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The environmental impact of wind turbine blades

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Abstract. The first generation of wind turbine (WT) blades are now reaching their end of life, signalling the beginning of a large problem for the future. Currently most waste is sent to landfill, which is not an environmentally desirable solution. Awareness of this issue is rising, but no studies have fully assessed the eco impact of WT blades. The present study aims to provide a macroscopic quantitative assessment of the lifetime environmental impact of WT blades. The first stage has been to analyse global data to calculate the amount of WT blade materials consumed in the past. The life cycle environmental impact of a single WT blade has then been estimated using eco data for raw materials, manufacturing processes, transportation, and operation and maintenance processes. For a typical 45.2 meter 1.5 MW blade this is 795 GJ (CO_2 footprint 42.1 tonnes), dominated by manufacturing processes and raw materials (96% of the total. Based on the 2014 installed capacity, the total mass of WTB is 78 kt, their energy consumption is 82 TJ and the carbon dioxide footprint is 4.35 Mt. These figures will provide a basis for suggesting possible solutions to reduce WTB environmental impact.

1. Introduction

Wind energy has developed rapidly over the last two decades to become one of the most promising economical and green sources of renewable energy, responding to concerns about use of fossil fuels and increasing demand for energy. The wind turbine industry is reaching maturity and is still growing steadily [1,2]. The first generation of commercial turbines are reaching the end of their design life, and attention is just starting to turn to the problem of what will happen to the waste as the generators are decommissioned. The environmental implications are significant, but at present there are no estimates of the potential magnitude of the problem. We are addressing one aspect of this, focusing on the blades. A large part of these high-value components is fibre composite, for which there is currently no satisfactory recycling route. The composites recycling industry will grow in the coming years, and one of its requirements will be estimates of the environmental impact the composites waste may cause.

A few life cycle assessments on wind turbines have been published. In 1999, Gürzenich [3] estimated the cumulative energy demand of a 1.5 MW 33 metre blade wind turbine to be around 14,000 GJ, varying slightly when the turbine is installed onshore, close-coastal or coastal. Subsequent studies have covered the environmental impact both of a single wind turbine and of a tens of megawatts wind farm [4–6]. There is a big range of results due to the different data sources and assumptions adopted. The scope of the studies is also limited to a couple of specific turbine models and so cannot provide a full picture of wind power ecological problems. In order to consider the technology development effect, Tremeac[7] compared the difference between 250 kW and 4.5 MW turbines. He found the energy consumption of the emerging turbines (4.5 MW) is much higher than

that of an early stage model (250 kW), but the unit energy consumption is similar. Crawford [7] evaluated the energy consumptions of 850 kW and 3 MW turbines. He found the energy consumption to be significantly higher than previous studies and that the size of wind turbines did not appear to be an important factor in optimising their life cycle energy performance. In all these studies the environmental impact of the blades has considered only the major materials (fibre and resin), with rated power used to estimate turbine size, so a number of contributing factors have been omitted. The present study looks at the environmental impact of all stages of the wind turbine blade lifecycle with a spectrum of blade models and a range of industry development scenarios. Analysis of the contributing factors provides insight into ways in which the environmental impact can be reduced.

2. Approach
Bills of materials (BOM) were obtained for 20 different blades from three different wind turbine blade manufacturers. Eco-data from the 2015 CES Selector database [8] was used to calculate the energy consumption, carbon dioxide emissions and water consumption during the life cycle (manufacture, transport, operation and maintenance stages) for different sizes, materials and regions. Visual disturbance, noise and ecological disturbance are not considered in this study. The system boundary was limited to the blade factory, transport route and wind farm.

2.1. Bill of materials
The analysis included all the materials used in blade manufacture categorised as major materials, supporting materials and consumables as shown in table 1. Personal protection equipment (e.g. gloves and masks) and reusable manufacturing equipment (e.g. scissors and moulds) are not included.

Table 1. Materials listed in the bill of materials.

