Aalborg University

Waste Management of End-of-Service Wind Turbines

Spyridoula Karavida, Reet Nõmmik

Siemens Wind Power

Aalborg University

Title

Waste Management of End-of-Service Wind Turbines

Aalborg University

Department of Development and Planning

Environmental Management and Sustainability Science

Thesis period

01/02/2015 – 03/06/2015

Thesis group

Spyridoula Karavida

Reet Nõmmik

Supervisors

Arne Remmen

Jonas Pagh Jensen

Copies: 3
Pages: 63
Appendices: 2
Pages of Appendices: 10

Abstract

Resource scarcity led to the use of more sustainable energy sources like wind energy. Wind energy is clean and renewable with no greenhouse emissions. However, a major problem related to this energy is waste derived from wind turbines that have reached their end-of-service lives. This thesis looks into the different materials that wind turbines are composed of, and suggests comprehensive solutions and concrete recycling guidelines in order to tackle the issue of waste management. This is substantiated by analysing secondary data from the existing literature and primary data from interviews and questionnaires, and using reliable theoretical concepts like circular economy and industrial symbiosis. Based on those principles, two detailed recycling guidelines have been created suggesting waste handling solutions of the cables and electrical and electronic equipment included in the wind turbines.

Acknowledgements

We would like to thank the following persons who were of great help in the whole period of this research.

First and foremost we would like to thank our supervisors, Arne Remmen and Jonas Pagh Jensen for their valuable help, constructive comments and guidance during our research.

We would also like to thank Pia Christoffersen, Tine Herreborg Jørgensen and Morten Sørrensen for their in-depth knowledge that they shared with us during the interviews.

Table of Contents

List of Figures

List of Tables

Reading Guide

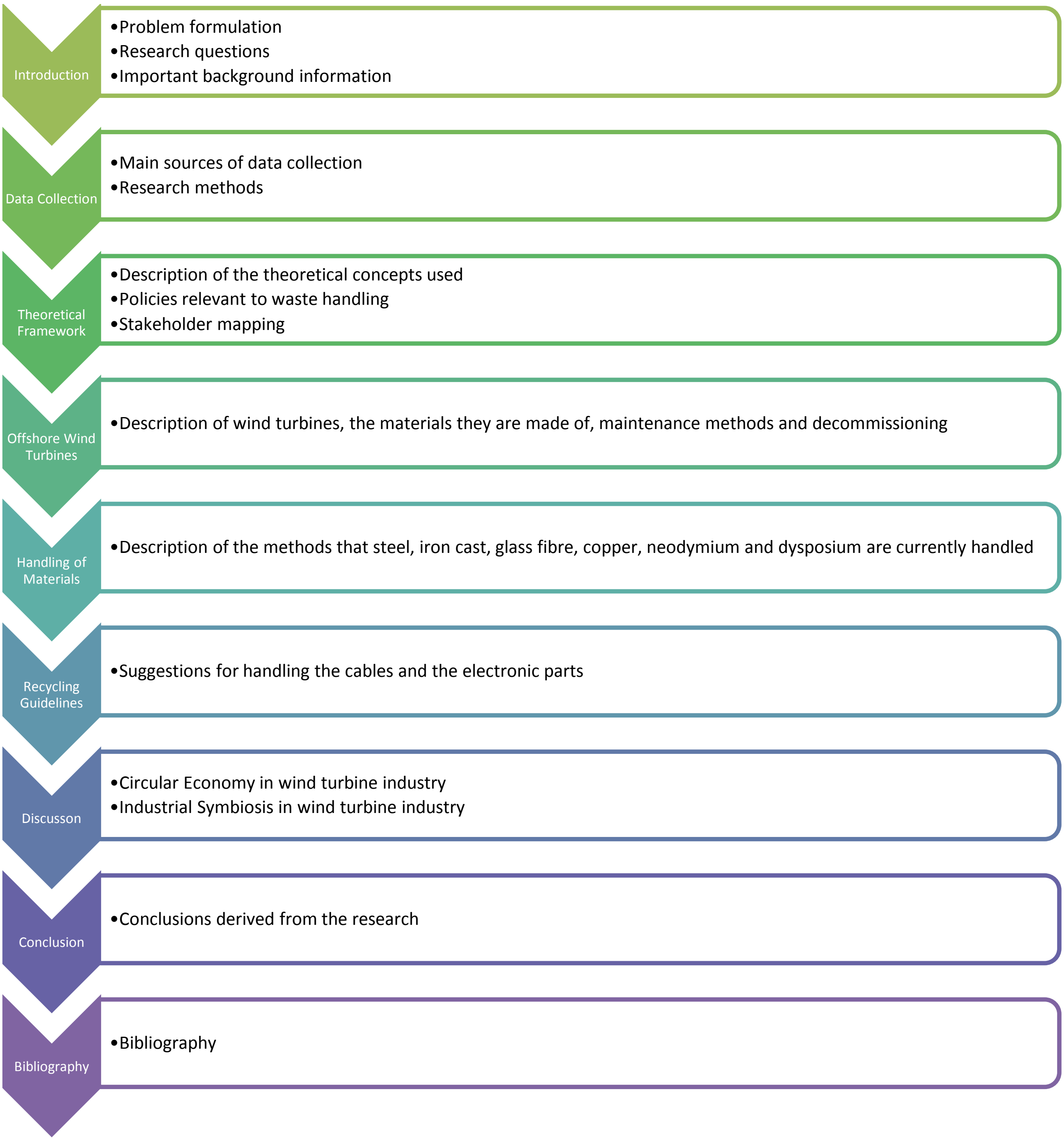
This thesis should be read as followed:

1. Chapters: referred in the text like: *1, 2, 3…*

2. Sections: referred in the text like: *1.1, 1.2…*

3. Paragraphs: referred in the text like: *1.1.1, 1.1.2…*

A general description of the chapters and their content is illustrated and described below.



In Chapter 1 an introduction acquaints the reader with the topic of the thesis and important background information are given. Namely issues like wind energy, resource scarcity and waste management are explained and the research questions are posed.

In Chapter 2 the research methods used in the thesis are described and the main sources of data collection are analysed.

In Chapter 3, the theoretical concepts used in order to substantiate this thesis are defined. Principles of Circular Economy and Industrial Symbiosis are described and illustrated in section 3.1 and 3.2. Furthermore, policies and legislations that have been considered relevant are given in section 3.3. In section 3.4 a broad stakeholder mapping is presented.

In Chapter 4 a general description of wind turbines' technical attributes is given in section 4.1. In Addition, the materials wind turbines contain are presented in section 4.2. Maintenance methods and decommissioning are described in section 4.3 and 4.4.

In Chapter 5 a detailed description of the materials included in a wind turbine is given, elaborating in the findings of chapter 4. Furthermore environmental benefits and important economic aspects from the current handling methods are defined.

In Chapter 6 the main product of this thesis is given, that is the concrete guidelines to handle cables and electronic waste of wind turbines that have reached their end-of-service life. All the previous chapters are combined in order to form the recycling guidelines.

In Chapter 7 the link between the theoretical part and the product of the research is explained. Namely the connection between chapter 3 and chapter 6 is presented.

In Chapter 8 the conclusions derived from the research are defined.

In Chapter 9 bibliography of the sources utilised in the document is given.

In the start of each chapter an illustration explains the main issues that will be analysed in the chapter. In the end another illustration summarises the findings of the respective chapter.

References

The Harvard Style is used for the references in this report, e.g. the references in the text follow this style: (Author, Year).

1. From Resource Scarcity to Wind Turbines and Waste Management Issues

This thesis looks into the wind turbine industry with the focus on end-of-life phase and material handling. In order to get a better understanding on the topic the first chapter gives an introduction to the formulated problem and explains what is being investigated.

1.1 Resource scarcity

The human population is constantly growing. With that, the consumption and need for resources increases as well. At the same time resources are not divided evenly around the globe, some countries have more than others and in some cases they are also difficult to access. Uneven distribution of resources and different financial possibilities to afford them are a potential source of conflict. In addition resources are often extracted in a non-sustainable way in developing countries and used in developed countries. This increases the inequality even more and can cause a situation where some areas get all the disadvantages like pollution from extraction and production plus exploiting the resources and other countries get all of the benefits like products with lower labour costs and can avoid pollution. When some specific resources are concentrated in a certain location the chances for a monopoly get high. One party will obtain a lot of power to decide on the prices and availability of a resource. Resource scarcity is connected with both the outcome of overusing the natural resources we have and dealing with the issues related to resource distribution.

Using renewable energy is one way to deal with the growing need for electricity and simultaneously ease the use of some finite resources like fossil fuels. At the same time resources and materials are required to build structures that produce renewable energy. For example wind turbines necessitate amongst other materials steel, fibreglass, iron, copper, and rare earth elements in the magnets. The size of the turbines and the amount of wind farms is growing with every year, meaning that more resources to build them are needed as well. In order to deal with resource scarcity the least wasteful solutions are the best – both for production and waste handling. When manufacturing wind turbines materials should be used in a sustainable way and after a turbine reaches its end-of-life it should not be wasted through disposal but reused and recycled as much as possible to help reduce the need for virgin materials and waste quantities.

1.2 Wind energy

Renewable energy can be produced by sources like wind, solar, hydro, geothermal, and tidal and biomass. When using more renewable sources for energy needs the dependence on fossil fuels decreases and energy production is made more sustainable since greenhouse gas emissions are avoided. The EU's renewable energy directive sets a target by 2020 that 20% of final energy consumption has to come from renewable sources (European Commission, n.d.). In the EU the biggest share of renewable sources comes from biomass and waste, followed by hydro and then wind energy. Though wind energy is not the number one source for renewable energy so far, it has been the fastest growing, with more than a fivefold increase between 2002 and 2012 (Eurostat, n.d.). In the EU a total of 128.8 GW is installed now (The European Wind Energy Association, 2015).

Wind power is clean, renewable energy source with no emissions of greenhouse gases. It is produced with the use of wind turbines which are equipped with blades moved by the wind. They spin a shaft, which connects to a generator and produces energy; i.e. wind turbines convert the kinetic energy from the wind into mechanical power that can be converted into electric energy with the use of a generator.

Usually, wind energy is produced in wind farms or parks that consist of a group of wind turbines in the same location. There are two kinds of wind farms; offshore and onshore. The first is located in bodies of water while the latter is found on the land. Offshore wind turbines take advantage of the high speed winds generated in the water, however they are more expensive than the onshore ones because they have higher installation and maintenance costs. The world's first wind farm was created in 1980 and was installed in southern New Hampshire, US and the first off-shore wind farm was created in 1991 in Vindeby, Denmark (The Guardian, 2008). In 2012 there were more than 225,000 wind turbines around the world located in 80 countries (Global Wind Energy Council, 2012).

1.3 Waste management

Traditionally a linear consumption model has been in use. It means that a product is manufactured, used and disposed after it has served its purpose or is no longer needed. European Commission statistics claim that currently in Europe 16 tonnes of materials per person per year are used and 6 tonnes of that becomes waste. Although waste management continuously improves in the EU, a significant amount of secondary raw materials, like metals, glass and plastics still get lost from the material stream due to faulty waste management (European Commission, n.d.). In order to make resource use more sustainable disposal should be replaced with other waste handling methods as much as possible. Consumer behaviour has to be changed, to make people reconsider their actions and come up with innovative solutions for product development, reuse and recycling. With improved waste management health and environmental issues can be reduced. The key is to move from the old linear consumption model towards a circular one, which aims to take measures in order to reduce landfilling and get as much out of resources as possible by keeping them in circulation.

1.4 Problem formulation

With the increasing human population and consumption more energy is required. Renewable energy sources are gaining popularity due to environmental regulations and interest in sustainable solutions. As a result wind farms are a growing industry – both in quantity and quality. In order to keep up with the fast technological development in this field a number of resources and materials, including steel, cast iron, glass fibre and copper are required. It is important to keep in mind that some natural resources are finite and measures have to be taken to avoid overexploitation and negative impacts on the environment deriving from extraction activities.

Once a turbine is manufactured its lifespan is around 20 – 30 years, after that they usually get either repowered or decommissioned. When the old turbine is no longer usable as much materials as possible should be salvaged in order to minimize the waste quantities. Parts made out of steel or valuable metals are relatively easy to recycle and economically beneficial as well. Other parts, like the blades made out of fibreglass composite are more challenging to handle. The reason for finding other solutions instead of disposal lies both in reducing waste quantities and minimizing the need for virgin materials. So far adequate researches regarding the management of the wind turbine parts for their end-service life is lacking. The aim of this research is to investigate the ways for their optimal handling in order to succeed in both environmental and economic level.

