emissions calculations on the amount of energy that went into each area of production, which differed from the method of calculations used in this study, resulting in an increase in lifecycle emissions. In this study, turbines with higher rated power tended to be those with greater tower heights. The higher the tower, the more steel needed for construction. Since the sensitivity analysis showed that altering steel had the greatest impact on the carbon intensity (Figure 2), increasing steel to increase the tower height also caused the total amount of CO_2 to increase. The heavier tower then necessitates an increased amount of concrete and steel reinforcements in the base, contributing to additional emissions. Heavier and larger turbines required the use of larger HGVs, which caused an increase in the transportation emissions. However, the increase in turbine materials had a proportionately larger effect on emissions than larger HGVs. Even though more HGVs with decreased fuel efficiencies were needed, the percentage of emissions from transportation decreased overall. A 3 MW turbine in Crawford [9] had a total embodied emission value of 5,054 tCO_{2eq}, almost five times the embodied emissions of the 3 MW turbines (1,045.5 tCO_{2eq}) in this study. Higher emissions may, in part derive from additional concrete used in constructing a larger foundation [9]. Despite higher total production emissions, 3 MW turbines in Crawford [9] had 50.8% more total offset emissions. This was possibly due to the larger capacity factor of 33%, offsetting 122,961 tCO_{2eq}, compared to the capacity factor of 25.8% and an offset of 81,538 tCO_{2eq} for the 3 MW turbine in this study. This implied that a change in capacity factor made a more substantial difference to the amount of emissions offset than the embodied emissions of the turbines.

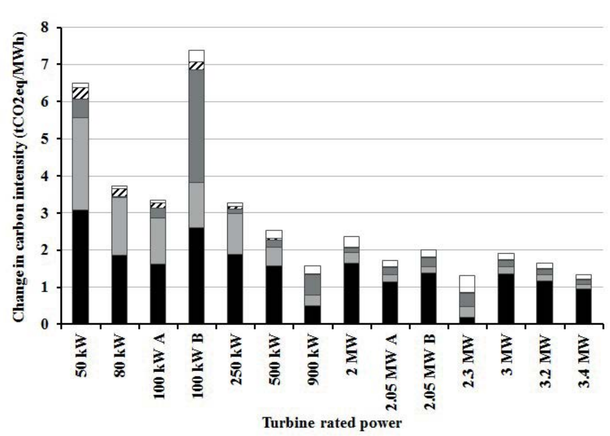

Figure 2: Outcome of a sensitivity analysis, expressed as change in carbon intensity, from altering the components of the turbine manufacture, transportation and installation by 25% for steel (black), concrete (light grey), foundation steel reinforcement (dark grey), machinery (black diagonal, summed from transportation distance, crane and excavator use) and other components of manufacture (white; summed from copper, epoxy, fiberglass, GRP and iron). The represented values would be either positive or negative for a 25% increase or decrease, respectively, from the embedded carbon intensity values for each turbine (Table 3).

Defining the parameters of the production sections affects the breakdown of total emissions. In this study, installation included the emissions from the foundation and steel reinforcement frame, however, if these values were included in the manufacturing portion, manufacturing would always have been the greatest contributor to emissions. Guezuraga et al. [11] included foundation production in manufacturing, resulting in manufacturing section accounting for 77.9% of total emissions for 2 MW turbines. In this study, foundation was categorized with installation, consequently manufacturing accounted for 84.1% of total emissions (2 MW turbines). Inclusion of the additional categories of operation and dismantling [11] also affects the percentage breakdowns of the turbine. This information was not available for all turbines considered within this study, so was not included. However, including these additional categories would lower the percentage of emissions from manufacturing.

With data showing the benefits of installing one turbine over the other, governments and planners can evaluate which turbine will be advantageous to install in order to meet their renewable energy and CO_2 reduction targets. The total production emissions were slightly higher for the 50 kW turbine than for the 80 kW turbine due to marginally higher manufacturing emissions. A difference of less than 1 tCO_{2eq} from production still results in an additional 120 days to the payback period of the 50 kW turbine (Table 3), all be it only an additional 1.6% of the turbines lifespan, and this was due to the 30 kW difference in rated power. Therefore the benefits of installing an 80 kW turbine are increased electricity production, lower atmospheric CO_2 emissions and less than two-thirds the amount of operational time to offset its embedded emissions, offsetting 826.8 tCO_{2eq} more than installing the 50 kW turbine.

Instead of installing 100 turbines with a rated power of 50 kW, if 100 turbines with a rated power of 80 kW were installed, an additional 82,680 tCO_{2eq} would be saved over the turbine's lifespan, or about 4,134 tCO_{2eq} each year. Alternatively, only sixty-three 80 kW turbines would need to be installed to achieve the same amount of electricity as one-hundred 50 kW turbines, but this would still offset an additional 3,342 tCO_{2eq} over 20 years.

The two 100 kW turbines resulted in very different total emissions and subsequent payback periods over their 20-year lifespans (Table 3).

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Turbine 100 kW_B was taller and required more concrete and steel for its installation, which required an additional 8.76 t of materials during its manufacture, resulting in an additional emissions of 23.4 tCO_{2eq}. These additional emissions caused the 100 kW_B turbine to require an additional 193.6 days for payback or a further 2.6% of its lifespan. Despite the higher emissions and longer payback period, when the total emissions offset over the turbines' lifespans are considered, the difference between the two is minimal. Turbine 100 kW_B only offsets an additional 2.8% of the 100 kW_A turbine's emissions. Thus the most significant difference between installing these two turbines was how long it takes to offset the emissions.