Major	Supporting	Consumable	
Carbon fibre UD	Steel accessories	Continuous filament mat	Resin flow pipes
Glass fibre UD	Copper accessories	Peel-ply/release film	T-fitting and infusion valve
Glass fibre multi-axial fabric	Aluminium accessories	Vacuum bag film	Mould cleaner and releasing agent
Resin	Balsa	Porous membrane	Hand Spray adhesives
Resin Curing agent	PVC	Flow mesh layer	Gel coat
Structural adhesives	Paint	Breather bleeder	
Structural adhesive curing agent	Putty	Vacuum bagging sealant tape	

2.2. Embodied energy
Data from the 2015 CES Selector [8] was used to calculate the embodied energy of the material in the blades. The CES data for glass fibre reinforced plastic (GFRP) and carbon fibre reinforced plastic (CFRP) was found to be in error, being much higher than the sum of fibre fabric and resin, so our calculations for these materials are based on data from the literature. The results of unit embodied energy, carbon dioxide emissions and water consumption are shown in figure 1.
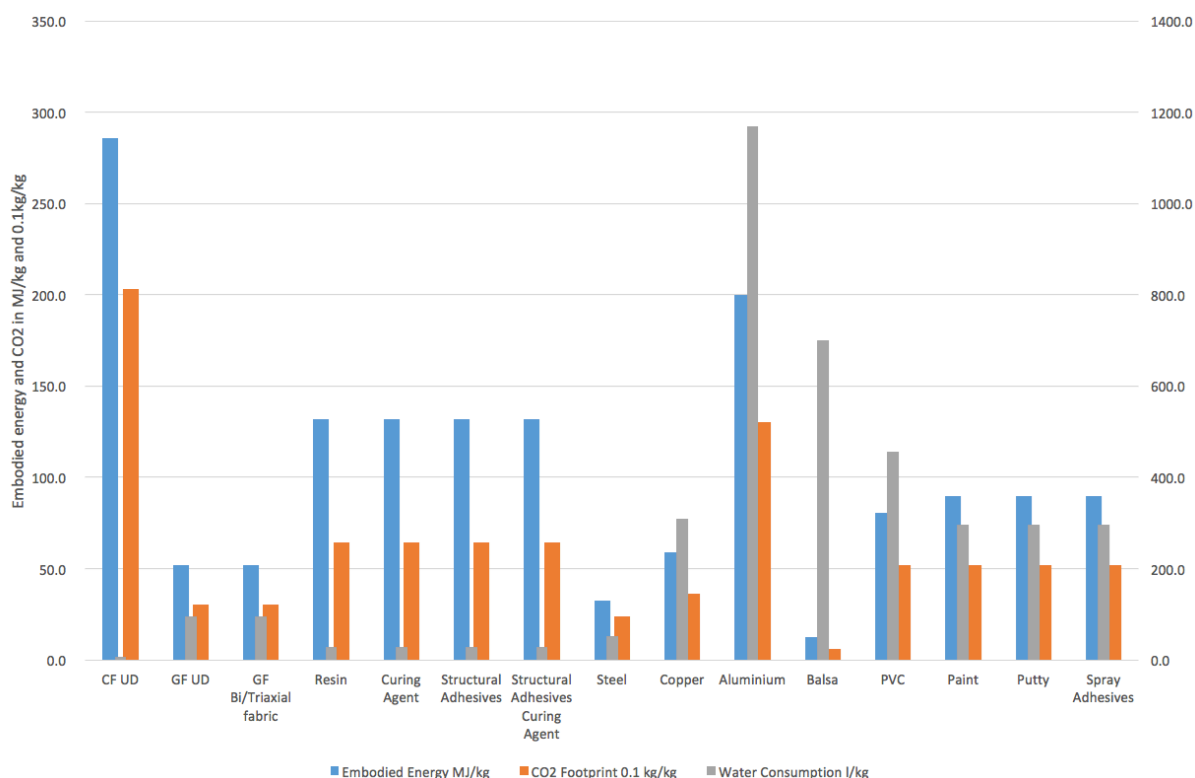
Figure 1. Eco-audit data.

2.3. Life cycle energy

2.3.1. Manufacturing. The material unit embodied energy multiplied by the material usage in the BOM was used to calculate the primary energy, carbon emissions and water consumption from the manufacture stage.

2.3.2. Blade size and transportation.

Table 2. Blade size class.

