FAIRTURBINE

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Summary

Nowadays the wind energy industry is mature and wind energy is one of the main sustainable energy sources. This toghether with a societal demand, creates an increased interest in end-of-life solutions and circulatity in wind turbine design.

The current study is inspired by the Dutch smart phone company FAIRPHONE. They design and manufacture a smart phone with longevity, circularity, fair materials and good working conditions in mind. The aim of the current project is to investigate how these principles can be included into the design of a FAIRTURBINE.

In the wind energy industry the main design drivers have been the levelized cost of energy (LCoE) and technical reliability. Beside that, for a FAIRTURBINE the material (resource) selection is based on effective resource use, by slowing down and closing resource loops. Furthermore, the resource choices during mining, manufacturing and product life should lower the environmental impact and reduce the social impact. In the current project, it is investigated how this can be included into the design. At the moment hands-on criteria are not available. As fair design criteria the following qualitative and quantitative tools are used:

- The circularity R-level;
- An environmental Life Cycle Assessment (LCA);
- A social impact assessment either by reports, a social LCA or in case of a OEM, inspection of the suppliers.

The defined fair design criteria are applied for two wind turbine components, the tower and the drive train. The composite blade is left out on purpose since already many projects are ongoing on end-of-life solutions for wind turbine blades.

For a representative 15 MW wind turbine an environmental LCA showed that steel is the material with the largest impact. From a circularity perspective steel is recyclable with the R-level Recycle. In the past composite has been studied as an alternative for a steel tower. Based on a decrease in R-level to Recover for composite material, this is not recommended.

Modern offshore wind turbines are equipped with permanent magnet synchronous generators (PMSG) in a direct drive as well as a medium speed drive train. These generators are known for their use of rare earth elements. The social impact, based on a social LCA with the PSILCA database, and the circularity of the two different drive train designs are compared. Within the limitation of the permanent magnet generator, the medium speed drive train with magnets produced in Japan can be rated as the most fair drive train. Using a direct drive permanent magnet generator and replacing it by a medium speed drive train, will increase circularity to R-level Reduce.

The study shows, that ’fair’ design criteria result in a different design. Since it takes into account the public interest more broadly than costs alone.

The project is funded by the TNO Knowledge Innovation Program.

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1 Introduction

In the wind energy industry the main design drivers have been costs and energy production as expressed in the levelized cost of energy (LCoE) and technical reliability. Nowadays the wind energy industry is mature and wind energy is one of the main sustainable energy sources. This toghether with a societal demand, creates an increased interest in end-of-life solutions and circulatity in wind turbine design.

The current study is inspired by the Dutch smart phone company FAIRPHONE. They design and manufacture a smart phone with longevity, circularity, fair materials and good working conditions in mind. The aim of the current project is to investigate how these principles can be included into the design of a FAIRTURBINE.

Before the FAIRTURBINE can be designed, criteria need to be formulated first to evaluate the different wind turbine designs. At the moment hands-on criteria are not available. Next an environmental LCA is performed on a representative 15 MW wind turbine. The defined fair design criteria are applied for two wind turbine components: the tower and the drive train. The composite blade is not considered on purpose, since already many projects are ongoing on end-of-life solutions for wind turbine blades.

The project is funded by the TNO Knowledge Innovation Program.

2 Fair design criteria

Traditionally in wind turbine design based on economics and reliability. Economics is expressed in a competitive levelized cost of energy (LCoE) based upon reliable technology, where longevity is expressed in future design life time of 30 to 35 years, where it is currently 20 years. The LCoE can be assessed using cost model, while the technical design is based on recognized standards and certifying bodies like DNV.

When thinking about the design of a fair wind turbine one realises that there is no definition is available, let alone design criteria to assess the fairness. This lack of hands-on design criteria is also observed in circular design by Sumter [1] when interviewing designers.

It was decided to take the FAIRPHONE as starting point. The design of their smart phone is based on longevity, circularity, fair materials and good working conditions [2]. To formulate it more generally, "fair" aspects in the design are about circularity, environmental and social impact. Where social impact covers the following topics:

- Labour rights and decent work;
- Health and safety;
- Cultural and natural heritage;
- Anti competitive behaviour;
- Enterprise corruption and bribery;
- Public sector corruption;
- Social responsibility along the supply chain;
- Socio-economic sustainability.

For a FAIRTURBINE the material (resource) selection is based on effective resource use, by slowing and closing resource loops. Furthermore, the resource choices during mining, manufacturing and product life should lower the environmental impact and reduce the social impact. To assess the fair design criteria the following qualitative and quantitative tools are proposed:

- The circularity R-level as in Figure 2.1;
- An environmental Life Cycle Assessment (LCA), Chapter 3;
- A social impact assessment either by reports, a social LCA or in case of a OEM, inspection of the suppliers.

The design process for the FAIRTURBINE could now look like as follows:

- Define the minimum Circularity R-level as part of the technical specification. In our opinion R8, recycling, should be the minimum.
- Produce a technically and economically sound basic design, using experience in a fair selection of the material.
- Perform an environmental LCA and assess the social impact.
- Focus in the design on improvement of the materials and components, having the highest environmental and social impact.
- Be ambitious and try to have the highest circularity level in the design.