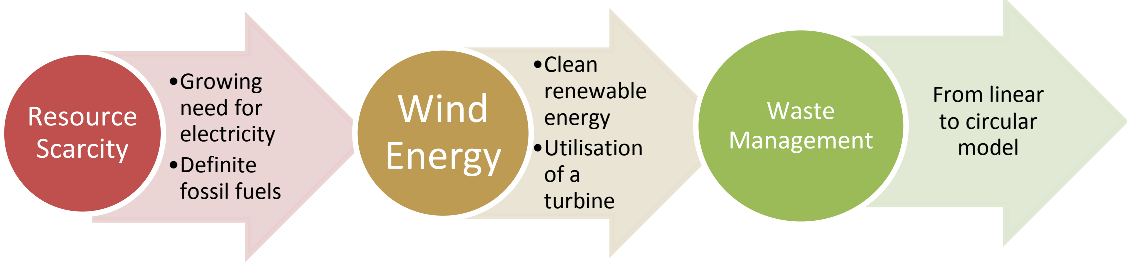
The focus of this report is on offshore wind turbines due to their higher maintenance and installation costs, bigger turbine sizes and challenges with accessing and dismantling. In addition offshore wind has a lot of potential in helping Europe to reach their renewable energy targets, thus becoming a field with growing interest (Global Wind Energy Council, n.d.).

1.5 Research Questions

How are the end-of-service wind turbines managed today and how could it be improved?

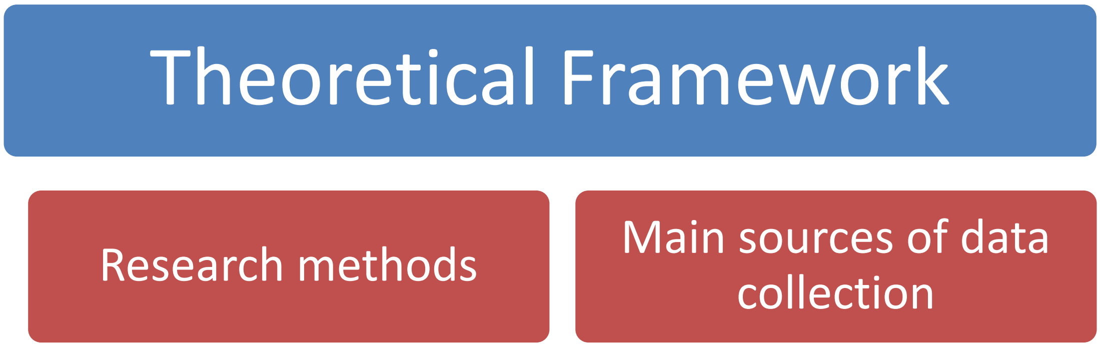
1. How are the materials in end-of-service wind turbines handled today?
2. How could material loops be closed for sustainable resource use?
3. How to communicate waste management related information between stakeholders?

Summary of Chapter 1



2. Data Collection

In this chapter the research methods used in the thesis are described and the main sources of data collection are analysed.



In order to ensure that the research questions will be answered in the optimal way, different research methods have been utilised; both qualitative and quantitative. As illustrated in Figure 1 below, in order to collect the most useful available data, a thorough literature review, two interviews and a questionnaire have been conducted.

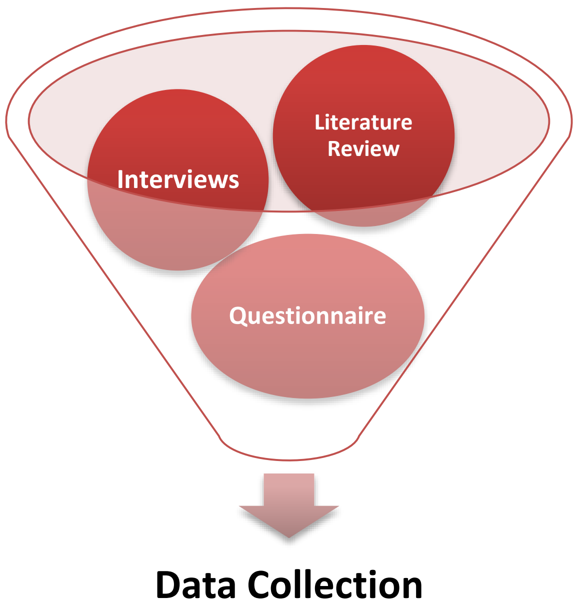


Figure 1: Data collection methods

2.1 Research methods

In general there are two types of research methods – quantitative and qualitative. "*Qualitative research is mostly used to gain an understanding of underlying reasons, opinions, and motivations*." (Wyse, 2011). The data collection measures are often focus groups, interviews, surveys and observation. Quantitative research at the same time aims to "*quantify the problem by way of generating numerical data or data that can be transformed into useable statistics.*" (Wyse, 2011). Measurable and numerical data is most often used; it is collected by measuring, or similarly to qualitative research through surveys and interviews (Wyse, 2011).

For this thesis both qualitative and quantitative data and approaches were used. For original data collection qualitative methods like interviews were used. Quantitative data collecting measures were mostly done by previous researchers who have published their work and statistical results, which were used with references in this paper.

The interviews conducted for this research were qualitative with the aim to gather insights on how wind turbine related waste issues are considered and handled by two different wind turbine manufacturers. In addition a short questionnaire was conducted with a representative from a recycling company to get a broader understanding of the topic.

Quantitative data, required for this report, was provided by Siemens Wind Power. They shared numerical data about their turbine composition and parts that are under electrical and electronic equipment. In addition statistical results from studies done by others were used to give an overview on the financial benefits and environmental impacts deriving from recycling different materials that are found in wind turbines.

2.2 Literature Review

The first step in order to have a better understanding of the topic of a research is a literature review. Literature review is *"The selection of available documents (both published and unpublished) on the topic, which contain information, ideas, data and evidence written from a particular standpoint to fulfill certain aims or express certain views on the nature of the topic and how it is to be investigated, and the effective evaluation of these documents in relation to the research design proposed"* (Hart, 1998).

In order to substantiate this thesis, a thorough literature review has been conducted. In this way a significant amount of secondary data was gathered. "*Secondary data research is considered as another researcher's obtained information, which is available for further re-analyses by others; such data supports intentions for different objectives*" (Smith, 2008).

The main sources of secondary data in this research were scientific articles, research books, official web-pages, regulations, official documents and statistical data. The internet was one of sources of data acquired from the literature review. Although internet sources are not always valid, our research is considered to be reliable since only web-pages and scientific articles have been utilised. Statistical data and regulations have been acquired strictly from web-pages.

2.3 Interviews

There are different types of interviews that can vary from unstructured to highly structured interviews. The type of the interview depends on how much control the interviewer will have over the conversation. For the purposes of our research we have conducted both types of interviews. Below definitions for the different kinds of interviews are provided.

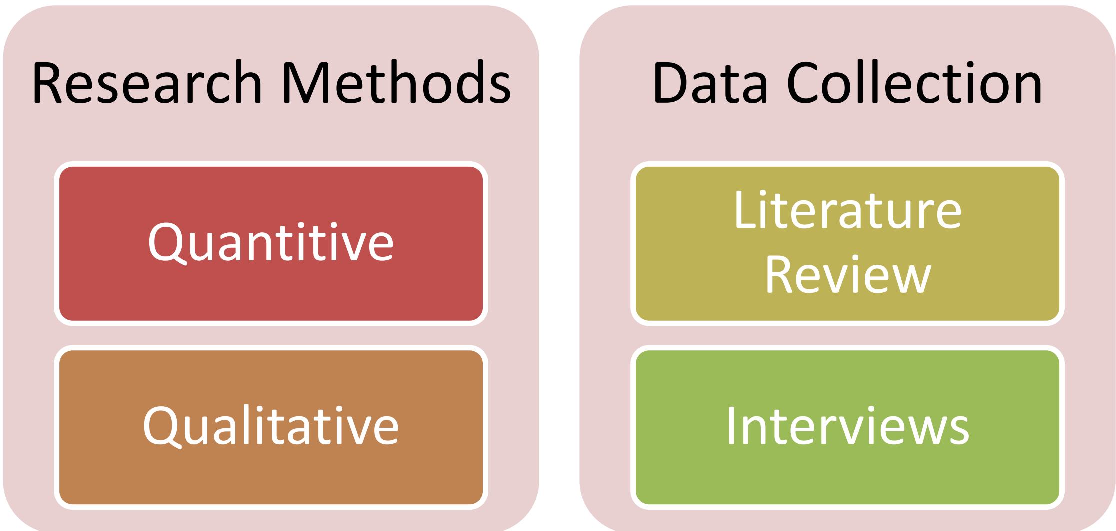
In semi-structured interviews, there is an interview guide that is followed including questions and topics that have to be discussed. It resembles to a conversation with the difference that there is a general direction in the discussion. It is used when the researcher wants to investigate thoroughly the topic and to understand deeply the answers that the interviewee provides (Harrell & Bradley, 2009).

In structured interviews, there are very specific questions that are asked and they follow a strict order and they resemble to a survey. Structured interviews have the advantage that their results can be generalized to a large population. However, they have the disadvantage that the interviewer is very limited in explaining the interviewees the questions that they do not understand. (Harrell & Bradley, 2009)

Two interviews and one questionnaire have been conducted with important stakeholders like wind turbine manufacturers and recycling companies. The aim of the two interviews was to get a better perspective on what challenges big wind turbine manufacturers, namely Vestas and Siemens, face. In addition we wanted to acquire a better understanding of current methods of material handling and clarify circular economy and industrial symbiosis potential. The questionnaire, in the recycling company, was aiming to investigate how materials that wind turbines contain are handled.

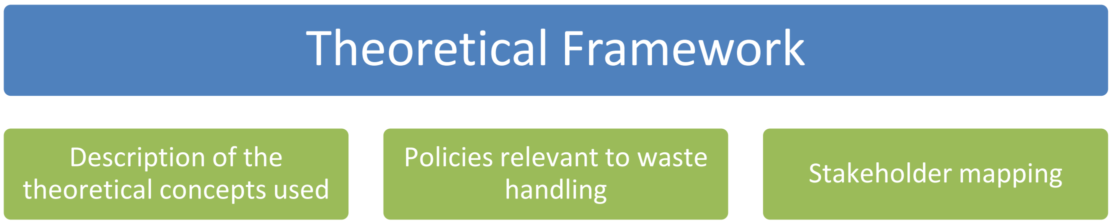
In the process of arranging and conducting the interviews several obstacles appeared. First of all geographical proximity was an issue. The interviewee from Vestas was situated in another city we couldn't visit. This problem was solved using the internet to connect instead of a face-to-face meeting. Another problem was the language since all our interviewees are Danish. However as it was proved they were all fluent in English, fact that enabled the best understanding of the questions and answers.

Summary of Chapter 2



3. Theoretical Framework

In this chapter, the theoretical concepts used in order to substantiate this thesis are defined. Principles of Circular Economy and Industrial Symbiosis are described and illustrated in paragraph 3.1 and 3.2. Furthermore, policies and legislations that have been considered relevant are given in paragraph 3.3. In paragraph 3.4 a broad stakeholder mapping is presented.



3.1 Circular Economy

Current production follows the linear model according which goods are produced from raw materials, then sold to the consumers via a distribution system, used by them and then disposed as waste. It follows the rationale “take, make, dispose” without efforts to reuse or recycle. Linear system shows great value losses in agriculture, processing, distribution, use and end of life (Ellen MacArthur Foundation, 2013). According to the Ellen MacArthur Foundation, future growth is doubtful if the linear model will continue to be the dominant one. For that reason, the concept of circular economy is introduced.

According to the Ellen MacArthur Foundation, ‘the circular economy refers to an industrial economy that is:

1. *restorative by intention*
2. *aims to rely on renewable energy*
3. *minimises, tracks, and eliminates the use of toxic chemicals and*
4. *eradicates waste through careful design*

The term goes beyond the mechanics of production and consumption of goods and services in the areas that it seeks to redefine (examples include rebuilding capital, including social and natural, and the shift from consumer to user). The concept of the circular economy is grounded in the study of non-linear systems, particularly living ones.’ (Ellen MacArthur Foundation, 2013).

Circular economy aims to decrease our dependency on sourcing new materials and distinguishes between and separates technical and biological materials or ‘nutrients’ according to the ‘Cradle to Cradle’ concept by William McDonough and Michael Braungart. Both material circles follow an attentively designed material cycle that aim to disassembly and refurbishment-if it is technical material. Biological nutrients are getting compost in the biosphere, while technical materials are designed in order to be used infinitely (Ellen MacArthur Foundation, 2013).