Class	Typical length (m)	Typical weight (tonnes)	Rated power (MW)
Early blade	Less than 40	6.50	1.5
Contemporary blade I	45	10.00	2-3
Contemporary blade II	55	14.00	3-4
Emerging blade	Over 60	25.00	6+

The large size of blades mean that transport options are limited to sea freight and road. Standard options for road transport are trucks capable of taking 14 or 32 tonne loads. Table 2 shows how blade weights have changed over time, divided into four classes. Although most blades are lighter than 14 tonnes and so could in theory be transported using the smaller 14 tonne trucks, due to their large size they normally need a large 32 tonne truck, and a truck can only carry only one blade a time. Transport energy is therefore calculated using data per kilometre for 32 tonne trucks, noting that they are not

carrying their full payload. There is some difference in truck fuel efficiency when they carry full load or half load, but it is hard to quantify in this case. We assume the fuel consumption is the same as when the truck fully loaded. The CO_2 footprint conversion is 0.071 kg/MJ in transportation process.

Table 3. Transportation eco data from CES 2015.

	Transport energy (MJ/tonne/km)	Transport energy per truck (MJ//km)
Sea freight	0.16	n/a
32 tonne truck	0.46	14.72
14 tonne truck	0.85	11.90

We set four scenarios to understand the range of energy consumption during the transportation stage. Generally, blade manufacturers try to make the blades close to regions where wind resources are abundant, where turbines are expected to be installed, to reduce the cost of transportation. For example, a Beijing blade manufacturer transports the blades 200 km by road to Zhangjiakou. However, local manufacture is not always possible so sometimes the blades must be transported over long distances, such as Beijing to Hami, around 2600 km. Sea freight is also commonly used. A Danish blade manufacturer will send blades from Esbjerg to London for installation, 600 nautical miles (one nautical mile is approximately 1.852 kilometres). In one extreme case a China manufacturer won a tender in Brazil; the blade factory is in Lianyungang, the sea freight will be around 13500 nautical miles. The results are shown in table 4.

Table 4. Transport energy consumption and CO_2 footprint.

	Energy (GJ)	CO_2 (t)
Transport Case road 200 km	2.94	0.21
Transport Case road 2593 km	38.17	2.71
Transport Case sea 600 nautical miles	1.78	0.13
Transport Case sea 13471 nautical miles	39.92	2.83

2.3.3. Operation and Maintenance. For operation and maintenance (O&M), we assume the blade life time is the 20 year design life. Routine maintenance and accidental damage are the two major waste sources in the O&M stage. Routine maintenance includes cleaning and minor and major repairs. During the initial few months of operation of new blades, some excess adhesive used in the blade manufacture becomes detached from the interiors of the blades and must be removed during blade maintenance periods. This is typically tens of kilograms for a 1.5 MW blade. Repainting and repair of small defects or stone damage are very common for most blades. Generally, 15 kg fibre and resin is enough for each of these minor repairs [9]. Major repairs only happen on specific blade batches and are usually caused by manufacturing defects or design defects. Such repairs typically involve re-strengthening work on major structures such as shell bonding, shear web bonding or the blade root. Each major repair job consumes tens to hundreds of kilograms of fibre, resin and adhesives [10].

Quite a few blades break in accidents due to extreme weather, with reports indicating that this causes failure in 1-3% of blades each year. Some failures need major repairs and some of them require replacement of the blade. These blades are treated as accidentally damaged blade waste.

Overall, the material usage in the maintenance stage is between 1.5% to 4.5% of the blade weight. Major materials used in this stage are fibre fabric and resin and we assume the usage ratio is 60% fibre and 40% resin. The equivalent energy consumption and CO_2 emission are presented in table 5.

Table 5. O&M energy consumption and CO_2 emission for a 10 tonne blade.

	Energy(GJ)	CO_2(t)
O&M@1.5%	12.6	0.66
O&M@3.0%	25.2	1.32
O&M@4.5%	37.8	1.97

2.3.4. End-of-life. A few possible recycling methods for fibre reinforced plastics have been identified in the literature, but the technology is not mature and most blades are currently sent to landfill. The environmental impact is assumed to be zero.