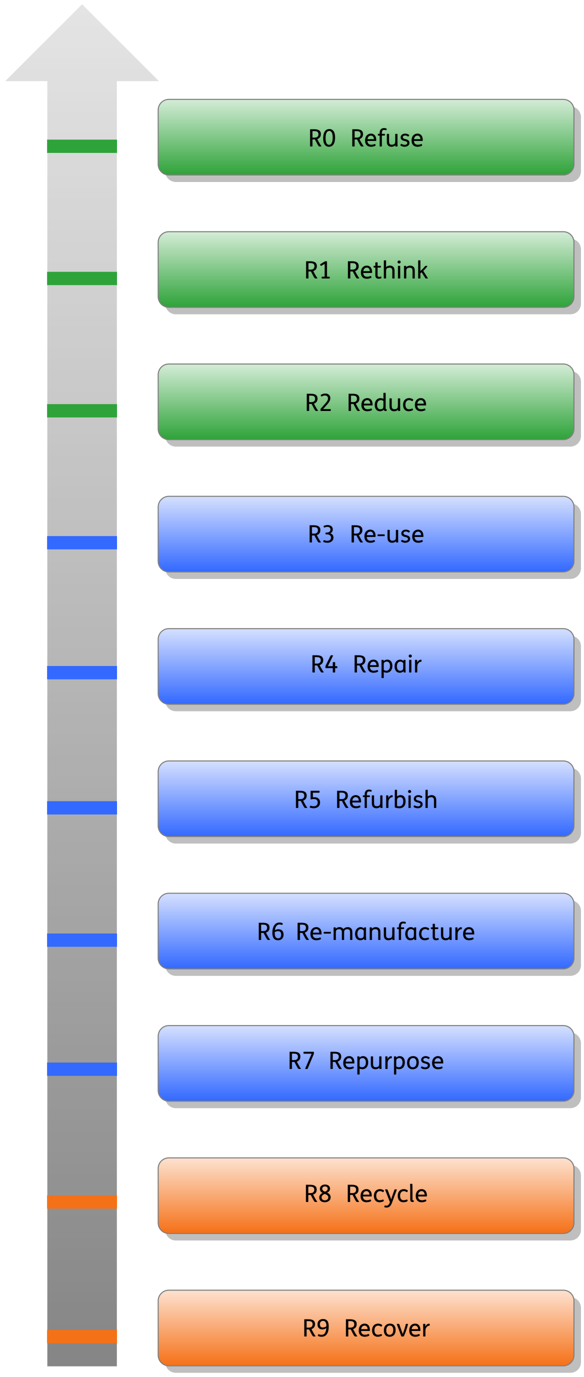

Figure 2.1: Circularity R-level from PBL report [3]. From linear to a circular economy.

An early example of evaluating different wind turbine blade designs both economically and environmentally is the Dutch BLADECO project [4]. The LCoE and LCA points are used for the assessment of the different blade concepts.

3 Assessing environmental impact

Wind turbines offer significant environmental benefits, however, it is essential to acknowledge that their production involves the use of various materials, some of which have a high environmental impact. Understanding and addressing the environmental footprint of wind turbine materials is crucial to ensure a truly sustainable future. To this aim, a component-specific study on a 15MW reference turbine is performed in order to quantify the environmental impact. In our analysis, only the material extraction and manufacturing phase will be covered for the LCA study using SimaPro.

3.1 LCA using SimaPro

This study is performed as a conventional process-based LCA, which is the recommended method for calculating carbon footprints and embodied energy. For this purpose, the SimaPro 9.1 software is employed with background data sourced from the Ecoinvent database v3.6.

3.2 Goal and scope

The goal of the present study is to perform a cradle-to-gate Life Cycle Assessment study for the reference 15MW wind turbine generator (WTG). During the analysis, we will include:

- The environmental impact & local content of the production and construction of WTG components;
- The environmental impact of electricity and water utilization;
- The environmental impact of logistics/transportation.

3.3 Reference turbine

A reference wind turbine must leap ahead of the present generation of industry wind turbines to be relevant today and in the next years, but not so far that aggressive technological developments are required. As a result, a reference wind turbine above 10 MW but less than 20 MW is required that follows the same growth trajectory as the GE Haliade-X and employs a similar drivetrain architecture and specific power. To this aim, IEA Wind 15 MW reference wind turbine [5] will be used as the reference turbine. In this study, scaling is performed (scale up from a reference 10 MW to 15 MW) considering the materials used, design adaptation and manufacturing considerations.

3.4 Life cycle inventory

Data were collected for different components of WTG. Detailed accounts of all items included in the inventory are given in Figure 3.1 below, with the supporting datacards used in the SimaPro tool. The sources of the Life Cycle Inventory (LCI) is scientific articles, material experts, engineers, etc., and externally from suppliers and operators.

