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Blade materials selection influence on sustainability: a case study through LCA

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Abstract. In this study, the environmental influence that blade materials have on the entire wind turbine lifecycle is considered. In order to quantify and compare the effects that a specific material's choice has with respect to one another, Life-Cycle Assessment (LCA) tools are used. Specific focus is addressed on aspects related to the wind turbine rotor-blade and how that affects the whole turbine. The blade lifecycle is divided into five main stages: (1) raw material sourcing, (2) blade manufacturing, (3) blade installation, (4) Operation and Maintenance (O&M) and (5) End-of-Life (EoL). Materials sourcing is found responsible for the largest contribution in Green House Gas (GHG) emission in the turbine and blade lifecycle. Particularly, a case study on a representative blade production in Siemens Gamesa Renewable Energy (SGRE) is disclosed and compared to a hypothetical blade production where a recyclable resin system is being used. The lifecycle assessment shows a 28% reduced amount of GHG emissions when the recyclable resin system is employed. By employing such resin system most of blade materials could be separated and re-used at the blade EoL, enabling a 90% blade recycling rate. An even greater advantage of achieving blade circularity is therefore envisioned.

1. Introduction

Compared to fossil-fuel power plants, renewable-energy power plants are considerably less impactful in terms of the environmental footprint and the equivalent CO2 released into the environment. During its lifetime, a wind power plant emits less than 1% of the CO2 emitted per kWh by an average power plant using fossil fuels [1]. This in itself represents a strong reason to transition from non-renewable to renewable energy sources. Renewable energy sources are often also considered sustainable energy sources, because their intrinsic ability to replenish (or renew) themselves naturally, allows for an endless supply of energy that can meet the needs of the present demand without compromising the ability of future generations to meet even an higher demand [2]. However, this definition does not consider the energy conversion technology (i.e. the wind turbine generator) that is used to transform the renewable energy source into the final product, being the electricity. For instance, aspects like the consumption of resources used to produce and deploy the wind turbine, the disposal of the wind turbine and its induced environmental impact should also be considered. To evaluate the relative burden of energy systems within the environment, full energy supply chains need to be considered on a lifecycle basis, including all system components, and across all impact categories [3]. To properly account for all these aspects, Life-Cycle Assessment (LCA) tools are used to quantify the footprint that a conversion technology has on the environment [4]. The most used quantity in LCA to define the environmental footprint of a



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conversion technology is the equivalent CO2 (CO2eq) which is directly related to Green House Gas (GHG) emissions [3]. Additionally, such assessments need to address a wide range of issues, such as land and water use, as well as air, water, and soil pollution, which are often location specific. To have a holistic view on the environmental footprint of a conversion technology, all stages in its lifecycle need to be identified and properly accounted, using a "cradle-to-grave" so to say approach. To fully prove that a new conversion technology has a lower footprint with respect to a more traditional technology (e.g. offshore wind turbine technology vs. coal power plant technology) all implications that come with the new technology should be addressed. This can often be a complicated task and a certain amount of assumptions needs to be made.

When analysing the lifecycle of a wind power plant, raw materials sourcing is considered responsible for most of the total CO2eq emissions [4]. This accounts for the extractions of raw constituents such as minerals, wood and oils, the processing to produce the raw materials (i.e. concrete, copper, steel, glass fibres, resin, lubricants), the transportation of those materials to the production site and the waste production associated with them. These emissions can, to a large extent, be re-gained by recycling and indeed the current practice for wind turbine materials is to recycle as many of the components as possible. To date, up to 85-90% of the turbine components can be recycled [5]. However, not all the turbine components can be recycled. The rotor blade and part of the nacelle canopy are produced out of thermoset based composite materials. To date, no well-established best-practice for recycling of thermoset composites materials exists on industrial scale [6]. This is due on the one hand because no clear legislation is yet in place on circularity for composite applications and on the other hand because the volumes of composite waste coming from different applications are still relatively small and discontinuous, making it difficult to create a solid business around recycling. Most of the composite blade waste is sent to landfill, or in some cases the blades are shredded into pieces and incinerated. In the latter case, an energy recovery from burning the composite organic fraction is obtained and the remaining glass fibres are used as fillers in cement production or other secondary applications [1].



Figure 1. Recycling processes for composites.

