Energy Efficiency Analysis of Wind Turbine Supply Chains

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1. **Introduction**

In the past years the general awareness of environmental challenges, like global warming, climate change, and greenhouse gas emissions has increased. Therefore, it has become necessary to evaluate and improve the use of renewable energy sources. (Demir and Taşkın, 2003)

To ensure the shift to renewable energy sources, the European Commission developed an energy directive determining that 20% of the total energy consumption should be fulfilled by renewable sources by 2020 (European Commission, 2015). The increasing focus on sustainable development, lead to rapid growth in the wind energy sector. For the first time a total capacity of more than 50GW of new wind turbines were installed in 2014. The global total installed wind energy capacity at the end of that year was 369.6GW. (Global Wind Energy Council, 2015)

In general, wind energy is considered environmentally friendly, but there have been concerns about its possible negative environmental impacts. The main issues are noise, visual impact and impact on wildlife. However, wind energy is increasingly viewed as an alternative to non-renewable energy sources. Therefore, the general population accepts some of these negatives more easily. (Magoha, 2014) Renewable energy sources are mostly presented as “green” and “clean“, but environmental impacts during their whole life cycle from “cradle to grave” are usually not considered. Although there are no direct emissions during the energy production process of a wind turbine, its production requires the consumption of energy and natural resources, including the release of pollutants. Thus, it is not only important to reach the goals set by the European Commission, but also to do this with as few emissions as possible. As any energy consumption causes emissions, it is necessary to keep the energy demand within the supply chain as low as possible, from raw materials extraction until disposal of the materials. This paper identifies the biggest drivers of energy consumption during the life cycle of wind turbines and offers possibilities for a more energy efficient design of the associated supply chain.

2. Life Cycle of Wind Turbines

One way to identify drivers of energy consumption can be the life cycle assessment (LCA) or modified hybrid methods thereof. For these, the life cycle and the structure of wind turbines must first be understood.

There are many different kinds of wind turbines, differing in their structure (with or without gearbox), power rating (from 150 kW to 8 MW), design (horizontal or vertical rotor), number of blades (two or three), hub height (50m to 149m) and field of application (onshore, offshore). (Enercon, 2015; Vestas, 2015) However different wind energy plants are, the main components are the same:

- tower
- nacelle
- rotor (hub, nose cone, blades)
- foundation
- cables (connecting the individual wind turbines of a wind farm)
- transformer station. (Vestas, 2006)

This paper does not analyze any specific type of wind turbine, but combines the results of several LCAs of different types to identify the main energy drivers and subsequently design a more efficient supply chain.

The life cycle of a wind turbine consists of six main phases, shown in Figure 1. It illustrates the steps of the life cycle, including raw material production, manufacturing, installation, operation & maintenance and decommissioning. Transportation processes are necessary between the phases 1 and 2 and 2 and 3, but also during phases 4 and 5, cp. Figure 1. In the following paragraphs, these phases are described in detail.

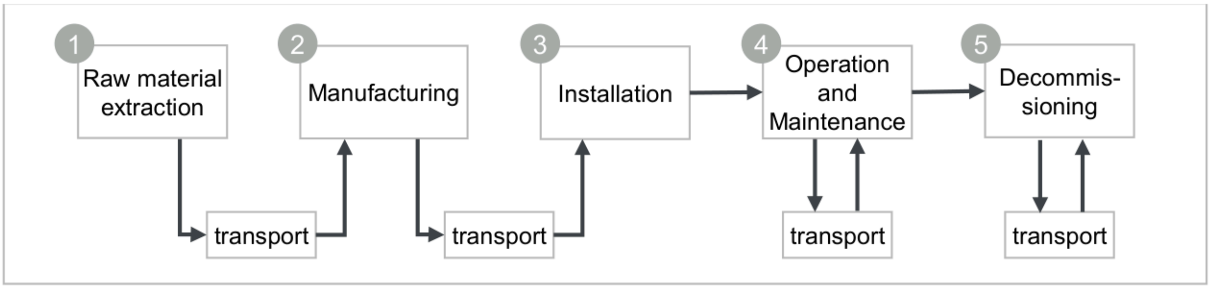

Figure 7: Life cycle of a wind turbine

2.1 Raw Materials

The materials used for wind turbines are often extracted in different countries. (Schleisner, 2000) Table 1 shows the most relevant materials used for the components of wind turbines. (Demir and Taşkın, 2003) The extraction of the different materials requires a lot of energy, with the extraction of iron ore needed to manufacture necessary steel components especially energy consuming. Another highly energy consuming process is the extraction of crude oil for the production of epoxy materials such as wind turbine blades. (Vestas, 2004) Some of the materials are secondary, i.e. recycled materials. In Germany, for example, 40% of copper is produced from secondary copper. If recycled steel is not used, energy consumption during steel production doubles. (Guezuraga et al., 2012)