Datacards	Amount	Units
Foundation 15MW		
Materials/fuels		
Steel, unalloyed {GLO}| market for | Cut-off, U	1318000	kg
Metal working, average for steel product manufacturing {GLO}| market for | Cut-off, U	1318000	kg
Aluminium, wrought alloy {GLO}| market for | Cut-off, U	9341	kg
Lead {GLO}| market for | Cut-off, U	10	kg
Copper-rich materials {GLO}| copper, anode to generic market for copper-rich materials | Cut-off, U	271	kg
Titanium {GLO}| market for titanium | Cut-off, U	50	kg
Epoxy resin, liquid {RER}| market for epoxy resin, liquid | Cut-off, U	1759	kg
Electricity/heat		
Heat, district or industrial, natural gas {Europe without Switzerland}| heat production, natural gas, at industrial furnace low-NOx >100kW | Cut-off, U	100937	MJ
Tap water {Europe without Switzerland}| market for | Cut-off, U	165491	kg
Electricity, high voltage {NL}| market for | Cut-off, U	202253	kWh
Transport, freight, inland waterways, barge {RER}| market for transport, freight, inland waterways, barge | Cut-off, U	23000	tkm
Tower 15MW		
Materials/fuels		
Steel, unalloyed {GLO}| market for | Cut-off, U	860000	kg
Metal working, average for steel product manufacturing {GLO}| market for | Cut-off, U	860000	kg
Aluminium, wrought alloy {GLO}| market for | Cut-off, U	3054	kg
Copper-rich materials {GLO}| copper, anode to generic market for copper-rich materials | Cut-off, U	375	kg
Welding, arc, steel {GLO}| market for | Cut-off, U	77	m
Titanium {GLO}| market for titanium | Cut-off, U	50	kg
Polyurethane, flexible foam {RER}| market for polyurethane, flexible foam | Cut-off, S	5278	kg
Electricity/heat		
Electricity, high voltage {DK}| market for | Cut-off, U	112000	kWh
Heat, district or industrial, natural gas {Europe without Switzerland}| heat production, natural gas, at industrial furnace low-NOx >100kW | Cut-off, U	364000	MJ
Transport, freight, lorry, unspecified {RER}| market for transport, freight, lorry, unspecified | Cut-off, U	79200	tkm
Nacelle and hub 15MW		
Materials/fuels		
Aluminium, wrought alloy {GLO}| market for | Cut-off, U	172	kg
Steel, unalloyed {GLO}| market for | Cut-off, U	258000	kg
Metal working, average for steel product manufacturing {GLO}| market for | Cut-off, S	258000	kg
Acrylonitrile-butadiene-styrene copolymer {GLO}| market for | Cut-off, U	18	kg
Cast iron {GLO}| market for | Cut-off, U	444000	kg
Polyvinylchloride, bulk polymerised {GLO}| market for | Cut-off, U	546	kg
Epoxy resin, liquid {RER}| market for epoxy resin, liquid | Cut-off, U	8100	kg
Glass fibre {GLO}| market for | Cut-off, U	18750	kg
Synthetic rubber {GLO}| market for | Cut-off, U	1840	kg
Polyethylene, high density, granulate {Europe without Switzerland}| polyethylene, high density, granulate, recycled to generic market for high density PE	4252	kg
Nylon 6-6 {RER}| market for nylon 6-6 | Cut-off, U	10	kg
Polycarbonate {GLO}| market for | Cut-off, U	4	kg
Polyethylene terephthalate, granulate, amorphous {GLO}| market for | Cut-off, U	63	kg
Lubricating oil {RER}| market for lubricating oil | Cut-off, U	500	kg
Neodymium oxide {GLO}| market for | Cut-off, U	12244	kg
Boric oxide {GLO}| market for | Cut-off, U	513	kg
Dysprosium oxide {GLO}| market for dysprosium oxide | Cut-off, U	440	kg
Steel, chromium steel 18/8 {GLO}| market for | Cut-off, U	54000	kg
Bark {Europe without Switzerland}| sawing, softwood | Cut-off, U	3000	kg
Copper-rich materials {GLO}| copper, anode to generic market for copper-rich materials | Cut-off, U	24000	kg
Cast iron {GLO}| market for | Cut-off, U	25238	kg
Ferroniobium, 66% Nb {GLO}| market for ferroniobium, 66% Nb | Cut-off, U	392	kg
Electricity/heat		
Heat, district or industrial, natural gas {Europe without Switzerland}| heat production, natural gas, at industrial furnace low-NOx >100kW | Cut-off, U	63212	kWh
Electricity, high voltage {DK}| market for | Cut-off, U	50067	MJ
Blades 15MW		
Materials/fuels		
Glass fibre {GLO}| market for | Cut-off, U	12543	kg
Epoxy resin, liquid {RER}| market for epoxy resin, liquid | Cut-off, U	13992	kg
Polyvinylchloride, bulk polymerised {GLO}| market for | Cut-off, U	2979	kg
Aluminium, wrought alloy {GLO}| market for | Cut-off, U	580	kg
Synthetic rubber {GLO}| market for | Cut-off, U	14	kg
Nylon 6-6 {RER}| market for nylon 6-6 | Cut-off, U	8	kg
Steel, unalloyed {GLO}| market for | Cut-off, U	2000	kg
Forging, steel {GLO}| market for | Cut-off, U	2000	kg
Metal working, average for steel product manufacturing {GLO}| market for | Cut-off, U	2000	kg
Cast iron {GLO}| market for | Cut-off, U	21600	kg
Wire drawing, copper {RER}| processing | Cut-off, U	500	kg
Carbon fibre reinforced plastic, injection moulded {GLO}| market for carbon fibre reinforced plastic, injection moulded | Cut-off, U	7463	kg
Copper-rich materials {GLO}| copper, anode to generic market for copper-rich materials | Cut-off, U	500	kg
Epoxy resin, liquid {RoW}| market for epoxy resin, liquid | Cut-off, U	700	kg
Glass fibre {GLO}| market for | Cut-off, U	19028	kg
Polyurethane adhesive {GLO}| market for polyurethane adhesive | Cut-off, U	54	kg
Polyethylene terephthalate, granulate, amorphous {Europe without Switzerland}| polyethylene terephthalate, granulate, amorphous, recycled to generic	6068	kg
Polymer foaming {RER}| processing | Cut-off, U	6068	kg
Polyurethane, flexible foam {RER}| market for polyurethane, flexible foam | Cut-off, U	162	kg