2.4. Energy payback time

Wind turbine energy generation (E_{gen}) is a function of rated power (P, in MW), capacity factor, and life span (t_s). Capacity factor is the ratio of actual energy production to full power theoretical production at continuous operation. The typical onshore wind turbine capacity factor (γ) is between 20-35%; we assume 30%. The rated power depends on the turbine model. The designed lifespan of a wind turbine blade is assumed to be 20 years. The annual energy production (AEP) is calculated as follows (24h in day, 365 days in year):

$$E_{gen} = P\gamma t_s \times 24 \times 365 = AEP \times t_s$$

Cumulative energy demand (CED) is an indicator for the overall life cycle environmental impact of many non-agricultural goods which is equivalent to energy consumption in this study. Energy payback time (EPBT) is a metric for the time taken for the system to generate the amount of energy required for its own manufacture, transport and installation, operation and disposal [11]. It is defined as:

$$EPBT = \frac{CED}{E_{gen}}$$

3. Results and discussion

The material usage and their proportion of the total blade energy of a typical small blade are shown in table 6.

Table 6. Material usage and energy consumption ratio of a 1.5 MW blade.

	Material by weight	Energy consumption
CF/GF fabric	60.4%	38.6%
Resin and adhesives	32.3%	56.7%
Steel	1.1%	6.0%
Copper	0.3%	2.5%
Aluminium	0.0%	0.6%
Balsa	2.3%	0.3%
PVC	1.7%	0.1%
Paint	0.9%	0.3%
Putty	0.7%	1.3%
Spray Adhesives	0.0%	1.3%

The total fibre content is around 60% of the blade weight and the resin with curing agent and adhesives is around 32%. As previous wind turbine LCA studies assume the materials in blades are 60% fibre and 40% resin [7,12], our result indicates that there is 8% difference between these studies and reality. Resin, curing agent and adhesives dominate the energy consumption (up to 57%). The unit primary energy of the fabric is lower, so despite the higher volume fraction of fibre its contribution to the whole blade energy is around 38%. Primary energies arising from other materials are low in comparison. The energy consumption of manufacture, transport and O&M are around 96.1%, 1.6% and 1.7% respectively.

Table 7. Eco results of 20 blade models from three manufacturers. Energy consumption, CO_2 footprint and water consumption are the results of one single blade. The energy payback time is calculated as the time taken for the turbine to generate energy equal to that required to produce three blades.

	Manufacturer A			
Model	40.2A-1.5	40.3A-1.5-IIIA	42.2A-1.5-IIIB	42.8B-1.5-IIIB
Rated power (MW)	1.5	1.5	1.5	1.5
Energy consumption (GJ)	627	606	699	689
CO_2 footprint (tonnes)	33.3	31.9	36.9	36.3
Water consumption (tonnes)	744	578	898	877
Total energy production (GJ)	283,824	283,824	283,824	283,824
Energy payback time (months)	1.59	1.54	1.77	1.75
	Manufacturer A			
Model	45.2A-1.5-IVB	45.2B-1.5-IV (Bolt embedded)	51.9-1.8-IV	56.8-2.0-IV
Rated power (MW)	1.5	1.5	1.8	2
Energy consumption (GJ)	795	775	924	1238
CO_2 footprint (tonnes)	42.1	41.1	48.7	65.1
Water consumption (tonnes)	989	959	1155	1458
Total energy production (GJ)	283,824	283,824	340,589	378,432
Energy payback time (months)	2.02	1.96	1.95	2.36
	Manufacturer B			
Model	DW93 (Carbon)	43.5-1.5	48.4-2	54.4-2
Rated power (MW)	2	2	2	2
Energy consumption (GJ)	1194	746	944	1129
CO_2 footprint (tonnes)	67.7	39.3	49.9	59.8
Water consumption (tonnes)	1079	1001	1227	1415
Total energy production (GJ)	378,432	378,432	378,432	378,432
Energy payback time (months)	2.27	1.42	1.80	2.15
	Manufacturer B			
Model	55-3.0	56.4-3.6	59.5-2.0	37.5-1.5-IIA+
Rated power (MW)	3	3.6	2	1.5
Energy consumption (GJ)	1299	1556	1461	624
CO_2 footprint (tonnes)	68.6	82.1	77.2	33.0
Water consumption (tonnes)	1599	1897	1845	741
Total energy production (GJ)	567,648	681,178	378,432	283,824
Energy payback time (months)	1.65	1.64	2.78	1.58
	Manufacturer C			
Model	40.25-1.5-IIIA+	42-1.5-IIIB-	47-1.5-IVB	51.5-1.5-IVB
Rated power (MW)	1.5	1.5	1.5	2
Energy consumption (GJ)	640	650	862	1049
CO_2 footprint (tonnes)	33.9	34.4	45.6	55.6
Water consumption (tonnes)	754	776	1038	1363
Total energy production (GJ)	283,824	283,824	283,824	378,432
Energy payback time (months)	1.62	1.65	2.19	2.00