The main principles of circular economy include the elimination of waste and careful design of the products, the differentiation of the consumable from the durable parts of a product, the replacement of the term consumer with that of user and the use of renewable energy. Elimination of waste is succeeding by disassembling or reusing. Methods like disposal of waste or recycling are considered energy and labour consuming. Durable parts of a product are designed in order to be used again or be upgraded. Consumable parts are made of organic, non-toxic material and they can safely be returned in the nature. The products will be leased, rented or be given to the users. In case they are sold, the user will be responsible for their return after their end-of-life. The energy used for this economy model is renewable (Ellen MacArthur Foundation, 2014).

The different phases of the circular economy are shown below in Figure 2. Namely, it all starts with the raw materials, then it comes the design, then the production and remanufacturing and after the distribution. Once distributed to the users the products are consummated, used, reused or repaired. Then they get collected and get recycled in raw materials again. The phases are intertwining each other, as materials can take part in the scheme in a cascading way (European Commisssion, 2014).

Figure 2: Main phases of circular economy model (European Commisssion, 2014)

According to the principles of the circular economy there are four ways to raise material productivity; the power of the inner circle, the power of circling longer, the power of cascaded use, and the power of pure circles. Namely:

- The power of the inner circle lies in the minimisation of the amounts of material used in circular economy-in comparison with the ones in linear economy- i.e. the fewer the materials, the less the reuse process and in result fewer costs and externalities.
- The power of circling longer is about the increase of the cycles-where cycles refer to reuse, repair or remanufacture-in order to avoid the extra costs of making a brand new product.
- The power of cascade use refers to the various possible use of a material through the value chain, before it is returned to the nature.
- The power of pure inputs refers to the use of clean, non-toxic materials in order to facilitate the collection and redistribution process and secure the endurance of the material (Ellen MacArthur Foundation, 2014).

The main principles on which the circular economy model is based are illustrated below in Figure 3. On the left side of the illustration the technical nutrients are shown while on the right side the biological nutrients are presented. The smaller circles indicate the optimal solutions and as they become bigger, less preferable solutions are indicated. Regarding the technical materials, recycle is the least preferable technology and then refurbishment and remanufacture follow, after that it comes the reuse of the product to conclude to the optimal solution, the maintenance. As far as it concerns the biological materials, the different processes include the biochemical extraction, -which can produce biomass and energy-, the anaerobic digestion, -which can produce biogas to be used for energy production- and composting-, where the material is disposed safely in the nature Landfill and energy recovery are the two solutions that have to be minimised in a circular economy model (Ellen MacArthur Foundation, 2013).

According to Ellen MacArthur Foundation, there are two types of material recycling; up-cycling and down-cycling. Down-cycling refers to the process of changing materials into new ones, which have less quality and not the same functionality. Up-cycling is the process of changing materials into new ones with better quality and higher functionality. In the middle of the illustration the down-cycling method is shown, where materials are transformed into energy or getting dumped in the landfills. In the sides the up-cycling method is illustrated, showing the materials getting restored either back in the biosphere or used infinitely by the users (Ellen MacArthur Foundation, 2013). However the up-cycling process has raised many controversies because it is difficult to make a better quality product from second hand materials.

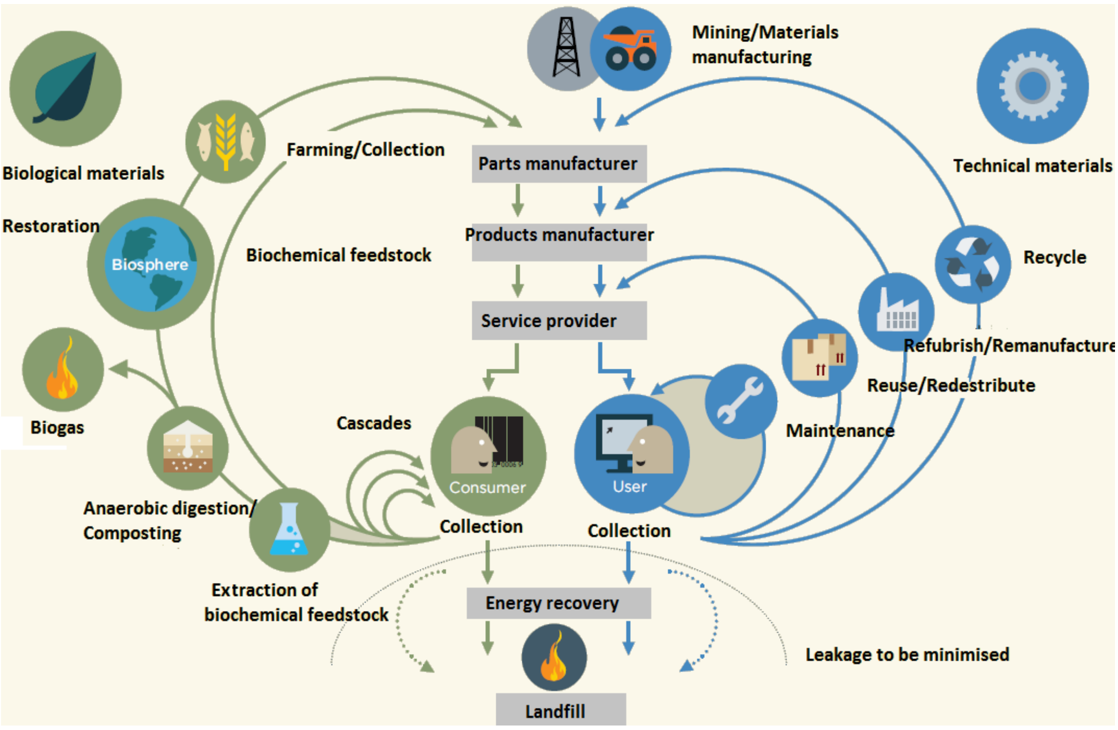


Figure 3: The Circular Economy principles (Ellen MacArthur Foundation, 2014)

Circular economy incurred critique, mainly because of the concept of eternal reuse that is not possible according to the second law of thermodynamics The Second Law essentially says that *'it is impossible to obtain a process where the unique effect is the* *subtraction of a positive heat from a reservoir and the production of a positive work. Energy exhibits entropy. It moves away from its source. In this sense, energy or heat cannot flow form a colder body to a hotter body. You cannot keep a continual flow of heat to work to heat to work without adding energy to the system. In machine terms, you have to add energy to get more work, and the ratio of heat to work will never equal 100% due to energy expanding away from its source.'* (Physics Planet, n.d.). Although the infinite reuse is not achievable, the main idea of circular economy is the use of materials for as long as possible.

3.2 Industrial Symbiosis

Circular economy is about closing material loops through maintenance, reuse and recycling with the aim to avoid waste incineration and-filling. In order to achieve this goal industrial symbiosis can be helpful by connecting companies or industries through resource exchange. These two concepts have a different approach but at the same time they support each other and help improve waste management.

'Industrial symbiosis is an association between two or more industrial facilities or companies in which the wastes or by-products of one become the raw materials for another.' (WRAP, 2014). It can help reduce raw material necessity and decrease the costs for waste handling. In addition it gives the involved companies a possibility to earn revenue from production by-products and residues. At the same time industrial symbiosis diverts waste from landfills and decreases carbon emissions. In general it opens up new opportunities for businesses and cooperation between existing industries (WRAP, 2014).

Industrial synergy is useful for all included parties and is mostly done for environmental and commercial reasons. Industrial symbiosis gives competitive advantage through collective approach. It is achieved by physical exchange of energy, water, materials or by-products, even by shared knowledge, expertise, assets, services and logistics (WRAP, 2014). When waste and by-products are reused in a systematic way, the need to extract raw materials decreases and the pressure on the environment is reduced (Costa & Ferrão, 2010). The economy is viewed as a closed system, where one's waste is someone else's 'food'. Industrial symbiosis tries to help businesses close material loops, with the objective to create industrial production systems that are similar to biological food chains in the way they function (Kapur & Graedel, 2004).

'Entrepreneurs can gain appreciable cost savings from reduced waste management, reduced infrastructure costs, and improved process and product efficiency. There are opportunities for other cooperative ventures such as joint purchasing, combined waste recovery and treatment, employee training, environmental monitoring and disaster response. The tangible environmental benefits include the reduction of greenhouse gas emissions and toxic air emissions, improving efficiency and conservation in the use of energy, materials and water, improving land use planning and green space development within the industrial complexes, and promotion of pollution prevention and recycling approaches.' (Kapur & Graedel, 2004).

The term 'Industrial Symbiosis' has been associated with Kalundborg in Denmark, illustrated on Figure 4, where different factories are gathered around an oil refinery and a combined heat and power plant. They use each other's waste energy and materials for their own production and processes (Energenz, n.d.). The arrows show the year when the collaboration was started and what resources go to whom. There are many different connections between industries through material or energy exchange. Some parties, like pig farms and cement industry, are in the system only as receivers by using the waste from other industries. Since industrial symbiosis is about using waste as a resource, all companies have to know, what is the composition of their waste and how it could be useful for someone else (Energenz, n.d.).

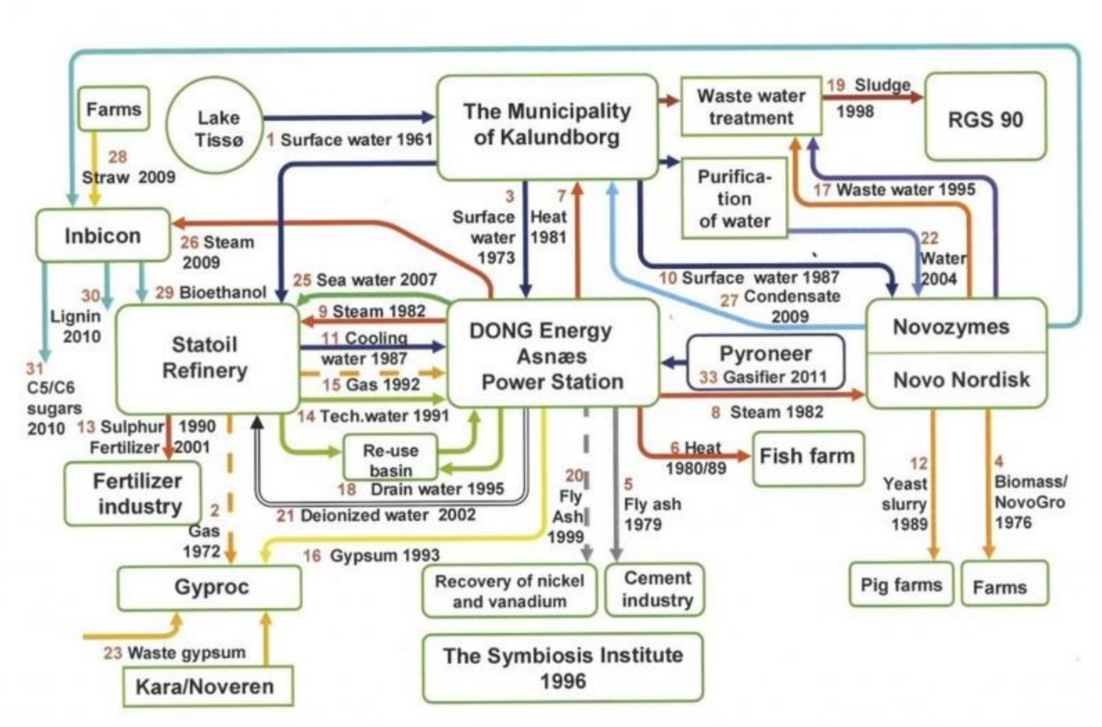


Figure 4: Industrial Symbiosis (Ellen MacArthur Foundation, n.d.)

Geographic proximity has been considered an essential part of industrial symbiosis, meaning that industries working together should also be located close. The reason derives most likely from Kalundborg which is considered one of the main role models for successful industrial symbiosis and there all the parties are quite close to each other. In addition due to the presumption that by-products have low value and should not be transported with high environmental or economic costs. However recent understanding is that geographical proximity might not play such an important role, it is dependent on the resource as well (Lombardi, et al., 2012). For example knowledge exchange is considered a part of industrial symbiosis and for that it is not that relevant where connected parties are located, or when organizing joint employee training. Geographical proximity can have an effect on whether industrial symbiosis between some companies or industries pays off, but it is always not the main case when working on developing new cooperation ways (Lombardi, et al., 2012).

Other important factors for successful industrial symbiosis are considered to be regulation flexibility, economic rationality and collaborative culture. This can again be illustrated with Kalundborg example, where a network of both formal and informal relations existed between the industries and regulatory authorities. In addition Danish waste legislation works on municipality level and is based on dialogues between actors. Lastly, Danish government has been active already from the ‘70s with regulations and economical instruments, like landfill tax, to prevent pollution, reduce emissions and move towards energy and resource efficiency (Costa & Ferrão, 2010).