Figure 3.1: Detailed accounts of all items included in the inventory.

3.5 Results

LCA results were used to identify hotspots in two dimensions: across the entire WTG product stage and within each component stage to the maximum resolution level according to the available data. The impact assessment was done using ReCiPe methodology, where the emissions are related to their damages to different areas, broadly classified into: ecosystems quality, human health and natural resources.

In this study, the unit used for expressing the environmental impact is Pt (Points). This unit is a single point score, which involves the multiplication of the normalized results of the different impact categories with a weighting factor that expresses the relative importance of each impact category.

The LCA results show in Figure 3.2, on a component level, that the contribution of the nacelle and hub is largest in Pt. In view of the environmental impact of materials it is steel and metal, see Figure 3.3.

The environmental impact of the material for the different components is given in the following figures:

- Foundation, Figure 3.4;
- Tower, Figure 3.5;
- Nacelle and hub, Figure 3.6;
- Blade, Figure 3.7.

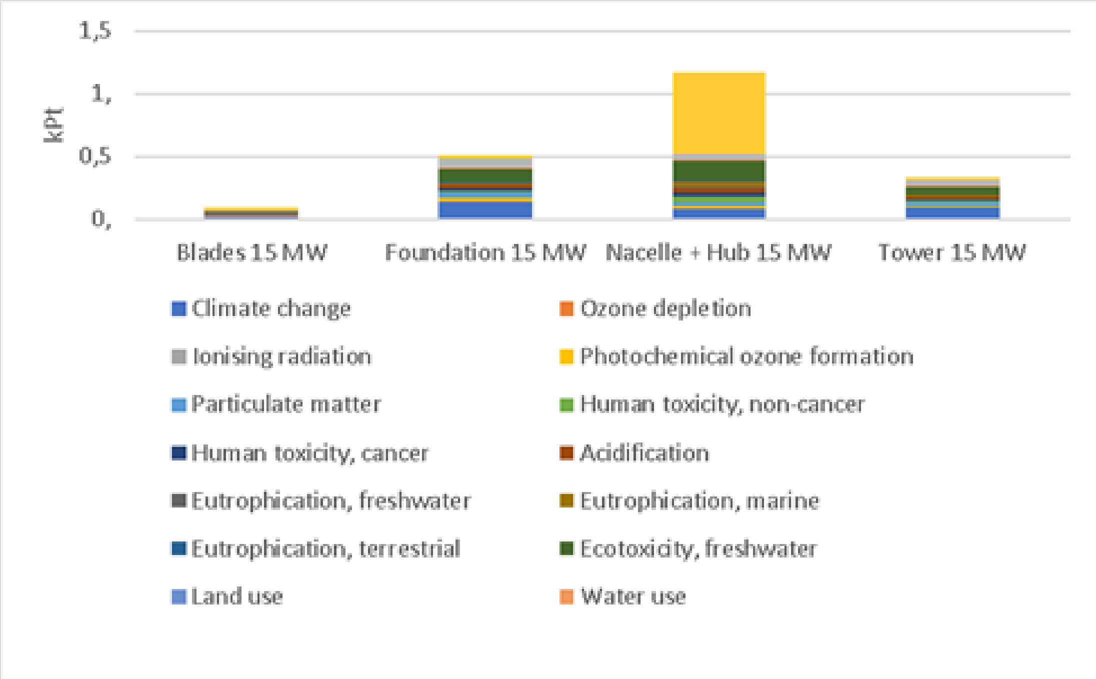

Figure 3.2: Environmental impact in Pt for the different wind turbine components.