Figure 1 shows the currently existing methods for recycling of thermosets composite materials. Two major classes of recycling methods exist: (i) mechanical recycling where composites are shredded into pieces and either used as fillers or short fibres for other applications and (ii) chemical recycling where the fibre fraction is recovered, or an energy recovery is obtained through combustion of the organic composite fraction [7].

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The European Composites Industry Association (EuCIA) agreed with the European Commission that co-processing of composite material in cement kilns is compliant with the European Waste Framework Directive 2008/98/EC and is considered both recycling and energy recovery [8]. However, this recycling/recovering method cannot be categorized as re-use and therefore it fails to fulfil the requirements for circularity. Other technological methods exist to recycle thermosets composites. The two major ones that rely on thermal processing of the material are pyrolysis and solvolysis. Pyrolysis is the thermal decomposition of materials at elevated temperatures in an inert atmosphere. It involves a change of chemical composition. The main drawbacks of this process are that it is intensively energy demanding and due to its high temperatures, it can only be used for glass fibres reinforced composites and not for carbon fibres that would undergo combustion. Solvolysis is a chemical depolymerisation that involves using a reagent to decompose the polymer matrix. This process largely depends on the type of polymer that is dissolved and generally it does not involve too high temperature (e.g. 200°C) to deteriorate the fibre fraction in the composite. The recovery process allows for reuse of the fibre reinforcement fraction usually in lower composite applications, whereas the resin fraction is degraded with the solvent and therefore lost. As a drawback, this process creates a certain amount of hazardous waste that still need to be dissolved or disposed.

Some research projects investigated the possibility of using blade sections as roofing for affordable housing but this will only be possible for limited applications and cannot be considered as a valuable option for circularity [9]. Because of the decarbonization and energy transition plans ongoing worldwide, the forecast for blade waste production are expected to increase exponentially in the decades to come to reach in the lowest case scenario a 43 Mt of cumulative blade waste by 2050 [10]. Therefore, blade circularity will be a strategic area of development within the industry in the next decade [5]. It becomes clear to the authors that a technological method to create circularity in the wind energy composite sector is necessary.

2. LCA study on SG 8.0-167 DD turbine lifecycle

To first understand where the most environmental values lies in the whole turbine lifecycle a reference LCA study was performed on one of the SGRE product the 8MW offshore wind turbine with 167m rotor diameter and 81m composite blade length [11]. This study will then be used as baseline when the LCA impact of a new technology needs to be assessed.

2.1. LCA Assumptions

The blade lifecycle is been divided into five main stages: (i) raw material sourcing, (ii) blade manufacturing, (iii) blade installation, (iv) Operation and Maintenance (O&M) and (v) End-of-Life (EoL) [1]. (i) Main types and quantities of materials and energy that had to be extracted and consumed to produce the turbine components and the elements needed to connect the wind power plant to the grid, i.e. substations and connecting cables were considered. (ii) For the manufacturing, data from Siemens Gamesa Renewable Energy's (SGRE) own production sites and from main suppliers were collected. Consumption data for manufacturing as well as waste and subsequent treatment are based primarily on annual manufacturing data from European production sites. (iii) Transport of materials to the manufacturing site is included in the data. Components, auxiliary resources, and workers are transported to the wind turbine site during the turbine installation. On-site installation includes preparing the site, erecting the turbines and connecting the turbines to the grid. These installation activities result in the consumption of resources and production of waste. Associated data has been collected from actual onsite installations. (iv) The SG 8.0-167 DD turbine is designed to a 25 years lifetime. Actual site data, including manpower, materials, and energy required for service and maintenance over the turbine's lifetime were collected. Wake, availability, and electrical losses have been included in the assessment to define a realistic estimate of annual energy production delivered to the grid. (v) At the wind power plant's EoL the components will be disassembled and the materials transported and treated according to different waste handling methods. For the turbine components, recycling was assumed to all recyclable material e.g. metals. Recycling leads to the recovery of materials, which subsequently reduces primary material extraction. The rest of the materials are either thermally treated or disposed in landfills. The EoL stage described here represents the current status of waste management options in Northern Europe. Planning a new wind power plant includes assessing the environmental impact of the installation and operation phases to minimize negative impacts. Often these assessments focus on birds, marine wildlife and visual impacts. How a wind power plant impacts its surroundings varies depending on its location. Being this site-specific, it was decided not to consider it in the LCA assessment.