3.3 Relevant Policies

Waste Framework Directive (Directive 2008/98/EC) sets general principles for waste management, including the waste management hierarchy (European Commission, n.d.), which is illustrated in Figure 5. The main priority is to reduce waste production, but if waste generation cannot be avoided the next step is to reuse materials as much as possible, if that is no longer viable, then next step is to recycle and make new products. Energy recovery from waste is considered to be the last option before land filling, which is the final measure to get rid of waste and should be avoided as much as possible.

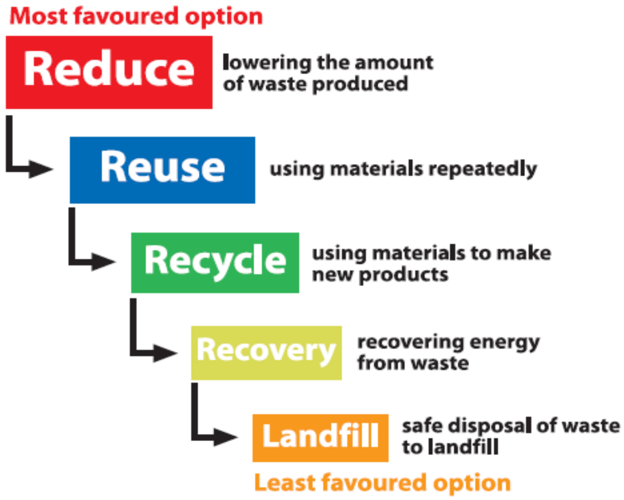


Figure 5: Waste management hierarchy (Ecoenergy Ventures, n.d.)

Waste Framework Directive is not directly regulating industrial symbiosis or circular economy, but they are connected nevertheless. The priority of waste management hierarchy is to reduce the generation of waste. With the help of industrial symbiosis and circular economy the chances to achieve it are higher. Industrial symbiosis sees waste from one industry as a resource for another industry, either through materials or energy, with the outcome of reducing land-filling and pollution. Circular economy aims to keep all materials in a circulation as long as possible, with that the need for virgin materials decreases and less waste is generated.

As mentioned previously, circular economy relies on the power of four circles which are minimizing the amount of used materials, circling longer, the power of cascaded use and using pure materials (Ellen MacArthur Foundation, 2014). All of these circles help to follow waste hierarchy set by Waste Framework Directive through waste reduction by closing material loops (see Figure 6). With keeping already used materials in a circulation the need for virgin materials decreases and with that also some waste is avoided. The idea behind recycling longer is that with maintenance, refurbishment and reuse, materials can be kept in the circulation longer and land-filling is avoided.

Cascaded use means, that a material can be used variously and for different purposes. For example, through recycling a material can lose quality but still be useful for something else and kept in the circulation instead of disposal. In order to make it easier to follow these circles, circular economy focuses on using pure non-toxic materials since this makes reuse and recycling both easier and cheaper. In general circular economy is in accordance with waste hierarchy because the outcome of it in broad is waste quantity reduction which is the main priority of the hierarchy. In addition they both promote reuse and recycling and work towards avoiding disposal.

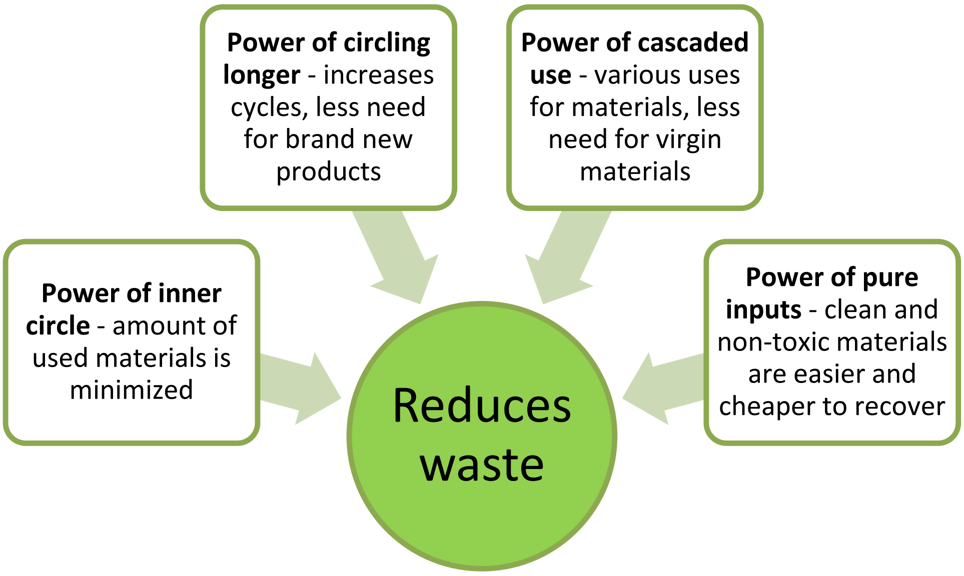


Figure 6: Power of four circles contributing to the highest priority of waste hierarchy

In addition the Roadmap for a Resource Efficient Europe recommends industrial symbiosis in order to improve how raw materials are reused and help companies work together to get the most out of their waste and by-products (European Commission, 2011). The strategy document 'Sustainable Industry: Going for Growth and Resource Efficiency' advocates industrial symbiosis as a policy instrument, citing Kalundborg as a practical example. Similarly, in 2010, the Organisation for Economic Cooperation and Development (OECD) recognized industrial symbiosis as 'a systemic innovation vital for green growth'. (Lombardi, et al., 2012).

Circular economy is an essential part of the resource efficiency agenda under the Europe 2020 Strategy for sustainable growth. The EU launched the Communication 'towards a circular economy: A zero waste programme for Europe' in order to promote the circular economy concept. However it is still underway and no specific regulations have been made (European Commisssion, 2014).

Neither circular economy nor industrial symbiosis is mandatory through laws or regulations. Nevertheless it is recognized by European Union that this can help with waste management and therefore should be taken into consideration in all types of production or industrial activities to minimize waste and get the most out of materials and by-products.

In addition to previously mentioned policies that are connected with industrial symbiosis and circular economy, there are also some more specific ones that regulate certain parts in a wind turbine. For example Directive 2012/19/EU which regulates the waste of electrical and electronic equipment (WEEE) and RoHS Directive 2002/95/EU that restricts the use of hazardous substances in electrical and electronic equipment. The WEEE directive aims to prevent waste, improve the management of WEEE, and contribute to circular economy and resource efficiency. For that it is necessary to improve the collection and treatment of end-of-life electronics in order to salvage reusable materials and safely handle hazardous substances (European Commission, 2015). The RoHS Directive restricts the use of hazardous substances in electrical and electronic equipment. The goal is to increase the reuse and recycling of electronics and require heavy metals like lead, mercury, cadmium, hexavalent chromium and flame retardants to be substituted with safer alternatives (European Commission, 2015). Both of these directives influence the handling of electrical and electronic parts of a wind turbine and contribute to more sustainable waste management.

3.4 Stakeholders mapping

In order to acquire the best understanding of the topic and be able to draw safe conclusions and make comprehensive suggestions it is useful to make a stakeholder mapping and analysis. This way it is possible to make the connections between the different driving forces, identify their interests and their grade of involvement. In addition useful interviewees were identified during this process. Stakeholder mapping is also essential in order to identify the potential parts that can use the recycling guidelines provided in Chapter 6.

The main stakeholders that have been identified include the manufacturers of wind turbines, owners of wind farms, and industries with similar interests, recycling companies, the government, municipalities and the European Union. Those stakeholders are grouped in three categories: business network, regulation network and knowledge network.

The business network includes:

- The manufactures that are one of the main stakeholders because they are able to control the amounts and types of materials they use. This way they can inform their clients about those facts and in consequence they facilitate the waste management of wind turbines. In addition, they can provide waste handling services to their clients, utilizing functioning parts of wind turbines that have reached their end-of-service life, designing for disassembly or by just having the material recycled in order to be used again in the production phase. The manufacturers can also put pressure on sub-suppliers by insisting that certain criteria have to be followed.
- The owners of wind farms are another critical stakeholder. They are the ones that have the obligation to handle properly the waste deriving from wind turbines and in consequence they are highly interested in the materials that the manufacturers use. They have the power to ask for easily handled materials and even create a market for waste management exclusively from wind turbines.
- Recycling companies are considered one of the drivers because they are possible buyers of materials deriving from wind turbines. However they are a part of the knowledge network described below.

The knowledge network includes:

- Industries with similar interests that are deemed to be one of the main stakeholders because based on the principles of industrial symbiosis and circular economy they have the potential to use materials deriving from old wind turbines and exchange important information and knowledge with the manufacturers and the owners of wind farms.
- Recycling companies are able to exchange valuable knowledge and expertise, in the basis of circular economy. Recycling companies can help to improve the efficiency of wind turbine industry by informing manufacturers about the difficulties they face with reusing or recycling their products. With this type of knowledge exchange it is possible to make changes in the design and manufacturing phase to maximize the material salvage potential.

The regulation network includes:

- The Government is the main institution that can imply legislations regarding the proper handling of wind turbine waste. This way all the other stakeholders will have a concrete motivation to actively make decisions regarding this waste and they will be 'forced' to take action.
- Municipalities are another important stakeholder because they have the power to motivate contacts between the different industries in their jurisdiction, coordinate events and bring together sectors in order to exchange knowledge, ideas and materials.
- The European Union has the power to publish directives and of course legislations that will dictate the proper handling of wind turbine waste. They can also invest on research related to the optimum handling of this waste.

In Figure 7 below the different stakeholders are illustrated in the three different group networks.

Figure 7: Stakeholders mapping

Summary of Chapter 3

Circular Economy

- is restorative by intention
- aims to rely on renewable energy
- minimises, tracks, and eliminates the use of toxic chemicals
- eradicates waste through careful design

Industrial Symbiosis

- association between two or more industrial facilities or companies in which the wastes or by-products of one become the raw materials for another

Relevant Policies

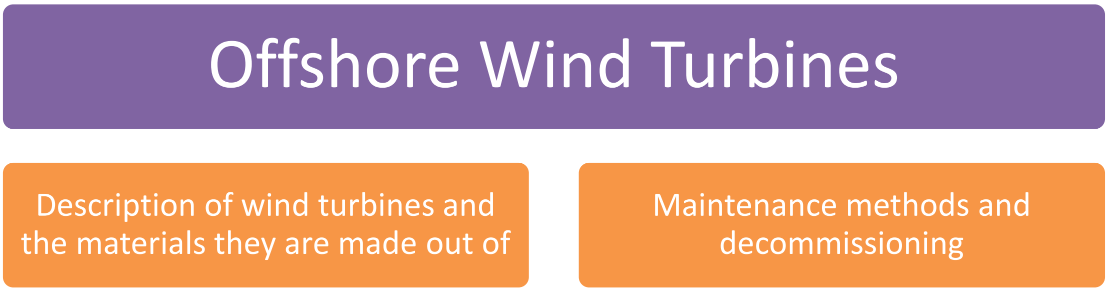
- Waste Framework Directive
- Europe 2020 Strategy
- Roadmap for a Resource Efficient Europe
- WEEE

Stakeholder Mapping

- Stakeholders from the Business Network
- Stakeholders from the Knowledge Network
- Stakeholders from the Regulation Network

4. Offshore Wind Turbines

In this chapter a general description of wind turbines' technical attributes is given in paragraph 4.1. In Addition, the materials wind turbines contain are presented in paragraph 4.2. Maintenance methods and decommissioning are described in paragraph 4.2 and 4.3.



Wind energy is clean and renewable and can help climate change tackling by reducing the need for fossil fuels. Offshore wind turbines are located in bodies of water – like oceans, lakes, fjords – in order to generate energy, taking advantage of the strong winds created offshore. The first offshore wind farm was established in Denmark in 1991 (Environmental and Energy Study Institute, 2010) including 11 turbines of 450 kW (Siemens AG, 2011). The offshore wind farms are a big challenge since higher capital is needed, the largest possible wind turbines are used, the risks are bigger and the access is a major issue (Wind Energy-The Facts, 2009). Below, in Figure 8, a picture of an offshore wind farm is portrayed.