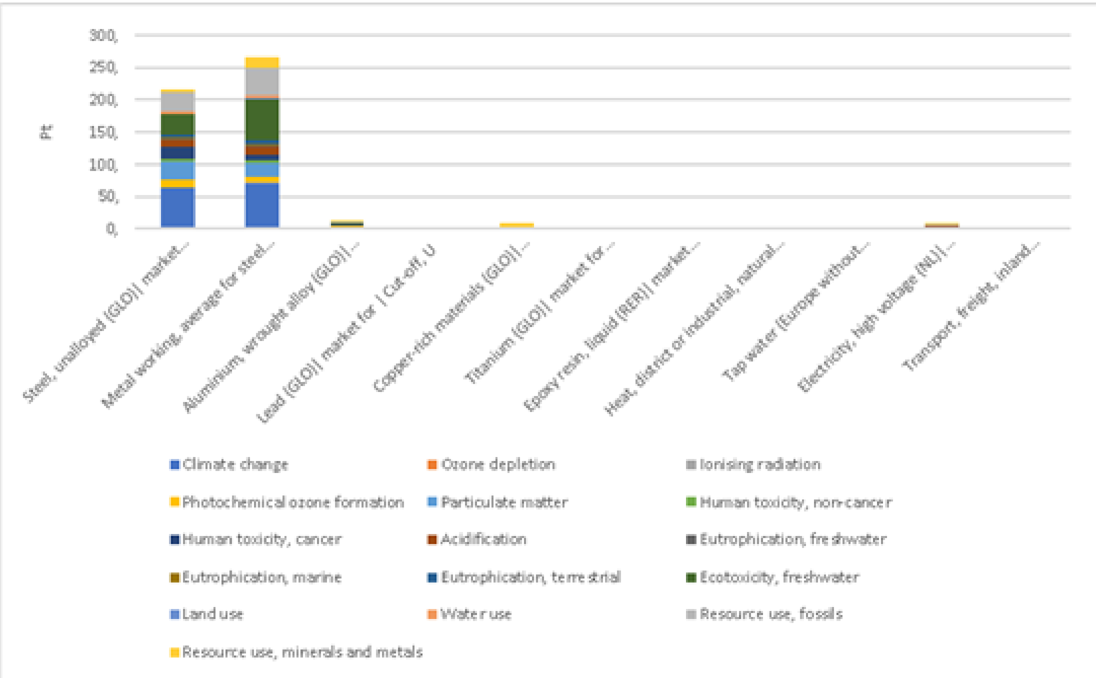

Figure 3.3: Environmental impact in Pt for the different materials.

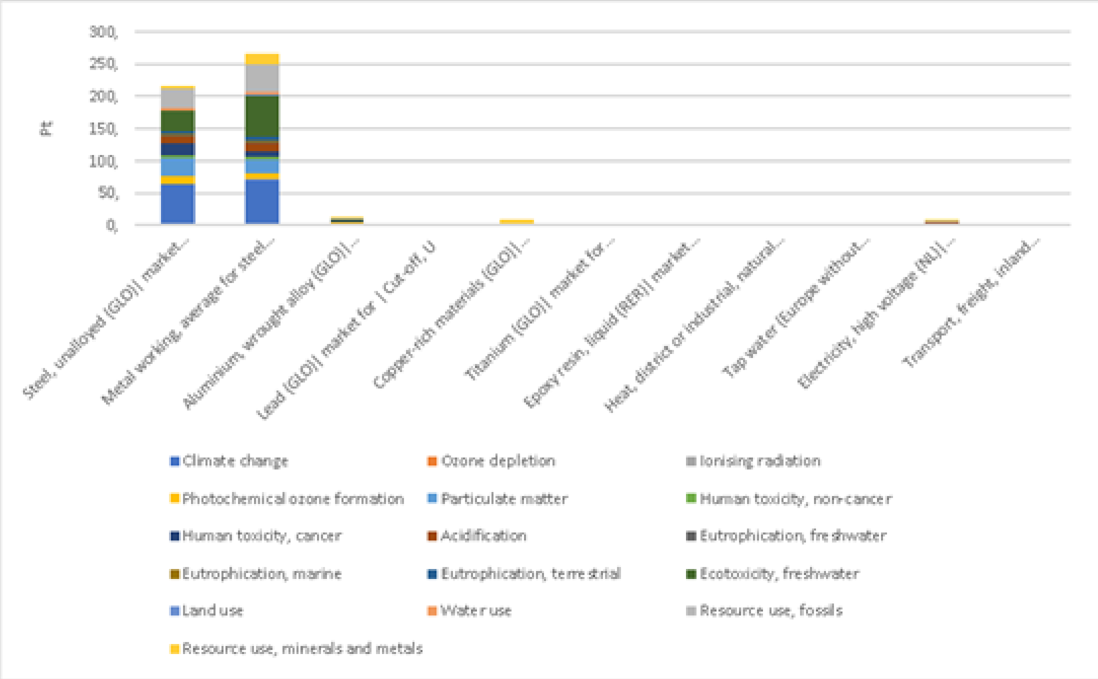

Figure 3.4: Environmental impact in Pt for foundation.