2.2. Breakdown of CO2eq per turbine lifecycle stage

When breaking down the CO2 emissions at each stage of the turbine lifecycle, it results immediately evident that the raw materials sourcing is responsible for more than 70% of the total CO2eq. This is understandable as most of the emissions are embodied within the materials that constitutes the turbine. The CO2eq/kWh breakdown per turbine lifecycle stage is depicted in Figure 2.



Figure 2. Breakdown of CO2eq/kWh per turbine lifecycle stage. Environmental Product Declaration SG 8.0-167 DD [1].

When a turbine is dismantled, it has not necessarily reached its EoL. Turbines are often replaced by larger turbines, allowing the dismantled turbines to be refurbished and sold for installation elsewhere. When disposing of wind turbines, recycling is usually the preferred solution. This not only prevents the materials from being sent to landfills, but also reduces the need for the extraction of primary materials. Therefore, a negative CO2eq impact is seen at the turbine EoL and dismantling stage in Figure 2. As already discussed in the introduction, metallic materials in the wind power plant components are to a great extent recycled at their EoL. Magnets from the direct drive turbines can be demagnetized, remagnetized and used or reused for new magnet production. Blades may be shredded and incinerated for energy recovery. The residues from fiberglass incineration can be used in other secondary applications e. g. for cement production. This process would not be allowed for carbon fibres composite blades and in both cases this process doesn't allow to reuse the materials. A better recycling strategy for blade materials seems therefore necessary.

2.3. Blade materials influence on turbine LCA

To better understand where the major CO2 contribution on blade materials lies and therefore decide which recycling strategy to favour, a blade materials LCA study limited to the CO2 equivalent emissions was performed. A normalized CO2eq. profile for each of the most common blade materials is presented in Figure 3. The carbon fibres impact profile is very significant compared to the remaining materials, underpinning the need for defining a suitable recycling strategy that would enable its reuse. This becomes even more relevant as the design drivers for larger offshore rotor blades will require employing an increased amount of carbon fibres in the blade bill of materials [12].

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Figure 3. Wind turbine blade materials breakdown for a SG 8.0-167 DD turbine.

Figure 3 alone cannot give the full overview on why not only carbon fibres, but also glass fibres and Epoxy resin materials are important element to consider when defining an appropriate recycling strategy. In fact, the two materials combined still represent more than 80% in weight of the blade bill of materials. Glass fibres make use of large amounts of sand, that is becoming a lack of resources and represents a growing environment damage with future direct impact on landscapes. Rare-earth as trace components are also used in fibre reinforcements. Even though these are small amounts (<1% in glass reinforcement weight), future sourcing demand for the forecasted business growth will result in a considerable amount. Epoxy resin materials are also to be seen in terms of their large share in future offshore rotor blades bills of materials, therefore their recycling/reuse would be the favourable scenario. All combined, it can be concluded that a recycling strategy that enables separation and reuse of carbon/glass reinforcement and resin without needing any major mechanical shredding of the composite material would be preferred. This should be somehow represented by a solvolysis process, where the process chemicals would allow to precipitate the resin material and reuse it for either the same or other composite applications. In addition to this, the process chemicals should also be recovered and reused in a closed loop process.

3. LCA case study on different blade resin system

In this section, the environmental impacts of substituting a conventional Epoxy resin system with a recyclable alternative for large offshore wind turbine blade manufacturing was investigated. It is out of the scope of this paper to discuss in detail the resin system considered, but it is worth to mention that this would enable blade material recycling at the turbine blade EoL. This will lead to a scenario, where the baseline model of landfilling used for the majority of blade LCA studies is no longer the most likely scenario, but rather a recycling of the resin (in the form of a thermoplastic), fibres, core materials and metals is considered. The earlier developed SG 8.0-167 DD turbine LCA assumptions are being compared to the new scenario using the recyclable resin system allowing for recycling of the main parts of the wind turbine blade and a new turbine LCA derived.