The detailed blade energy consumption data for all models is presented in table 7. We find that longer blades generally have higher energy consumption, because they need more material to manufacture. As a secondary factor, the in-house waste level also varies between models and

manufacturers which may be caused by inaccurate control of fabric and resin usage. Better control would reduce material usage, energy consumption and cost. Use of carbon fibre allows a lighter blade; this weight saving benefits the whole wind turbine system. However, the unit energy consumption of CFRP is 5.5 times to that of GFRP. When the full GFRP blade is compared with a similar size partial CFRP blade (CFRP spar cap, rest of the blade is GFRP), the partial CFRP blade energy consumption is around 50% higher than for a GFRP blade and the energy payback time is 15% longer (table. 8). NEEDS [13] predicts that carbon fibre is expected to account for up to 50% of fibres in blades by 2025, which would lead to a more serious environmental impact in the future. Putting this in context, however, we note that the blade primary energy accounts for 6-10% of the wind turbine energy [4,7], so this increment in blade energy consumption will not hugely affect the overall environmental impact of wind turbines. Carbon fibre is a high value material, so there is incentive for developing recycling routes which may provide future benefits.

Table 8. GFRP and CFRP blade comparison.

Model	45.2A-1.5-IVB (full glass fibre, GFRP)	45.3-DW93 (carbon fibre spar, GFRP+CFRP)	% increase of CFRP over GFRP
Total energy consumption (GJ)	795	1194	+50.3%
Total CO_2 footprint (tonnes)	42.1	67.7	+60.9%
Total water consumption (tonnes)	989	1,079	+9.1%
Energy payback time (months)	2.02	2.27	+12.7%

Our results differ from earlier results in the literature. Wagner [4] calculates that the energy consumption of an early (and therefore comparatively small) 1.5 MW-33 metre turbine rotor (3 blades plus cap) is around 1140 GJ and 8.4% of turbine energy consumption with turbine energy payback time at 6 months. For a 3 MW turbine, Crawford [7] estimates these numbers as 5050 GJ and 6% with nearly 12 months turbine payback time, but this result is questionable because it uses a glass fibre fabric embodied energy of 168 GJ/t which is double the number used in most literature. Our present study is expected to have greater accuracy because of the large sample size and up-to-date data.

4. Conclusions

- The energy payback time of blades is between 1.54 and 2.78 months, increasing with blade scale-up. Large wind turbines reduce the levelized cost of electricity (LCOE), but the blade environmental impact is growing rapidly.
- The same rated power blades can have environmental impacts differing by up to 46% (40.3 compared to 47-IVB). The reason is that the early stage blades are installed in higher wind speed sites, so the blades are relatively short. Newer blades are commonly installed in medium and low wind speed regions. Although the rated power is the same, the new blades are longer than the old ones with more material usage, and the environmental impact is increased.
- The energy consumption and carbon dioxide emissions of CFRP blades are much higher than GFRP blades. If blades contain up to 50% CFRP in 2025 as predicted, the environmental impact of WTBs will significantly increase compare to current calculations.
- Manufacturing waste varies in-house and between manufacturers. For example, if manufacturer A can reduce the manufacturing waste level to their best level, it could reduce the material usage between 6% and 23%. But the average manufacturing waste of manufacturer B is lower than others, so there is clearly scope for improving industry norms.
- The manufacture stage accounts for more than 96% of the whole blade life cycle energy consumption, with transport and O&M accounting for 1.6% and 1.7% respectively.

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