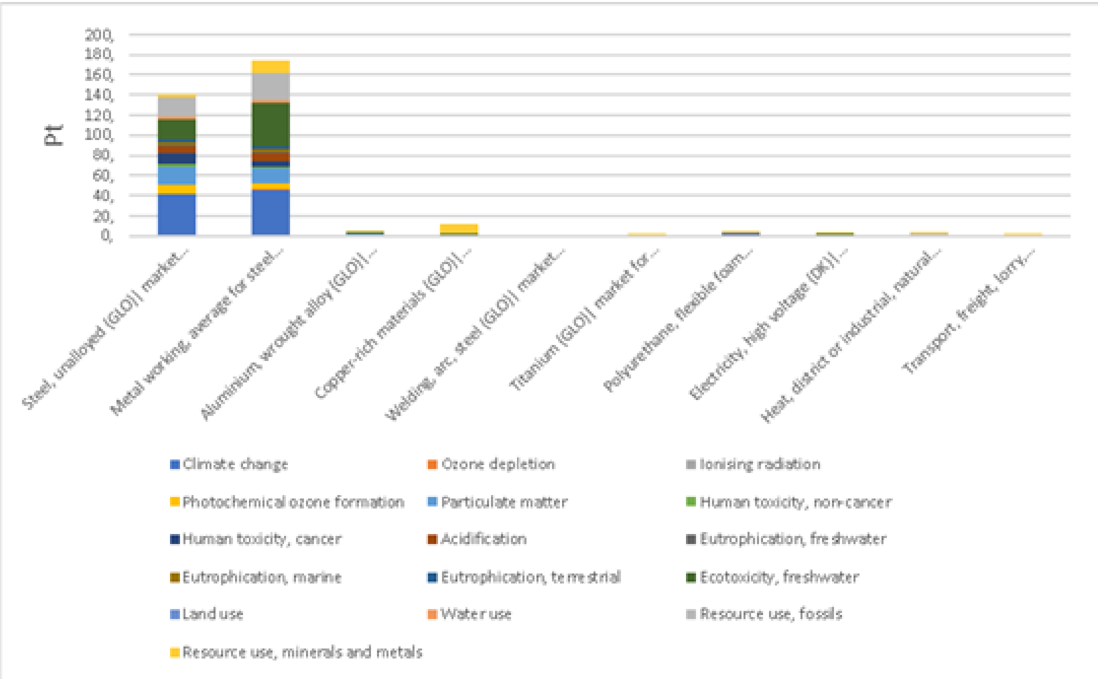

Figure 3.5: Environmental impact in Pt for tower.

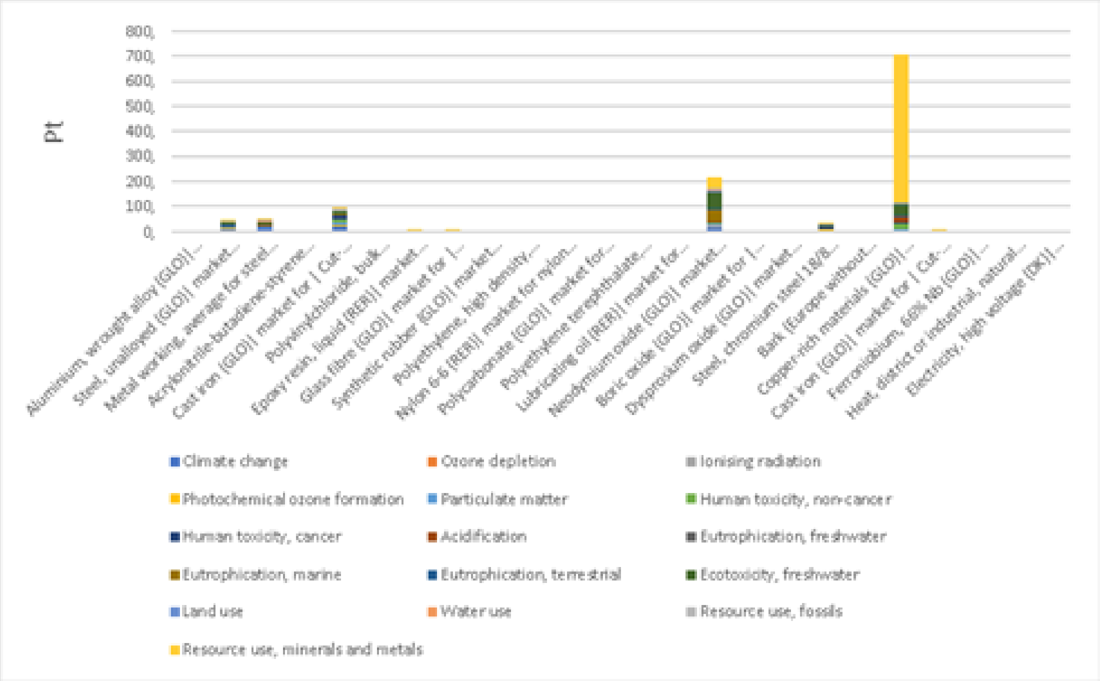

Figure 3.6: Environmental impact in Pt for nacelle and hub.