Component	**Foundation**	**Tower**	**Nacelle**	**Rotor**	**Other Component**
Material	Concrete Steel Iron	Steel Aluminum Plastic Copper Paint	Steel Copper Aluminum Iron Epoxy/Resin Fiberglass	Steel Fiberglass Epoxy/Resin	Aluminum Copper

Table 5: Materials of wind turbine components (cf. Demir and Taşkın, 2003)

2.2 Manufacturing

The components are either manufactured at a supplier or at the manufacturer. The most energy intensive component manufactured is the tower of the wind turbine, due to its large dimensions. (Guezuraga et al., 2012)

2.3 Installation

Wind towers are generally installed by cranes and other typical construction machines and tools. To install a wind power plant, an infrastructure of foundations, electric cables, cable trenches, paths and road connections, and transformer room must be built on location. (Ardente et al., 2008)

One of the first steps at the construction site is building a road giving access to the location of the wind turbine for equipment during construction and future operations. It must accommodate cranes and trucks delivering the large parts of the wind turbine. The wind turibine foundation is constructed out of reinforced concrete. After it is finished the wind turbine segments are delivered and built. (We Energies, 2009) For offshore wind turbines, the installation conditions are more complicated, due to construction requirements, special installation equipment, like crane ships, and weather conditions.

2.4 Operation and Maintenance

The lifetime of wind turbines is calculated as around 20 years. (Vargas et al., 2015) As wind turbines are computer-assisted, daily operation requires negligible permanent personnel. However, maintenance and control cycles are necessary. Inspections are done 3 to 4 times a year. (Ardente et al., 2008) Service is carried out in the form of oil changes and renewing lubricant. Geared turbines need more maintenance, because of the bigger number of rotating parts. (Guezuraga et al., 2012) In general, it is expected that one blade and 15% of the nacelle’s components, including half the gearbox, will be replaced over the lifetime of wind turbines. (Vargas et al., 2015)

2.5 Decommissioning

After a lifetime of 20 years, wind turbines must be disassembled before their parts can be recycled or disposed of. The process of disassembly is similar to installation. *Vestas* assumes that 90% of the metals are recycled and 10% landfilled. Composite materials like glass fiber components and plastics are mostly incinerated. (Vestas, 2006) As mentioned before, it is important to recycle most of the materials to reduce the energy consumption required during raw material mining for wind turbines.

2.6 Transport

Transport processes connect the phases of the wind turbine life cycle. They are responsible for carrying the materials used for the wind turbines between the manufacturing steps and the place of installation. More than 10 trucks are necessary for the transport of one wind turbine, due to the large dimensions of its components. (Gasch and Jochen, 2012)

3. Life Cycle Assessment

One way to analyze the life cycle of a wind turbine is the life cycle assessment, a “cradle to grave” analysis to investigate the environmental impact of a system. ISO 14040 defines the LCA as analysis and evaluation of the inputs, outputs and the potential environmental impacts of a system during its lifetime. (ISO 14040, 2006) The LCA approach is to compare the environmental impacts of different products and the energy used in their production. This is of great importance especially for renewable energies. As mentioned before, renewable energy plants are not zero-emission energy sources, as they require energy over their lifetime. Some argue that the energy used to produce renewable energy infrastructures is not paid back during its lifetime. (Schleisner, 2000) Using LCA helps prove the contrary. It can be applied to identify process steps with the biggest environmental impacts, and thus to support the development of an environmentally oriented supply chain management. (Bonou et al., 2015)

A number of LCA studies focusing on the manufacturing and installation of wind turbines already exists. However, the process of disposal is often neglected. A study that analyzed 72 LCAs found that they all studied the manufacturing phase, 70% studied the installation, 56% studied operation and maintenance, but only 19% included the decommissioning phase. (Liberman, 2003)