Figure 8: The Offshore Wind Farm Horns Rev 2 in Denmark (The Telegraph, 2011)

For the installation of wind turbines, a support structure is needed; consisting of the foundation on which the turbine is standing and the system the foundation is connected to the seabed (4C Offshore, 2015). The procedure for the installation of wind turbines is demanding and begins with the transportation of the different parts to the site. Once the vessel arrives, firstly the tower is located onto the foundation. Then the nacelle is lifted and the rotor and blades are placed. The last step is the commissioning of the wind turbines. Some tests regarding their proper function are conducted and the wind turbines are ready. Manufacturing companies provide service and maintenance within the guarantee period or longer (Siemens AG, 2011). Leading companies in wind turbines manufacturing are Siemens Wind Power, Acciona, Alstom, DongFang, Enercon and Vestas Wind Systems (WindPower Monthly, n.d.). Siemens Wind Power is a leading company in the manufacturing of offshore wind turbines (Siemens AG, 2011).

An illustration of an offshore wind turbine installation is given below in Figure 9.

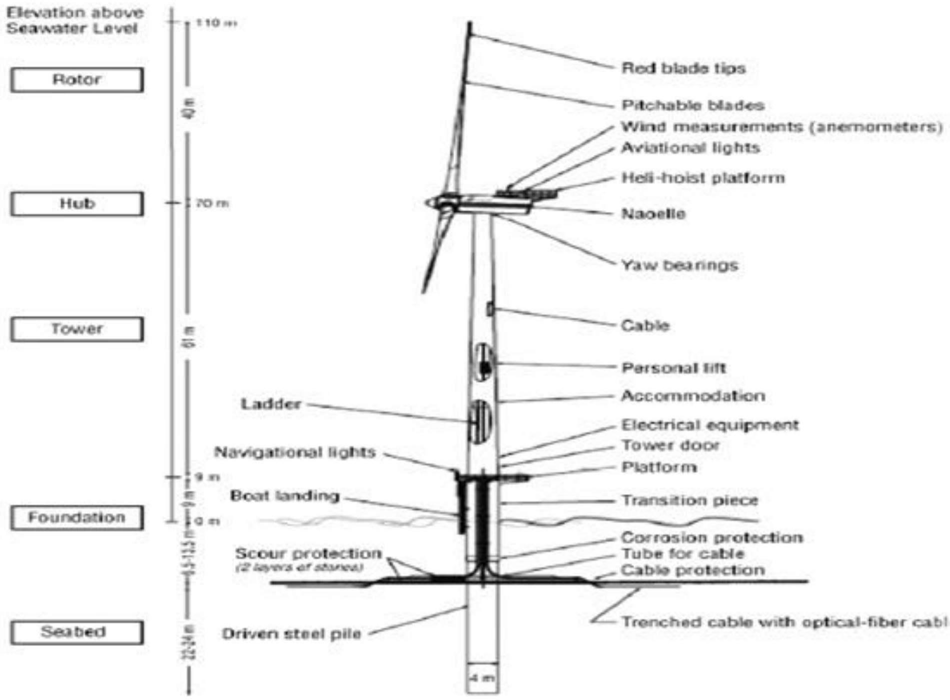


Figure 9: Main parts of an offshore wind turbine installation (OCS Renewable Energy EIS, n.d.)

4.1 Technical Description

The main parts of an off-shore wind turbine are the rotor, the blades, the rotor hub, the blade pitch system, the main shaft and bearing, the magnet or the gearbox, the generator, the mechanical brake and the yaw system (Siemens AG, 2011). One of the modes Siemens uses for offshore installations is the SWT-3.6-107 wind turbine (Siemens AG, 2011). A description of this model follows.

The rotor contains three blades in horizontal axis made of fibreglass-reinforced epoxy with aerodynamic design. It has the ability for pitch regulation with variable speed in order to generate the optimal power. The diameter of the rotor is 107 m and the rotor sweep is 9000 m^2. The blades have 52 m length and they have no openings in the joints, fact that constitutes them resistible to water and lightning. The rotor central part, the hub, is cast in nodular cast iron and has enough space for two technicians during repair and maintenance. The blade pitch system is activated when wind surpasses a certain speed and the blades are feathered for safety reasons. The gearbox is a three-stage spur planetary one and ensures low noise levels; it also includes fail-safe a mechanical brake. The yaw system is used to keep the rotor facing into the wind and to unwind the cables that are sprawled to the base of the tower. The generator converts mechanical energy to electrical energy; it is equipped with advanced ventilation systems. The tower of the turbine is a steel tube with a height of 80 m (Siemens AG, 2011).

The wind turbine functions automatically, starting its operation when the wind has a speed of 3-5 m/s. The rated power output is 3600 kW (Siemens AG, 2011).

The main parts of the SWT-3.6-107 wind turbine are illustrated below in Figure 10.

1)Spinner, 2)Spinner bracket, 3)Blade, 4)Pitch bearing, 5)Rotor hub, 6)Main bearing, 7)Main shaft, 8)Gearbox, 9)Service crane, 10) Brake disc, 11)Coupling, 12)Generator, 13)Yaw gear, 14)Tower, 15)Yaw ring, 16)Oil filter, 17)Generator fan,18)Canopy

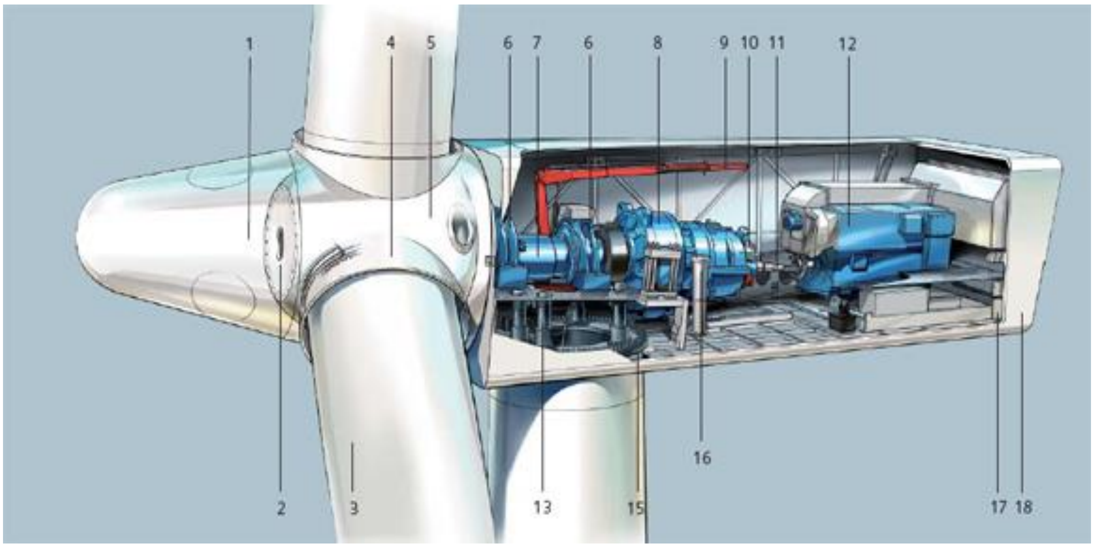


Figure 10: Wind turbine SWT-3.6-107 (Siemens AG, 2011)

4.2 Material

The main material used in a wind turbine is steel, since the biggest part, the tower, is made out of it (Windpower Engineering & Development, 2011). Nacelles are made out of glass fibre composites or steel and protect the components, that are enclosing, from the environment (Mishnaevsky, 2011).The blades are made out of laminated materials like balsa wood, epoxy, carbon fibre, and fibreglass (American Wind Energy Association, 2013).The main shaft is made out of iron cast and the cables consist of aluminium, copper and plastic (Newport Metal Recycling, n.d.). More specific description of the materials and their handling is reflected in the next chapter. The exact turbine material composition is shown in Appendix B, but due to confidentiality reasons the public version of this report does not include it.

4.3 Maintenance

It takes around five years to develop a new type of a wind turbine; in addition the planning of a large offshore wind farm can take 5 – 10 years and the usual design lifetime of a wind turbine is estimated to be 20 – 25 years. Taking all of these years into consideration means that all the design decisions made today will affect the decommissioning and recycling of wind turbine materials 30 – 40 years in the future (Andersen, et al., 2014). Due to that, maintenance, repair, potential re-use and recycling scenarios have to be considered already at an early planning stage.

Usually wind turbines are visited twice a year for regular maintenance, with wind farms it takes around 3 – 5 days. The goal for the future is to improve the reliability of the turbines and decrease the frequency for preventive maintenance to not more than once a year. In addition to the turbines, regular maintenance is required for the substructures and cabling as well. Relevant maintenance aspects for an offshore wind farm are (Rademakers, et al., 2011):

- Turbine reliability – offshore turbines have to be designed in a way that all the components are more reliable and resilient to offshore conditions compared to onshore turbines. This is usually achieved by reducing the number of components, selecting parts with higher quality, applying climate control and integrating automatic lubrication systems.
- Turbine maintainability – accessing offshore turbines is more challenging and in order to ease the maintenance and repair process modular design and internal cranes for hoisting materials are often used.
- Weather conditions – due to potentially strong winds and wave heights preventive maintenance work is carried out during the summer months, where the weather conditions are usually milder.
- Transportation and access vehicles – transport is mainly done by vessels but personnel is sometimes transported with helicopters.
- Crane ships – for replacing bigger components like blades, gearbox or nacelle, large crane ships have to be hired (Rademakers, et al., 2011).

There are two different maintenance methods – total productive maintenance (TPM) and reliability-centred maintenance (RCM). TPM is centred on people and has proven to be prosperous in optimizing the effectiveness of equipment and eliminating breakdowns. It has a main focus on people and the basics like cleaning, lubrication and tightening to make sure that the equipment is well-functioning. The goal is to detect all the potential wear-outs as soon as possible to avoid service failure. RCM is centred on assets meaning that it focuses on designing as reliable products as possible. Most of the effort is put in already at designing phase with the aim to detect potential hot-spots and find solutions that require as little maintenance as possible. In addition maintenance is usually categorized into two approaches – corrective and preventive. Corrective maintenance is about repairing breakdowns and failures. Preventive is doing smaller maintenance work to ensure that the parts are running smoothly and failures are avoided. Mostly it consists of repair, service and component exchange (Rademakers, et al., 2011).

Getting access to turbines offshore is more difficult compared to onshore turbines. Due to that, one of the main issues that need to be addressed when planning an offshore wind farm is how to minimize the need for maintenance and at the same time maximize access to turbines. When it comes to nacelle design the strategic choice is between nacelle systems that are with integrated design but can be more difficult to maintain locally and parts are not so easily replaceable. At the same time longer lifespan and reliability can be achieved. The other option would be modular design with more easily accessible components and replacement of broken parts. Cranes are needed for maintenance work and in some cases a heavy duty internal crane is already included in the nacelle system. An alternative way, used both by Siemens and Vestas, is to have a lighter internal winch that is used to raise the heavy crane transported by a maintenance vessel. It can also be used to lower components that require removal down to the vessel. The dilemma still remains – which components should be maintained offshore and which should be taken onshore for refurbishment or replacement and where is the limit for replacing the whole nacelle or turbine instead of trying to repair faulty parts (Gardner, et al., n.d.).

To maximize the access to wind turbines one possibility could be to add a helipad on the nacelle, which is doable design wise, but can end up being rather expensive for regular personnel transportation. Access is usually by boats, but with that restrictions follow as well – with significant wave height of greater than 1.5 meters and wind stronger than 12 m/s boat transfers cannot be performed. In the UK offshore wind farms the standard boat and ladder access is possible around 80% of the time which is too low for good availability. Usually accessibility is even worse during winter when there is also the highest chance of turbine failure. To achieve around 90% accessibility rates, it needs to be possible to access wind turbines with wave heights between 2 and 2.5 meters. New access challenges derive from future bigger and further off-shore wind farms. Most likely the need for helicopter transportation will increase, larger vessels than the ones currently in use are required and offshore accommodation platforms like in oil industry are necessary. An example of an innovative approach to accessibility and maintenance issues are Statoil/Hydro and Siemens with cooperation for new technology to develop wind turbines that float; the outcome of their project can affect how new wind farms are designed (Gardner, et al., n.d.).

Wind turbine blades get in contact with rain which can cause erosion and damage the material. When dealing with offshore turbines the issue is even more severe since the repair or replacement of blades is more costly. In addition due to sea salt aerosols in the air, blade erosion rates for offshore turbines can be twice as high compared to onshore ones. For example at the wind turbine park Horns Rev 1 off Blåvands Huk in Denmark, during three years more than 200 blades have been repaired on 80 turbines. With the need for frequent maintenance the wind farm operation costs decrease and at the same time mechanical damage reduces the energy efficiency of a wind turbine. It is estimated that due to the surface roughness of a damaged blade electricity efficiency can go down around 5% (Stolpe, et al., 2014). In order to keep wind turbines running at their full potential maintenance is necessary. In addition to rain droplets, blades are also vulnerable when colliding with solid particles like sand and insects and even ultraviolet radiation and large temperature variation can cause damages. An efficient and cost-effective solution to protect the blades is to use coating which can help maintain optimal electrical efficiency and reduce the need for maintenance (Stolpe, et al., 2014).