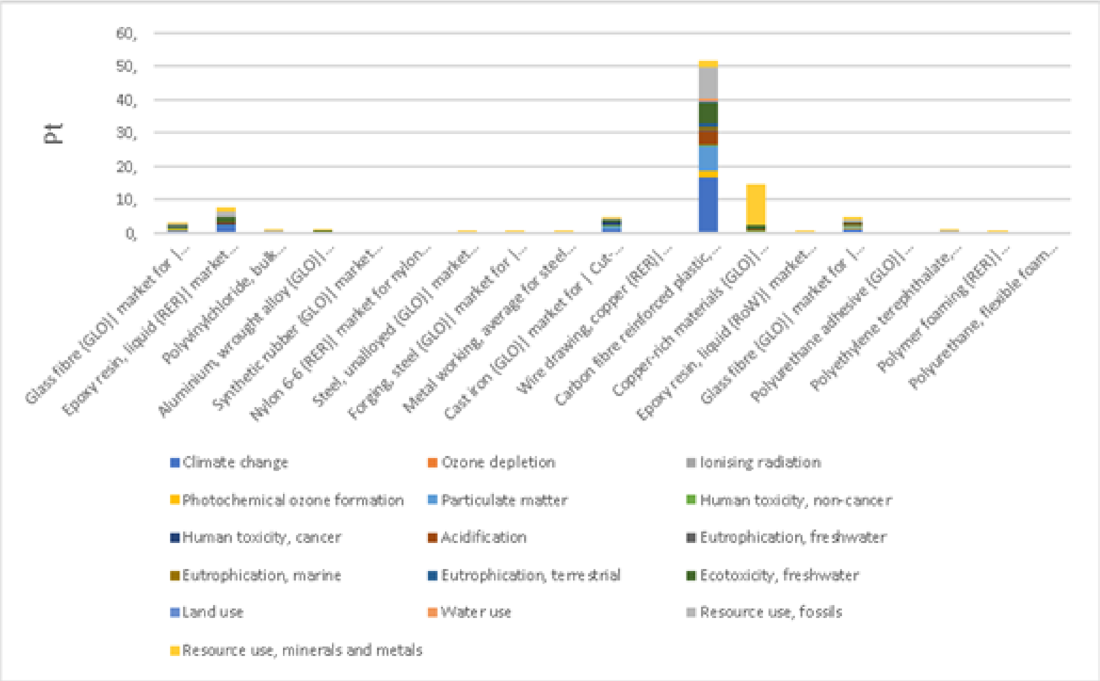

Figure 3.7: Environmental impact in Pt for blade.

4 Changes to the turbine

4.1 General

Since this project is a first step towards a FAIRTURBINE, not all wind turbine components will be subject to the current study. Goal of this chapter is to apply the criteria on circularity, environment and social acceptance in design. In the previous Chapter 3 an environmental LCA was applied for a 15 MW wind turbine. The environmental LCA can be used as a sieve for design concepts applying alternative materials or to identify the materials with the highest impact. Here the interaction with circularity and social acceptance is also investigated. How well do the fair criteria work in design?

It was decided to focus on two wind turbine components, the tower and the generator, for two reasons. First the tower is selected because steel is a dominant material according to the environmnental LCA analysis and as such a good example to apply the defined fair design criteria. Secondly, the Permanent Magnet Synchronous Generator (PMSG) is selected, because of its use or rare earth elements Neodymium, Praseodymium, Dysprosium. These materials are of the strategic importance for the energy transition. Beside that is the PMSG is relevant from a social acceptance point of view. Since the end-of-life of blades are already a topic of research in for instance the EU-project Eolo-HUBs [6], blades are excluded.

4.2 Tower

A wind turbine tower consists for more than 98% out of steel and as such, has good credentials from a recycling point of view. An alternative might be “green” aluminium. However, here the composite IDL-tower will be discussed since for this tower a TNO report [7] with an environmental LCA analysis is available. The composite tower is made of glass fibre and polyester resin. Note the report is about a 10 MW machine. For the tower only circularity and the environmental impact are considered. The social impact is excluded.

In the LCA analysis both composite tower + foundation and steel tower + foundation are considered. According to the report the reduction in mass by the composite tower directly results in a reduction in mass of the foundation by 33%, decreasing the environmental impact of the composite tower case. See Table 4.1.

Table 4.1: Tower and foundation masses for IDL-tower and steel case [7]

	IDL-tower	Steel case
Tower [mT]	320	790
Transition piece [mT]	162	251
Monopile [mT]	788	1186

This is important because the report states in case of towers only, “ *The (probable) waste incineration scenario adds several environmental impacts, e.g., in the categories climate change and human health, which are relatively large, 25-30% impacts of the materials and manufacturing stage of the composite tower. The steel tower on the other hand has a low impact recycling scenario at the end-of-life*”. From a circularity point of view steel is on R8 recycling level, while composite is on R9 recovery level. In this case steel tower is preferred as most circular.

Unfortunately there is no public information found that verifies the material reduction in foundation. It should be noted that a significant reduction of material in the foundation can also be realized by selection a jacket instead of a monopile as the Mangrove report [8] shows.

4.3 Generator

Modern offshore wind turbines are equipped with permanent magnet synchronous generators (PMSG) in a direct drive or medium speed drive train. These generators are known for their use of rare earth elements. In case of a wind turbine generator Neodymium, Dysprosium, Praseodymium and Terbium. In their study "Wind turbine technology battles: Gearbox versus direct drive" Van de Kaa et. al. [9] concluded, that the cost of energy and reliability are the most important determinants for technology success and that both technologies still have an equal chance of achieving success. In case of the generator, circularity and social impact is discussed.