3.1. Methodology

Data were collected for each phase of the lifecycle. Primary, data derives directly from SGRE internal data (i.e. material composition), whereas manufacturing, installation and operations and maintenance data is directly taken from previous SGRE internal LCA assessments. As for this study, the main differentiator is at the EoL scenario, the analysis will focus on the impact from going from 90% landfill and 10% incineration to recycling of the main parts of the blade such as resin and fibres. Figure 4 below is to illustrate the interchanges between the ecosphere and technosphere evaluated in this study [13]. For the impact assessment, the software used is SimaPro using the EcoInvent Data using the Impact2002 methodology to evaluate environmental impacts.

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Figure 4. System boundaries – illustrative figure based on Bonou et al. 2016 [13].

Table 1 outlines the main assumptions used for the baseline study of the wind turbine blade and the comparison with its recyclable alternative. From the table, it is quite clear that the difference is within the end-of-service-life phase, where landfilling and incineration are replaced by recycling of the resin system (in the form of thermoplastic, or substitute to PA or PC), the fibres (assuming 90% recycling rate), metals and incineration of the remaining parts of the blade.

	Baseline assumptions	Recyclable alternative	
Materials	Net weight per blade ~34t	Main difference is in the hardener, so the resin system is modelled as similar	
	• Fibres ~60%	to baseline with the exception that	
	• Resin ~28%	production waste is being recycled	
	• Wood ~8%	instead of incinerated.	
	 Plastics ~2% 		
	• Paint ~1%		
Transportation	Modelled from suppliers to Aalborg and from Aalborg to Esbjerg pre-assembly site-	Similar to baseline	
Manufacturing	Manufacturing in Aalborg, use of real production data for	Similar to baseline, however, waste can be recycled	
Installation	Use of installation data from recent project	Similar to baseline	
Operations & Maintenance	Use of O&M data from installed base regarding maintenance need, change of component, etc.	Similar to baseline	

Table	1.	LCA	comparis	on study	assumptions.
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End-of-life	Non-recyclable	Recyclable
	• 90% landfilling, 10% incineration	 Resin can be recovered and used as replacement for Polyamide or Polycarbonate thermoplastics Glass fibres can be recovered, with expected 10% lower properties (due to sizing removal, fibre misalignment etc) and recycled Carbon fibres can be recovered with expected 10% lower properties (due to sizing removal, fibre misalignment etc) and recycled Metals can be recycled Paint, coating and core materials will be incinerated

3.2. CO2eq LCA comparison

When analysing the full lifecycle of a set of wind turbine blades, it is evident that the recyclable solution is favourable from a CO2eq perspective as the overall lifecycle emissions will be reduced by 28% through recycling of resin, fibres and metals and feed this back into the material cycles. Another interesting observation is that from the EcoInvent data, polycarbonate has a CO2eq. profile that is much higher than epoxy resin, so the recycling of the resin in a fairly light process (i.e. acidic solution with 90°C process temperature) will result in a favourable situation as high impact plastic is being substituted by the recycled material.



Figure 5. Estimated tons of CO2eq saved per turbine (SG 8.0-167 DD) by using a recyclable resin system as opposed to a conventional epoxy resin system.

4. Conclusions

To summarise, the current study showed that raw materials are responsible for 71% of the CO2eq emission on a representative 8MW offshore wind turbine lifetime and due to the non-recyclable nature

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of blade materials, their CO2eq emissions impact is remarkable. Therefore, investing efforts in research and innovation to diversify and scale-up composite recycling technologies, to develop new, highperformance materials with enhanced circularity and to design methodologies to enhance circularity and recycling abilities of blades are required. At the same time, existing treatment routes like cement coprocessing must be deployed more widely to deal with the current waste streams. Finally, the scientific understanding of the environmental impacts associated with the choice of materials and with the different waste treatment methods should also be improved by extensive use of LCA tools.

An LCA comparative study employing an innovative recyclable resin system has proven to cut on CO2eq emissions by 28% with respect to a conventional epoxy resin system. This under the assumptions that the blade materials can be recycled with a 90% rate. Only CO2eq impact has been calculated using the data available based on assumptions, extrapolation of recent installations as well as using the EcoInvent database for material emission profiles. This study can therefore only be considered a screening study, and a full study must be carried out to validate these preliminary findings. Nonetheless, the indicators show that recyclable resin systems are environmentally superior to the baseline alternative under the assumptions used.

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