4.4 Decommissioning

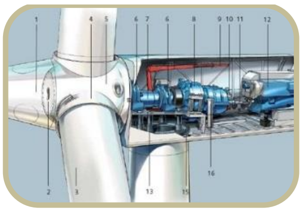
When a wind turbine reaches its end of use phase and repairing it is economically and technically not viable it has to be decommissioned. It is considered to be like the installation process in a reverse order; the electrical infrastructure, rotor, nacelle, tower, transition price and foundations are removed. Compared to oil, gas and other offshore installations decommissioning wind farms is a more straightforward process (Januário, et al., 2007).

For example Vestas begin their decommissioning process by emptying the turbine from oils and other hazardous substances that are potentially harmful for the environment. As the next step the wind turbine generator is disconnected from the cables. When the generator is removed, the blades, hub, nacelle and tower should be removable in the reverse order and manner as they were put up, while using similar equipment as well. The parts are transported onshore where usually everything except the blades made out of fibreglass are re-used or recycled. The substructure of the turbine is cut and lifted out of water, then transported onshore for recycling. Usually it is not possible to remove the entire pile that is buried under the sea; the sediment is removed about 2 meters below the level of the seabed and the pile gets cut out at the same depth. The foundations are in most cases left under the sea since removing them is often technically unfeasible and costly (Januário, et al., 2007).

The electrical service platform is decommissioned after all the cables are removed. Heliport, ladders and boat platforms are cut off and transported onshore. The submarine cables that connect the turbines with the shore have a life span of around 40 years and they are buried approximately 2 meters into the sediment to protect them against anchors or fishing devices. During decommissioning the cables are disconnected, then cut below seafloor and hoisted up. All the metal from the cables are expected to be recycled (Januário, et al., 2007).

Offshore wind turbine removal has a high cost and alternative methods for the usual decommissioning process are under development. One proposed method would be taking the turbine down in a same manner as cutting trees – with that the costs for disassembly and vessels would be decreased. Oils and other potentially hazardous substances would be drained as a first step and then the tower would be cut and it falls into the ocean in a controlled manner. Afterwards the turbine would be lifted from water and transported onshore. Same method is currently being used for reefing-in-place oil and gas structures. This method includes some problems that need to be solved, for example safety issues, including looking out both for personnel and marine life. In addition structural integrity has to be kept in mind as well, to make sure that the tower does not hit water with too much force causing the components to break. It is necessary to keep the tower from sinking and take into consideration that it can weigh around 400 tonnes and require a large crane and vessel for transportation. Flotation can be achieved by making the tower and nacelle watertight and with the help of airbags it is possible to hinder it floating vertically due to the nacelle. The weight can be reduced by cutting the tower into sections (Kaiser & Snyder, 2011).

Summary of Chapter 4



Technical Description

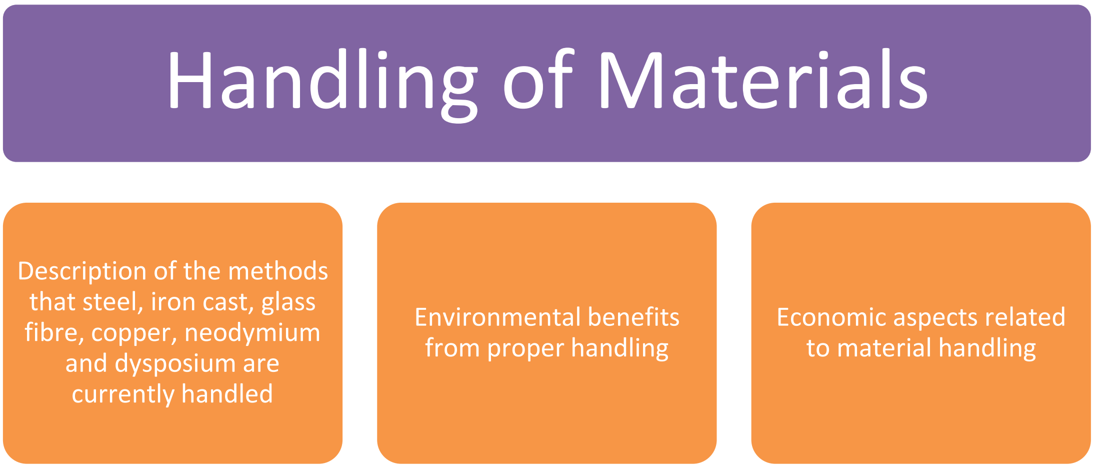
Materials

Maintenance

Decommissioning

5. Handling of Materials in Wind Turbines

In this chapter a detailed description of the materials included in a wind turbine is given, with the purpose to give an understanding on the waste handling methods used today. Furthermore environmental benefits and important economic aspects from the current handling policies are defined.



End-of-service lives of wind turbines constitute a major issue the last years. Different parts of wind turbines are getting recycled or reused but significant amounts of material is just land-filled. This practice has raised difficult questions to the wind industry regarding the sustainability of their current disposal methods. Life cycle assessments have helped to get a better understanding of the main environmental impacts stemming from offshore wind farms. The three main sources identified are bulk waste deriving from the tower and foundation; hazardous waste in the nacelle components and greenhouse gases, for example from steel production. These challenges should be kept in mind when dealing with design, decommissioning and recycling (Andersen, et al., 2014).

Getting rid of blades is considered to be a major problem when talking about wind turbine recycling. There are still high uncertainties on how to handle them properly and safely. Fibreglass itself is a low value material, the size of the blades complicates the recycling process and when cut, fibreglass creates a hazardous working environment (Andersen, et al., 2014). Other significant parts are the tower, the generator and gear, the cables and the nacelle.

Wind turbines can be either reused or recycled. Wind turbines or their parts are used in developing countries (Yang, et al., 2012). Second hand turbines that are reconditioned are in demand all over the world, both due to its 40% smaller price and around two year waiting lists for new ones. Eastern Europe, Latin America and Asia are among the biggest buyers of used turbines. Even small community-owned renewable energy schemes could be interested in purchasing second hand turbines. For example in 2004, Isle of Gigha Heritage Trust brought three used Vestas turbines and they generated almost all of the electricity the people on the island need. As a creative solution in the Netherlands wind turbine blades are turned into playgrounds for children (BBC, 2013). Another innovative approach is turning smaller blade parts into benches, or using them for bus stop shelter construction; it is even potentially possible to reuse major parts of blades to produce smaller blades for smaller turbines (GenVind, n.d.).

As mentioned earlier, the main materials used for wind turbines are steel, iron cast, glass fibre and copper. In the following paragraphs a thorough description regarding the handling-recycling, reuse, disposal-of those materials is presented. Moreover, the main parts made of the respective materials are been analysed.

5.1 Handling of Steel

Steel is infinitely recyclable and its recovery at the end of life service covers upfront costs, because of the value of steel scrap. If steel parts are not reused they can return to the steelmaking process (World Steel Association, 2012). Steel is the most recycled material on the planet. According to the American Iron and Steel Institution, for the year 2012, up to 88% of the steel produced was recycled (American Iron and Steel Institution, n.d.). The chemical attributes of the material allow its perpetual recycling with no consequences in its performance and its use in different products. It does not lose its main properties like strength, ductility and formability. Since steel is an alloy of iron it has other elements in it as well, which depend on the purpose of the steel and are added to achieve the required quality. This can later make it challenging to identify and sort the scrap into similar groups of material. Another issue is separating those alloying elements or other metals in a cost effective way when recycling. According to study by Yellishetty, et al. (2011), each time a metal scrap goes into recycling, the residual concentration increases, making processing more difficult. The most difficult to extract from scrap are copper, tin, nickel and molybdenum and their concentration increases in each recycling loop. Removing residues can become expensive thus primary production route will be preferred (Yellishetty, et al., 2011). Steel scrap is used in the production of new steel. Main sources of recycling steel include scrap from steel factories, off-cuts from manufacturers and obsolete scrap-from products in their end-of-service life (BlueScope Steel, n.d.).

Environmental Benefits

Recycling scrap steel reduces greenhouse emissions and saves up to 56% energy in comparison with making metal from ore (West, n.d.). It decreases as well significantly the use of natural resources. Namely, recycling one tonne of steel conserves one tonne of iron ore, 635 kg of coal and 54 kg of limestone (West, n.d.). The process of recycling steel is simple; the material is collected, and then transported to a recovery facility where it gets separated and crushed into large bales. The bales are then transferred to steel mills where they get mixed with other steel scrap, then melted and new steel is produced (Environmental Protection Agency, 2014).

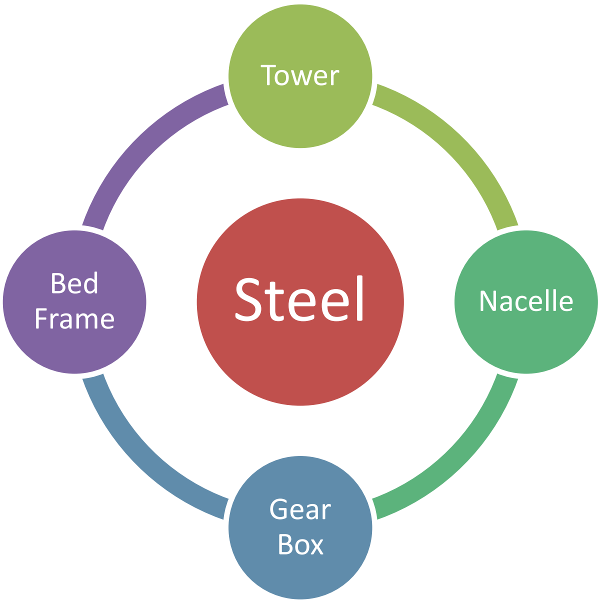


Figure 11: Wind Turbine parts made of steel

Steel parts

The tower (Figure 12) of a wind turbine is made from steel and in the majority it has a tubular shape. Towers can represent as much as 65% of the weight of the turbine (Ancona & McVeigh, 2011). The maximum tower diameter is around 4.3 m. The longer the blades, the taller the tower should be, in order to maximise yield.

Figure 12: Wind Turbine Tower (Greenergy, n.d.)

The gearbox and bed frame are both made out of steel. In a gearbox small amount, less than 2% of all the used materials can be copper and aluminium as well (Ancona & McVeigh, 2011). Bed frame connects the tower with the shaft and the gearbox regulates speed. The nacelle can be made out of steel as well and it sits at the top of the tower covering all the generating parts of a turbine. For example in side of it are the gearbox, the brake and the generator (Hexcel, n.d.). The nacelle can weigh around 125 tonnes with the machinery in it (Siemens, n.d.).

5.2 Handling of Iron Cast

Cast iron is 100% recyclable. It can easily be recovered and processed for reuse (Newport Metal Recycling, n.d.). Common sources include old cars, steel beams, household appliances, railroad tracks, ships, bottle tops, food tins, paint cans and aerosols (Business Recycling, 2013).

Environmental Benefits

Recycling of cast iron has great benefits on the environment because it diverts it from landfill, diminishes the need to extract and manufacture raw material and contributes significantly to less greenhouse gas emissions.

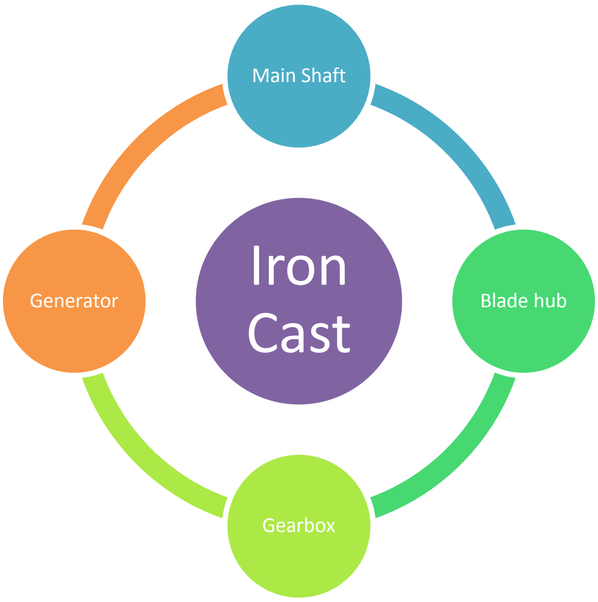


Figure 13: Turbine parts containing iron cast

Iron cast parts

Main shafts (Figure 14) on a wind turbine are mainly made of iron cast. The blades spin the shaft which is connected with the generator that produces the electricity (European Wind Energy Assosiation, n.d.). Other turbine parts that include iron are the gearbox, generator and the blade hub (Martinez, et al., 2009).