In the JRC report [10] the role of rare earth elements in wind energy is discussed. With an increasing demand of rare earth elements it is important for Europe to secure access to raw materials. At this moment there is a high global awareness off the dependency on China. As a result mines in Australia, Canada and the United States are (re)opened. However the separation and refining of the rare earth oxides is almost entirely done in China.

Figure 3.3 shows that, for an 15MW offshore wind turbine, the environmental impact of rare earth materials in the LCA is relatively small. Nevertheless, in general mining has an impact on the environment and the health and safety of workers and local communities. Dependent on the power of governments and legal institutions corruption and tax avoidance occurs. An example of the adverse impact of mining is given in Box 2 of the report [11].

Box 2: Concrete examples of adverse impacts caused by the mining of minerals used in wind turbines.

Neodymium: China – Large-scale water and air pollution

The sourcing of one of the most important minerals for generators – the neodymium in the permanent magnet – takes place in China. China produces 90 per cent of the world's rare earth neodymium. However, in the city of Baotou(North China), a humanitarian disaster is taking place.

In order to extract neodymium, it is mixed with uranium and thorium. These radioactive elements, along with a slew of other toxic chemicals, get dumped into the local environment after use. In fact, for every tonne of neodymium produced, it has been reported that between 340,000 and 420,000 cubic feet of poisonous gases are produced along with 2,600 cubic feet of acidic water and one tonne of radioactive waste. A pool of more than 120 km^2 full of toxic mud and waste has appeared. As a result, groundwater in the area is radioactive, the air contains high concentrations of toxic substances, and plants, animals and people have become ill and died. In the meantime, poisonous water from the lake is slowly mixing with water of one of China's main waterways, the Yellow River.

In the paper by Werker et. al. [12] a social LCA is applied based on the Product Social Impact Life Cycle Assessment (PSILCA) database, version 2.0. PSILCA provides four impact categories to analyze the stakeholder group of value chain actors:

- Anti-competitive behavior or violation of anti-trust and monopoly legislation,
- Active involvement of enterprises in corruption and bribery,
- Public sector corruption,
- Social responsibility along the supply chain.

In the study by Werker et. al. [12] three different rare earth mining locations were selected.

- Mountain Pass in the USA;
- Mount Weld in Australia;
- Bayon Obo in China.

In all three cases the electrolysis takes place in China, while the magnet production is done in Japan, Malaysia and China for Mountain Pass, Mount Weld and Bayon Obo respectively.

Finally from a social impact point of view, permanent magnets produced in Japan and using Mount Pass ore are preferred based on a social LCA. Mount Weld and Bayon Obo show comparable results. The social LCA is a relatively new approach and still under development. One important issue is the difficulty to obtain reliable data on corruption and bribery. In case of no data available, this is rated as a low risk in the social LCA. This may lead to an underestimation of the risk of corruption and bribery in countries.

Having discussed the geopolitical impact and the mining, the focus will now be more on the permanent magnet generator itself. Siemens Gamesa applies the direct drive permanent magnet, Vestas a medium speed geared drivetrain. On their website, Materials and Rare Earths [13], Vestas claims that a geared drive train uses about 10 times less rare earth elements than a direct drive. This is supported by the paper of Moghadam and Nejad [14], that describes three optimized analytical 15 MW drivetrain designs, a direct drive, a medium speed geared drive and a high speed geared drive. The optimized direct drive generator has 11 ton permanent magnets and a drive train efficiency of 96%, while the medium speed generator has 1 ton on permanent magnets and a drive train efficiency of 97%. The mass of the permanent magnets confirms the statement by Vestas.

Looking purely at the permanent magnets from a circularity point of view, they are hardly to recycle and are not reused. So it the rating is between R9 and R8. In the article by Jin [15] magnet-to-magnet recycling is discussed as a new promising end of life technology. The advantage of the technology is twofold. First it reuses all the magnet materials in new magnets. Secondly a mechanical process rather than chemical one is applied, reducing the environmental footprint. In the master thesis by De Waal [16] recycling of permanent magnets in offshore wind turbines is studied. Since the recycling of Waste Electronic and Electric equipment is more mature and because of similarities this recycling route is followed. In the study it was observed that the disassembly of permanent magnets at wind turbine scale is challenging, because of weight and the brittle material. For an efficient disassembly the permanent magnets need to be demagnetized thermally and locally. In the thesis a concept is developed for this.

Within the limitation of the permanent magnet generator, the medium speed drive train with magnets produced in Japan can be rated as the most fair drive train. Using a direct drive permanent magnet generator, like Siemens Gamessa, and replacing it by a medium speed drive train, would increase circularity to R2 level.

5 Conclusions

In the wind energy industry the main design drivers have been costs and energy production as expressed in the levelized cost of energy (LCoE) and technical reliability. For a FAIRTURBINE the material (resource) selection is based on effective resource use, by slowing and closing resource loops. Furthermore, the resource choices during mining, manufacturing and product life should lower the environmental impact and reduce the social impact. In the current project, it is investigated how this can be included into the design of a FAIRTURBINE. As fair design criteria the following qualitative and quantitative tools are proposed:

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The study shows, that ’fair’ design criteria result in a different design. Since it takes into account the public interest more broadly than costs alone.

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