Under site conditions where either combination would generate electricity equally well, there would be fewer negative environmental impacts related to the installation of a single 500 kW turbine than two 250 kW turbines, and installing a single 500 kW turbine saves 2 tCO_{2eq}. While the saving is small for a single comparison, it becomes more significant when considered for a wind farm of 5 MW comprising of either 250 or 500 kW turbines, where the savings rise to 216 tCO_{2eq}. Similarly, due to the high carbon intensity of the 50 kW turbine (Table 3), installing a single 250 kW turbine instead of five 50 kW turbines saves 147 tCO_{2eq}. Installing a single 500 kW turbine instead of ten 50 kW turbines saves 315 tCO_{2eq}. While these savings are not significant for such small wind farms, when scaled up, the savings increase. For example, if the wind farm were 5 MW, installing 250 kW turbines instead of 50 kW turbines would save 2,937 tCO_{2eq}. If the 500 kW turbines were installed instead of 50 kW turbines, the savings would be 3,153 tCO_{2eq}. The savings continue to increase with larger turbine powers. To establish a 6 MW wind farm, constructing two 3 MW turbines instead of three 2 MW turbines result in a substantial savings of 719 tCO_{2eq}.

This study implies that it is advantageous to install larger turbines than multiple smaller turbines. Despite the greater rotor diameters and tower heights of higher power generators, these additional materials are not enough to counter the amount of additional electricity larger turbines are able to generate [21]. Rather, the total amount of materials is still less than what would be used to install multiple smaller turbines. The savings are small when the total amount of electricity is low, but when the potential wind farm increases in size, the savings become more substantial. With concerns over rising CO_2 levels and resulting climate change, these savings are important to consider. Emission savings can be amplified substantially if the installation of fewer, but larger turbines as opposed to numerous small turbines is focused upon in future UK wind projects. With hundreds more turbine installations currently needed to meet Government renewable energy and carbon reduction targets it is necessary to consider the savings at a larger scale than from individual turbines.

With regard to this, the current financial incentive scheme would appear to be out of kilter with the ideal distribution of turbines if the end goal was to reduce carbon emissions embodied in energy production. Higher rated power turbines have a greater ability to reduce carbon emissions on a per kilowatt basis and have the shortest payback periods both in terms of carbon and percentage of lifetime (Table 3). However, financial incentives are skewed to encourage wind farm developers to install a greater number of lower power turbines, which have more embedded CO_2 per kilowatt hour and have longer payback periods, to achieve the same amount of power that could be generated from a single or few higher-power turbines.

In order to promote the installation of turbines with the highest ability to offset carbon emissions, a re-evaluation of the UK Government's FiT scheme, to account for embodied carbon emissions of the turbines, is needed.

In considering wind energy compared to other energy sources, the carbon intensities for the turbines analyzed ranged from 5.4 to 29.5 $kgCO_{2eq}$/MWh. The range Varun et al. [39] established for wind turbines was 9.7 to 123.7 $kgCO_2$/MWh. The turbines considered in this study fall near the lower end of this range due to the limited information available from manufacturers, where more detailed information available, including shipping to the country of installation and the decommissioning of turbines, the carbon intensity would be higher. Renewable technology emission values for wind, solar PV, biomass, solar thermal, and hydro, have overlap [40], but wind has the lowest value for the top of its range. This suggests that even if the additional data were available and included, it is unlikely the turbines would increase their range of carbon intensities to surpass biomass's maximum of 178 $kgCO_2$/MWh. To do so, the 100 kW turbine with the highest carbon intensity would need to have its production emissions increase so substantially that the carbon intensity were six times greater.

With carbon intensities for coal and natural gas ranging from 900 to 1,200 $kgCO_2$/MWh and 400 to 500 $kgCO_2$/MWh, respectively, it is unlikely that carbon intensities from wind turbines would become high enough to rival those of coal and natural gas [41]. The only conventional power system any of the turbines exceeded in carbon intensity was nuclear, which has a carbon intensity of 24.2 $kgCO_2$/MWh [42]. Only the 50 kW turbine and the 100 kW_B turbine exceeded this (26.1 and 29.5 kg/CO_{2eq}/MWh, respectively).

Conclusion

Onshore wind turbines have greater embodied carbon emissions as their rated powers increase. This results from the increased materials necessary to produce the turbines. However, when the carbon emissions from production are compared against the amount of electricity each turbine produces, the higher-rated turbines produce lower carbon emissions for their electrical output. Thus it is advantageous to install fewer larger turbines rather than many small turbines in order to minimize carbon emissions while maximizing electricity generation. However, current FiT scheme settings may way make it more financially viable for installation and production companies to capitalise on the installation of lower rated turbines, which will offer a greater financial return in the current market despite having less environmental benefit. Even though smaller turbines produced higher emissions per kilowatt hour of electricity, their carbon intensities were still well below those of non-renewable sources, such as coal, and were on the lower end of renewable energy technologies. This indicates that despite the carbon emissions necessary to produce turbines, they are still one of the best options currently available for producing low-carbon electricity.

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