To evaluate the energy and environmental performance of wind turbines the energy payback time gives a comparative index for renewable plants. The payback time states the time to recover an initial investment. (Ardente et al., 2008) However, the energy payback time compares primary energy with electricity produced by a wind turbine, which is not representative. In contrast, the primary energy payback time (PEPBT) compares the primary energy input (E_{In}) and the primary energy produced during the life cycle. (Tremeac and Meaner, 2009) This could be implemented by converting the electricity produced ($E_{Out;Elec}$) by the wind turbine into primary energy by using an energetic supply factor (ESF) (for Germany e.g. about 3.0 kWh Primary Energy Equivalent per kWh electricity). (Wagner et al., 2011)

$$PEPBT = \frac{E_{In}}{E_{Out;Elec} * ESF} \tag{1}$$

This paper focuses on the energy input and output and the primary energy payback time. Environmental impacts of wind turbines are not discussed in detail.

Six LCAs from other previous studies, chosen for their consideration of energy calculations, are analyzed and summarized in Table 2. Only the data for the energetic supply factor is assumed based on the German ESF factor to calculate the primary energy payback time, since it is not considered equally in the LCAs analyzed. Furthermore, the table shows the different types of wind turbines and the corresponding turbine heights, location (onshore/offshore) and the estimated lifetime. In addition, the energy data for the previously defined life cycle phases are listed in the table. Not all researches define these phases in the same way, with raw material extraction, manufacturing and installation often seen as one phase.

Wind turbine			LCA						Energy			
Type	**Height [m]**	**Life [years]**	**Raw Material extraction [GJ]**	**Manufacturing of Components [GJ]**	**On site installation [GJ]**	**Operation and Maintenance [GJ]**	**Decommis-sioning [GJ]**	**Transport [GJ]**	**Energy Input [GJ]**	**Energy Output [GJ/ year]**	**Energetic supply factor**	**Primary Energy Payback time [years]**
660kW onshore	55	20	not considered	2.316	1.234	264	70	247	4.127	4.157	3,02	0,33
		20		56,12 %	29,90 %	6,40 %	1,70 %	5,98 %				
1,8 MW gearless onshore	65	20	6.411		included in transport	418	235	532	7.596	11.772	3	0,22
		20	84,40 %			5,50 %	3,10 %	7,00 %				
2 MW gearbox onshore	105	20	11.880		included in transport	774	436	985	14.076	21.528	3	0,22
		20	84,40 %			5,50 %	3,10 %	7,00 %				
2 MW gearbox onshore		25	17.594	1.359,3		167,8	218,3	243,4	19.583	25.200	3	0,26
		25	89,84 %	6,94 %		0,86 %	1,11 %	1,24 %				
4,5 MW gearbox onshore	124	20	52759			5.242	-3.480	15.631	70.152	42.120	2,87	0,58
		20	75,21 %			7,47 %	-4,96 %	22,28 %				
5 MW gearbox offshore	90	20	150.250			39.167	2.333	included in the phases	191.667	70.200	3,007	0,91
		20	78,39 %			20,43 %	1,22 %					

Table 6: LCA comparison (cf. Ardente et al., 2008; Guezuraga et al., 2012; Ghenai,2012; Tremeac, Meunier, 2009; Wagner et al., 2011)

3.1 Raw Material

The first step during a life cycle of a wind turbine is the extraction of raw materials. Most of these materials come from non-renewable sources. The majority of scientific studies on wind energy LCA do not investigate the energy needed for the raw material extraction further. Usually only the amount of material is shown. The demand of energy to extract for example iron ore is not discussed. Those papers which do imply the energy for the material extraction refer to data from software like GEMIS (Guezuraga et al., 2012) or LCA databases like GaBi EDIP. (Vestas, 2006) Only one LCA (2MW, gearbox, onshore) examines the energy consumption of the raw material stage and calculates nearly 90% of overall energy consumption for this stage.