Figure 14: Main Shaft (Tongyu Heavy Industry, n.d.)

5.3 Handling of Glass Fibre

When it comes to wind turbine waste handling, parts made from glass fibre are currently one of the most challenging due to the size of them, recycling complexity and low market value.

Environmental Benefits

Glass fibre production is energy intensive and often relies on fossil fuels, which emits greenhouse gases and affects global warming (Joshi, et al., 2004). The main environmental issue connected with fibreglass is that it does not degrade. Meaning that when it is land-filled it will stay there (Phakos, 2011). In addition when a material is disposed, potential energy and materials are lost as well, which is not a resource efficient way of handling waste.

Economic aspects

From year 2009 to 2010 the production volume of fibreglass in Europe went up 25%, reaching one million tonnes. Nevertheless the cost of recycling processes and the low market value for recycled fibreglass materials are the main barriers for achieving higher recycling rates. The cost for new glass fibres is around 1.3 – 2.6 €/kg, giving it a little financial incentive to use recycled ones (Cherrington, et al., 2012). Another worry is that mechanical recycling processes like milling and grinding require a lot of electricity and that might make recycling economically not feasible (Yang, et al., 2012).

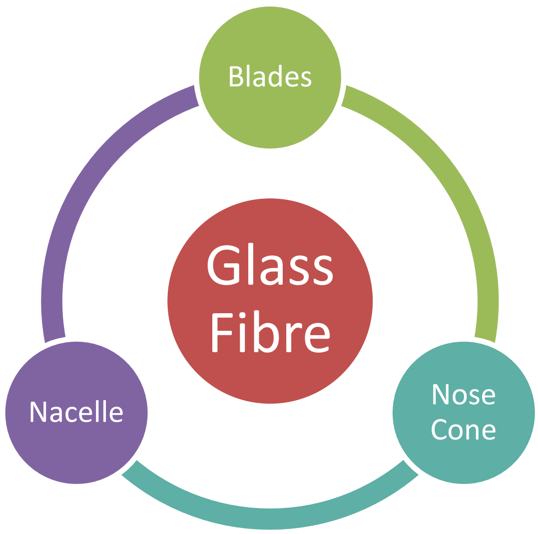


Figure 15: Wind Turbine parts made of glass fibre

Glass fibre parts

Siemens makes their blades out of fibreglass-reinforced epoxy resin. Their most used offshore wind turbine model, SWT-3.6-107, has a blade length of 52 meters (Siemens, n.d.). Globally the wind industry is increasing both by number and by the size of the turbines. With that the waste stream of blade materials grows as well and needs to be managed in an environmentally friendly way.

Currently the main way is to landfill or incinerate end-of-life wind turbine blades. As mentioned previously, EU has a waste hierarchy where energy recovery is a more preferred solution compared to landfill (Cherrington, et al., 2012). Since glass fibres are considered incombustible the recovered value of glass fibre reinforced composite is mostly determined by the proportion of polymer in it (Pickering, 2006). Incineration is a widespread method in Denmark where composite waste is mixed with around 10% municipal solid waste (Cherrington, et al., 2012). The issue with incineration of turbine blades is that around 60% of the scrap is left behind as ash since it has a high quantity of in-organics in the composite. The ash from incineration can potentially be a pollutant and is either land-filled or recycled as a substitute construction material. In addition the composites used in the blades have a low heating value and limited electricity efficiency which makes incineration seem to have a short future and recycling is considered to be the best alternative (Yang, et al., 2012).

Wind turbine blades are difficult to recycle because they are made out of matrix, fibres and fillers making it a complex material composition and they cannot be remoulded as a result of the cross-linked nature of the resins. In addition the blades are exposed to harsh conditions like hail, snow, salinity, humidity, extreme temperature and lightning during the 20 year lifespan of a wind turbine. As an outcome the quality of the fibres decreases and it might not be possible to reuse them in structural components like new turbine blades. Another obstacle for recycling is the size of the blades making it logistically difficult to dismantle, transport and cut them (Cherrington, et al., 2012).

Another possibility is to burn fibre reinforced plastic in cement kilns for cement production. The estimation is that around 10% of the fuel input could be substituted with polymer composite material like fibreglass (Pickering, 2006). All of these proposed recycling methods are ways of down-cycling. It is considered unlikely that recycled glass fibre reinforced plastics can be used in new blades since it will have lower strength compared to virgin materials. Nevertheless those glass fibres can be used in heat insulation materials in buildings instead of just being disposed (Larsen, 2009).

Figure 16 illustrates where blades, nose cone and nacelle are located on a wind turbine. The nose cone is made from the same material as blades – fibreglass. The nacelle can be made out of fibreglass as well. The main function for a nose cone is to protect the hub casting and it weighs around 0.5 tonnes (Barnes, 2011). The nacelle sits at the top of the tower and covers all the generating parts of a turbine (Hexcel, n.d.).

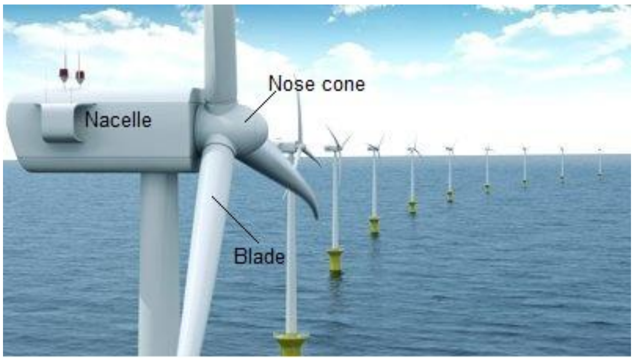


Figure 16: Offshore Wind Turbine Parts (Shutterstock, n.d.)

When it comes to the environmental and economic impacts, disposal, incineration, reuse and recycling – the same problems and possibilities occur with nose cone and nacelle as with the blades. They are made from the same material but the main difference comes from the dissimilarities in the sizes and material quantities. Meaning that, it is easier to transport the nose cone into a recycling facility due to its smaller measurements.

5.4 Handling of Copper

Copper is an easily recycled material and the recycled one can worth up to 90% of the cost of the original (Resources SchoolScience, n.d.). There are two kinds of copper scrap, old and new scrap. The old one is derived from products that are no longer in use, e.g. old pipes and taps, disused electrical cables etc. New scrap is derived from off-cuts of products made in the industries.

Environmental and economic benefits

Recycling copper has significant benefits both for the environment and the economy. Namely, emission of dangerous gases like sulphur dioxide during copper extraction can be avoided. In addition, landfill costs can be avoided. If copper scrap is pure then it is possible to achieve a high performance product. If it is mixed, there are still ways to use it by adjusting its composition or diluting it. If it is contaminated beyond the limits it can be re-refined using proper techniques (Copper Development Association, n.d.).

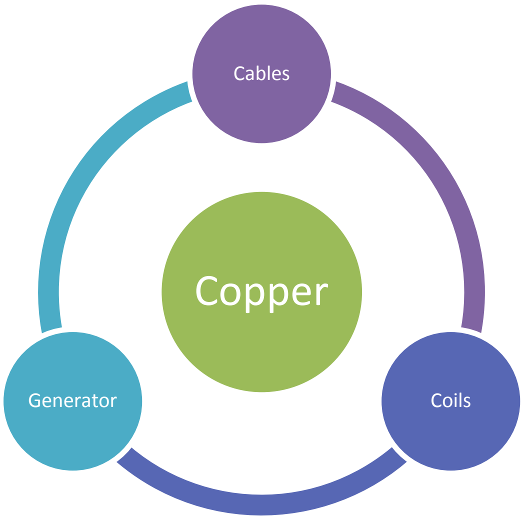


Figure 17: Wind Turbine parts made from or consisting copper

Copper parts

The cables and coils of a wind turbine are mainly made of copper in addition the direct drive turbine generators have copper in them as well. The cables in the nacelle transfer data and communication signals and cables carry power from the generator (Zipp, 2012).

5.5 Handling of Neodymium and Dysprosium

Neodymium is the second most abundant rare-earth element (Lenntech, n.d.). Dysprosium improves the magnets' performance in high temperatures and the resistance to demagnetization (Arnold Magnetic Technologies, 2012). Recycling rare earth elements helps with the so-called balance problem. With primary mining of neodymium an excess of more abundant elements, for example lanthanum and cerium, are generated and need to be sold as well. Hence with neodymium recycling the total amount of rare earth ores extraction can be reduced. Up until 2012 only 1% of all rare earth elements were recycled, recycling rates for neodymium and dysprosium are lower than 1%, leaving noticeable potential to improve how these materials are handled. The main reasons for such low recycling rates derive from inefficient collection, technological challenges and lack of incentives.

Large, easily accessible magnets, for example the ones in wind turbines, could be reusable in their current shape and form. Due to the long lifespan of such applications, there are not enough available magnets to reuse in new manufactured wind turbines. Direct reuse is the most economical way of handling magnets because it requires low energy usage and no chemicals, and in addition no waste gets generated (Binnemans, et al., 2013; UNEP, 2011). The issue with direct reuse of magnets in wind turbines lies that the turbines produced in the future can have different shapes and sizes that require magnets with changed properties as well. In those cases the magnets could be cut smaller and used directly in other applications.

Environmental benefits

Neodymium can be recycled and as a result the recycled magnet has fewer environmental impacts due to the energy savings and decreased emissions (Lee, 2014). A study showed 80% less human toxicity and 60% energy savings when using recycled neodymium for magnets instead of mining it. The best solution so far is to dismantle products manually and avoid crushing, which can mix different materials and result in up to 90% of rare-earth metal losses. Recycling chances are higher, when these rare-earth metals are in industrial instead of consumer products. A good example is an offshore wind farm, where it is necessary to reduce the need for maintenance and it can be achieved by using permanent magnets. These magnets contain hundreds of kilograms of rare-earth elements and are concentrated in the same location; later there is a higher possibility that these magnets are collected and recycled properly (Marshall, 2014).

Economic aspects

Both neodymium and dysprosium are estimated to be in short supply in the next 10 years. Currently the demand exceeds the supply (Iamgold Corporation, 2012). China accounts for 40% of the reserves and 90% of the global production (Binnemans, et al., 2013). China has a lot of power when it comes to price regulation and decreasing or increasing the production quantities. Due to that it is even more important to develop efficient recycling methods to keep the rare metals in circulation.

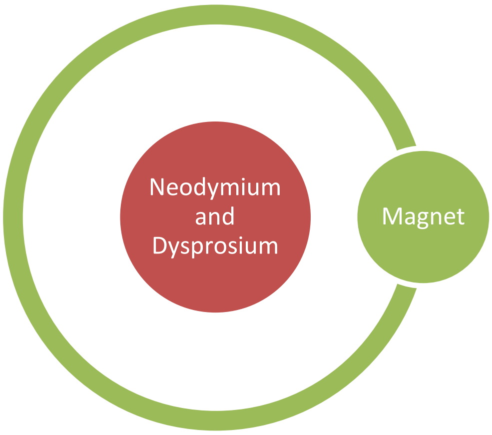
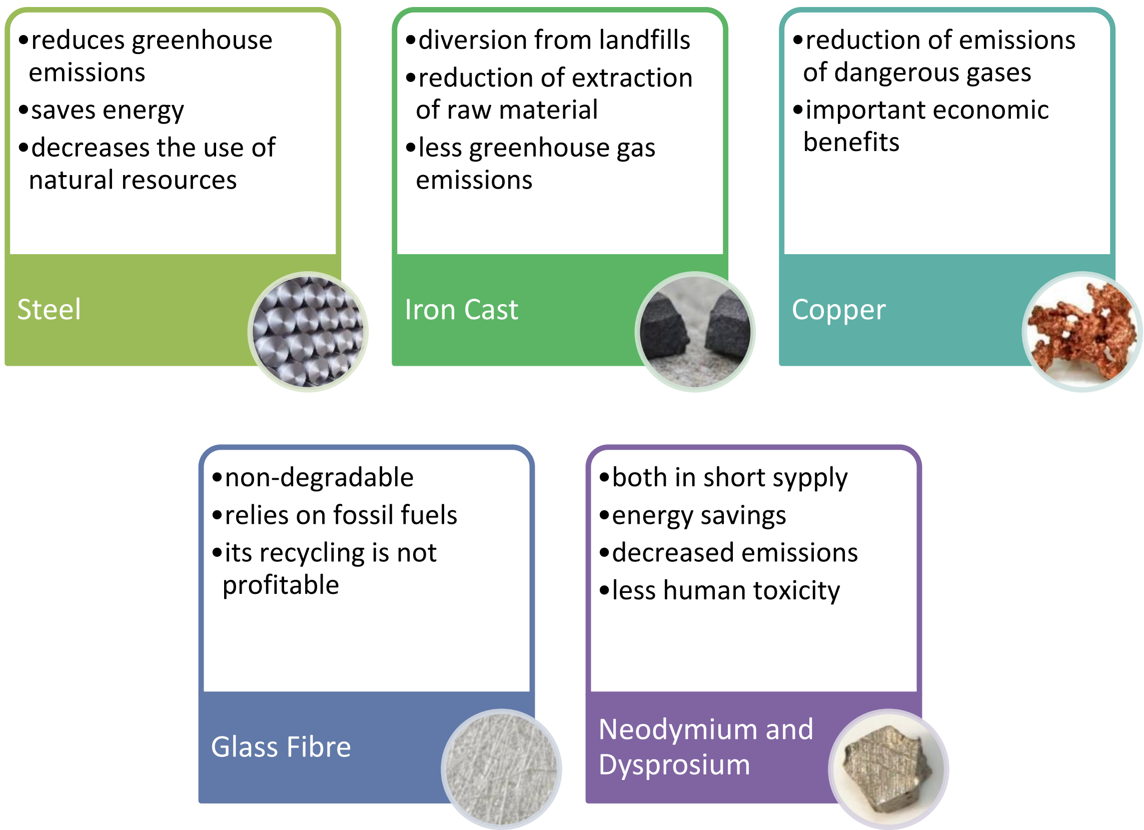