The most energy intensive process in raw material extraction is the production of stainless steel followed by concrete and cast iron owing to their large material input. The biggest energy consuming process per kilogram is the production of plastics. (Guezuraga et al., 2012)

3.2 Manufacturing

This phase is supposed to be the most energy consuming one according to all but one of the analyzed LCAs. Most LCAs studies consider manufacturing and raw material extraction as one phase, consequently leading to the connection of energy consumption for raw material extraction and turbine manufacturing. *Ardente et al.* state the tower manufacturing with 50% as the most energy consuming process of the component manufacturing, (Ardente et al., 2008) followed by the second largest contributor – nacelle production – that has to be divided into gearless and geared nacelles. The gearless nacelle construction (28%) requires significant more energy than a geared nacelle (12%) caused by the heavy direct drive gearless generator. (Guezuraga et al., 2012)

3.3. Installation

The installation is the least described phase. The energy data is included either in the manufacturing phase or in the transport energy data (see Table 2). The main contributor in this phase is the energy expenses for the machines, like cranes and excavators.

3.4 Operation and maintenance

For onshore wind turbines the energy consumption during the operation and maintenance phase is about one to eight percent. The energy consumption for offshore wind turbines is much higher (20%) due to the long distances that have to be traversed by boat or helicopter. Only one fifth of the energy for offshore operation & maintenance is used for changing spare parts, oil and lubrication. (Wagner et al., 2011) As mentioned before, the energy expenses for geared turbines are higher than for gearless turbines, because the gearbox needs more maintenance.

3.5 Decommissioning

The phase with the lowest energy requirements is the decommissioning phase. This is because the energy regained during the recycling or the incineration processes is subtracted from the energy needed for the disassembling and the recycling process itself.

3.6 Transport

The amount of energy used for the transport phase is usually less than 10% of the total energy consumption of a wind turbine's life cycle. The main drivers are the distances between raw material and component supplier to the manufacturing plant and the distance between manufacturing plant and installation site. For off-shore locations, the energy expenses are even higher due to the larger distances and transport modes.

3.7 Energy Input

Focusing on the energy input, the data indicates a broad variation of consumed energy during the life cycle. This variation may be caused by many factors. One of these factors is the power category. There is a significant connection between output size of a turbine and the energy required for its construction, mainly due to the rising material input for bigger turbines. In addition, the height of the turbine tower necessitates a larger material input and therefore a greater energy input. Another factor is the type of wind turbine: a gearless wind turbine needs less material and only half of the energy in comparison to a geared turbine. The last impact factor on the input energy is the location of the wind turbine.

3.8 Energy Output

The energy output is highly dependent on the rated energy output of the wind turbine: The bigger the turbine, the higher the possible energy output. More factors are the geographic location, tower height and system efficiency. (Crawford, 2009)

According to *Enercon* the energy production is mainly influenced by the location of the turbine. An offshore wind turbine could deliver up to 50% more energy than an onshore turbine. (Enercon, 2012)

3.9 Primary energy payback time

The calculated primary energy payback time ranges from 0.22 to 0.91 years. This means no matter which power category a wind turbine, the plant is energetically amortized in less than one year. Nevertheless, the data shows that an offshore wind turbine needs more time for the energy payback than an onshore turbine. As this paper only analyses one offshore LCA, this may not be representative.

3.10 Energy Value Stream Mapping

In this paper, the methodology of energy value stream mapping is used to identify the main energy drivers of the life cycle of a wind turbine. Therefore, the method of value stream mapping, a lean enterprise technique to document, analyze and improve the flow of information or materials, is extended with energy data. (Erlach, 2013)

The energy value stream mapping is conducted based on Table 2. The data show that the first three energy phases are combined to one phase. The energy consumption ranges from 75% to 97%, illustrating that the first three phases are the main energy consumer during the life cycle of a wind turbine, cf. Figure 2. All processes during these phases are value adding. The operation and maintenance phase is partly value adding and partly non value adding, but necessary. The same applies to the decommissioning phase, because the recycling processes regain energy and value, but the disassembling does not directly add value. The transport connecting these phases is a not value adding, but it is clearly necessary.

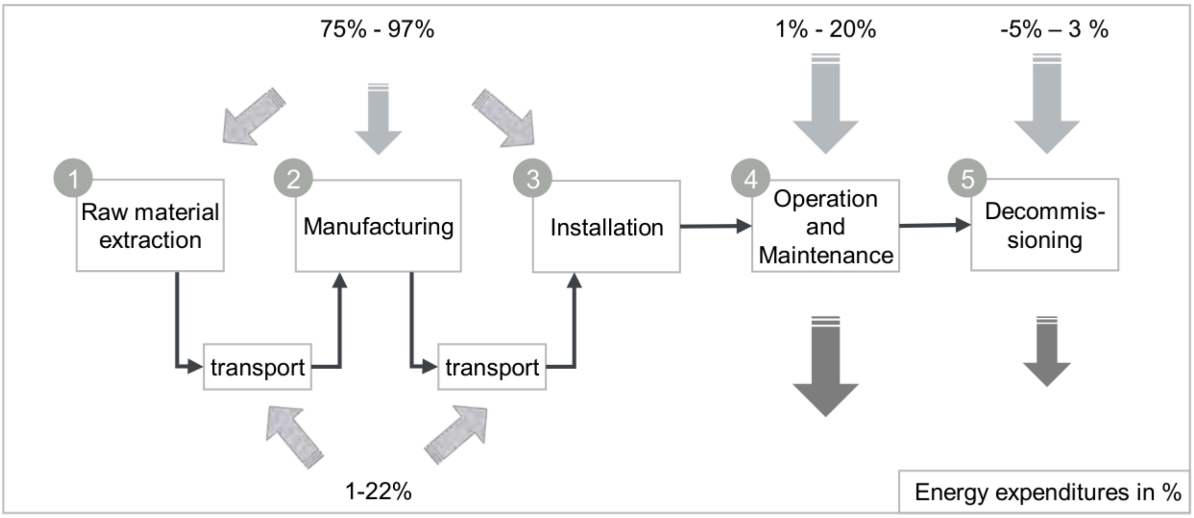

Figure 8: Energy Value Stream Mapping

4. Energy Efficient Supply Chain

The potential of an optimized supply chain of wind energy turbines is outlined by an example in the following paragraph. Figure 3 displays an extract of a wind turbine supply chain from cradle to grave. It shows the different components of a wind turbine while the discussion focuses exemplarily on transport processes of the tower for an onshore wind turbine. For a holistic approach, all components and supply chain processes as well as the different manufacturing processes need to be analyzed.
Based on this exemplary supply chain different location scenarios are developed which result in different energy consumptions. The energy data are based on distance and transport modes, calculated with the tool ECOTRANSIT. (EcoTransIT, 2015) Different transport modes are considered and their energy consumption is computed for each route. The modes considered are sea ship, train, truck and barge. Sea ship and barge transport in addition include transportation by truck for distances from and to the ports.

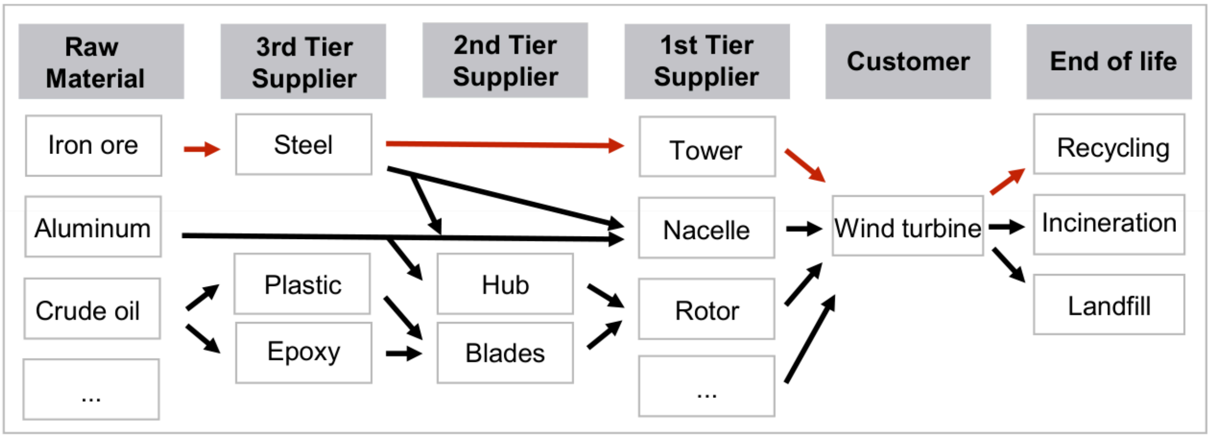

Figure 3: Wind turbine supply chain

The location of the tower manufacturer is predefined to be close to the German North Sea, while the locations for iron ore extraction, steel mill and recycling are interchangeable. According to the world mineral production, three main producers of iron ore are China, Australia, and Brazil. In addition, the biggest producers in Europe are Russia and the Ukraine. (Brown, T.J. et al., 2015) These five producers are included in the energy efficiency analysis. For the steel mill process three different sites in North Germany (Bremen, Eisenhüttenstadt and Salzgitter) are considered, while for the site of the wind turbine a radius of 130 km around the tower manufacturing is assumed. This area covers all relevant locations on and near the German North Sea coast. In the next step, the supply chain is modified in terms of locations and transport modes to identify the most energy efficient combination. For the main component of the tower, steel, a mass of 200 t is assumed for the calculations.

4.1 Transport optimization

Starting at the raw material extraction, the energy required for the transportation of those materials strongly varies with the mining location. Reducing the distance between mining location and wind turbine manufacturing site leads to a sharp decrease of energy consumption. Changing the transportation mode also offers potential to decrease energy consumption. Transport by train and boat are highly efficient in terms of energy used per transported weight. Analysis shows that transporting iron ore from the Ukraine to any of the steel mills considered consumes the least amount of energy. However, to reduce the overall consumed energy from the mine to the tower manufacturer, the distance between the steel mill and the manufacturer must also be analyzed. Table 3 shows all energetic optimal relations from each iron mill considered to the tower manufacturer. The most energy efficient way to transport iron ore to the tower manufacturer at the North Sea is from the Ukraine via Bremen with a consumption of 167GJ. In this scenario, the first distance is traversed by sea ship via the Mediterranean Sea to Bremen and from there by train to the manufacturer. In comparison, the transport from the world's largest iron ore producer China consumes about 100 GJ more.

Iron ore mine to steel mill		**Steel mill to tower manufacturer**		**Energy [GJ] iron ore mine to tower manufacturer**
Location of mine	**transport mode**	**Location of steel mill**	**transport mode**	
Ukraine, Krywvj Rih	sea ship	Bremen	train	167
Ukraine, Krywvj Rih	train	Eisenhüttenstadt	train	183
Ukraine, Krywvj Rih	train	Salzgitter	train	182
Russia, Kursk	train	Bremen	train	204
China, Benxi	sea ship	Bremen	train	265
Brazil, Carajás	sea ship	Bremen	train	335
Australia, Tom Price	sea ship	Bremen	train	509

Table 7: Excerpt - transport energy from iron ore mine to tower manufacturer

For reasons of simplicity (and due to the large dimensions of the pre-mounted tower parts, which are difficult to transport by train) only truck transport is viable from tower manufacturing to installation site. For this stage, an energy consumption of 27 GJ is calculated. The same applies for the transportation of the disassembled tower to a steel recycling yard; also assuming a 130 km radius leading to an energy consumption of 27 GJ. In the **best scenario only 221 GJ in total are necessary for the entire transport of the 200 t steel** tower components. To illustrate the potential of improving the supply chain under energy efficiency aspects, it should be noted that this amount is **less than the 247 GJ** listed in Table 2 **for the transport** of a 660 kW wind turbine, requiring only **66 tons of steel**.

4.2 General optimization

Besides the argued potentials considering transport processes a variety of other optimization potentials can be identified over the life cycle of wind turbines. As mentioned before, the manufacturing phase itself is very energy intensive. Optimizing the processes that transform the components into wind turbines certainly has potential to save additional energy. Currently, steel is difficult to replace as the ideal material for wind turbines, but **material saving options**, like lattice or concrete towers should be considered. To solve the acceptance problems of lattice towers, General Electric developed the space frame tower – a lattice tower covered by a cladding. This tower type eases material needs and transport efforts. (General Electric, 2014) The introduction of **modular towers** with **smaller components** also shifts the location of value creation. The more components mounted and installed on-site, the lower the transport requirements and energy consumption, due to **smaller transportation metrics**. Finally the **manufacturing processes** itself should be further analyzed, especially because of their great impact on the total energy requirements.

At the end of the life of a wind turbine, the foundation normally remains in the ground covered by soil. A possibility to save energy is to **re-use** the foundation or to recycle the reinforced concrete. Moreover, it is essential to focus on the recycling process to improve the efficiency of material use and to save energy. Especially glass-reinforced plastic components like turbine blades should be considered for recycling. Currently the blades are shredded and thermally recycled. (Isenburg, 2015) New **recycling processes** need to be developed to allow re-use of these materials.

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