Figure 18: Magnets contain Neodymium and Dysprosium

Neodymium and dysprosium parts

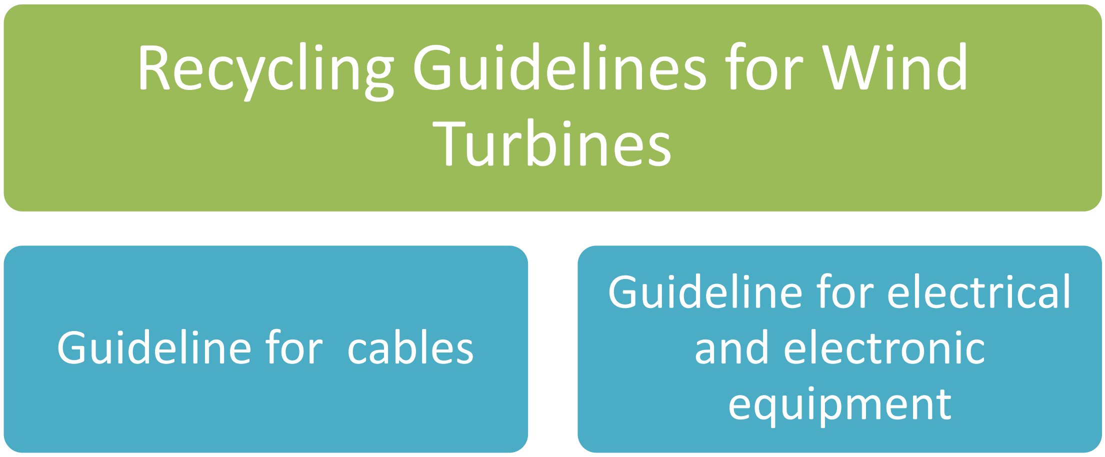
Permanent magnets use rare earth elements like neodymium and dysprosium. Since gearbox failures are one of the main issues with wind turbines during their operation phase, a solution could be to eliminate the use of gearboxes and replace them with permanent magnets that are connected with the generator (Hatch, 2009).

Summary of Chapter 5



6. Recycling Guidelines for Wind Turbines

In this chapter the main product of this thesis is given, which is the guidelines on how the cables and electronic waste of wind turbines that have reached their end-of-service life are handled. Siemens already has a guideline for the blades and the magnets but it would be useful to have similar documents for all of the parts in a wind turbine since it gives a better overview on the challenges and opportunities. It can also be helpful in information exchange between stakeholders with the purpose of helping each other improve wind turbine design and waste management.



6.1 Recycling Guideline for Cables

Wind turbines require cable solutions for both nacelles and towers. The typical composition of cables used by Siemens Wind Power is 18% copper, 30% aluminium and 52% of polyethylene. In their offshore wind turbines around 2500 kg of cables are used, with their length varying from 10 cm to several meters (Pagh Jensen, 2015).

There can also be rubber cables that transmit energy produced in the generator to the transformer and connect the transformer with the switchgear. These cables are covered with rubber layer which is waterproof, resists abrasion and protects the cable. With offshore wind turbines submarine cables are needed as well, to transport power from wind farms to the grid on land. The cables used for that usually have cross-linked polyethylene insulation (Nexans, n.d.).

Depending on the location of an offshore wind farm the length of required cables can differ. With the distance of 2 – 15 km from the shore, it is considered to be a near-shore wind farm (Gill, 2012). Meaning that, there are wind farms tens of kilometres further from the shore than the near-shore ones, which also require cables to connect with the grid on land. In addition the amount of turbines in a wind farm and the distance between them has an effect on the total length and weight of the cables. The more cables are required the more materials are needed to produce them and when they are no longer usable or needed they have to be handled in an appropriate way.

End-of-life processing of cables

When decommissioning offshore wind farms the infield and export cables are left buried below the natural seabed level or protected by rock-dump. In case they have become exposed they will be removed in the same manner as they were installed (Ramboll Wind, 2010).

Reuse

Cables can be reused when they are not damaged. It can depend on the original purpose of the cable, how long and in what conditions it has been in use. For that reason reuse potential should be assessed for each case separately.

Recycling

The standard recycling process for cables starts with shredding, and then the ferrous parts are removed with magnets, followed by fine granulator and moving on to the separation table. On the separation table the copper and aluminium granulates, and plastic or rubber covering the cable gets sorted and separated. After these processes the metals can achieve 99.5% purity (Eldan Recycling A/S, n.d.). The technology for further recycling of copper and aluminium is already established and is not seen as an obstacle. Plastic and rubber parts after the separation process can be further recycled in respective facilities.

A potentially problematic area is recycling the plastic waste from cables. The main motive behind recycling cables derives from the salvage of valuable metals. For plastics it is more about regulations against disposal making it economically more viable to come up with recycling methods. If the plastic is in thermoplastic form, like polyethylene (PE) it is relatively easy – it can be re-melted and made into new products (Borealis, n.d.). It is more challenging with cables that have cross-linked polyethylene (XLPE) insulation, like the ones connecting offshore wind farms with grids on shore. Most of XLPE is burned or landfilled since it is a non-thermoplastic that cannot be re-melted. There are ways to recycle XLPE, but the recycled products have a lower quality compared to virgin material and thus have not gained popularity. New methods, like using supercritical alcohol are currently under investigation to improve the properties of recycled XLPE and make it compatible with virgin material (Ashihara, et al., 2008). The economic feasibility of XLPE recycling and its environmental impacts require further assessment.

Landfill

The cables buried under the seabed with expectation to be in use for at least for the lifespan of wind turbines are designed as harmless as possible. They are supposed to affect the marine life and environment as little as possible after the installation process and in most cases they are left buried when the wind farm reaches its end-of-life. Other, non-buried cables or buried cables that do get removed should not be landfilled due to the valuable metals in them and well established recycling methods.

What else can be done?

In addition to the cable waste that is a result of an end-of-life wind turbine, there are always some losses and waste deriving from the manufacturing and/or installation process. It is not possible to avoid using cables but the amount of cable waste can be reduced. As it became evident from the interview with Siemens Wind Power, collaboration with cable manufacturers to decrease material losses have been successful. Instead of selling cables with fixed length with the result of losses from cutting them later into proper size, they can now be bought with adjustable length. This type of seemingly small changes can help reduce waste and unnecessary material costs.

Communication is a key for better waste management solutions. It applies to wind turbine cables as well. Cable producers, turbine manufacturers, turbine owners and waste handling companies should give each other feedback on the challenges they face that the other parties could help to resolve. Without sharing ideas and concerns cable producers might not be aware of their products' difficulties to reuse or recycle and will not make any changes. All involved parties should work together with the purpose of improving their product or service quality, for example through joint projects, workshops and recycling guideline development.

6.2 Recycling guideline for WEEE

Waste of electrical and electronic equipment, or shortly WEEE, is a waste stream that is regulated in the European Union by Directive 2012/19/EU. WEEE is a complex material mixture that includes hazardous components which can damage both human health and the environment, when not properly managed (European Commission, 2015). It is estimated that around 2% of total weight of waste deriving from electrical and electronic equipment is toxic substances, like polychlorinated biphenyls (PCB), lead, mercury or cadmium among others (Cabrera-Cruz, et al., 2014). In addition, electronics production requires scarce and expensive materials, for example gold and rare earth elements, making it important to use resources in a sustainable manner (European Commission, 2015).

Who answers for WEEE?

Waste treatment tendency has for a long time been about finding the closest and cheapest way of disposal. Today the original equipment manufacturers play a key role in the policy development. OECD has defined the environmental policy approach as Extended Producer Responsibility (EPR), with the aim to extend the responsibility of a manufacturer until the products end-of-life phase. This approach takes into consideration the entire life cycle of a product and makes producers consider the environmental aspects already in the production phase (OECD, n.d.). The WEEE Directive follows the same principle, with the objective to prevent waste and when it is inevitable then through reuse, recycling and recovery, reduce disposal and salvage secondary raw materials. The importance of eco-design is emphasized as well, to encourage collaboration between producers and recyclers with the aim to make reusing and recycling easier and more efficient (Directive 2012/19/EU, 2012).

EPR is sometimes also called ‘Producer Take-back’ and it refers to waste management system where manufacturers take the responsibility to safely handle their products after they are no longer usable. With that responsibility there is more motivation to use environmentally safer and fewer materials in the production and to design their products to last longer and be easier to reuse and recycle. The manufacturers will have a personal gain when they are able to keep the waste costs down (Electronics TakeBack Coalition, n.d.). Extended producer responsibility makes it the manufacturers’ obligation to handle end-of-life electronic and electric equipment, but not the collection of them (Zoeteman, et al., 2010).

For a well-functioning WEEE management, separate collection and safe transportation are crucial elements. Through effective collection and transportation valuable materials can be recovered with higher quantities, it also helps to neutralize the potentially hazardous parts of a product. E-waste system designers should work towards safe collection of the largest potential amount of WEEE; avoid mixing different types of waste; and find ways to deliver the collected waste into treatment facilities with minimal damages and material losses. Most common collection methods are permanent drop-off locations; special drop-off events; and door-to-door pick up (McCann & Wittmann, 2015).

End-of-life processing of WEEE in wind turbines

In 2012 the WEEE Directive was updated and now it includes photovoltaic modules. Wind turbines, as a whole, are still not covered by the Directive, but the scope of the directive will be extended to cover all electrical and electronic equipment in 2018. Meaning that, wind turbine industry should acknowledge that the directive might influence them more in the near future (Cherrington, et al., 2012). Currently some appliances of a wind turbine, for example lights and smoke detectors, classify under WEEE Directive, which are shown in Appendix B. Due to confidentiality reasons that appendix is not included in the public version of this report.

Reuse

Collected WEEE gets screened to detect reuse potential; anything that can be repaired or refurbished is separated from the waste. Reusable WEEE is tested to ensure electrical safety and functionality. When the electrical and electronic equipment passes the test it can be reused, if not, it gets dismantled and when possible some of the parts will be reused. The parts that are not suitable for reuse will go into recycling (Wiser Recycling, n.d.).

The challenge to achieve higher reuse rates can be connected with consumer habits and fast technological changes. The dilemma lies in the situation where reusing an old appliance helps to contribute to resource conservation by decreasing the need for virgin materials and production but at the same time fast technological development has come up with products that often require less energy in their usage phase compared to the old ones (Truttmann & Rechberger, 2006). This causes a situation where choosing one over the other decreases some impacts on the environment and increases others. In addition the appliances can become technologically outdated and not suitable for further reuse, buying new products can also be cheaper than repairing old ones or new appliances can have better features or aesthetics (McCann & Wittmann, 2015).

Recycling

WEEE that cannot be reused is usually dismantled manually to separate the parts and different materials as much as possible. If it cannot be dismantled or it is too large do to it manually, the product gets shredded and then the lower value material gets recycled. Most electronic and electrical equipment consists of materials, like plastics, metals and glass which already have a developed recycling technology (Wiser Recycling, n.d.; Health and Safety Executive, n.d.).

For example the lights in a wind turbine can consist of around 80 – 90% of glass, 7 – 14% of plastic and metal, 1 – 3% of fluorescent powder and up to 0.01% of mercury. Roughly around 95% of these materials can be reused or recycled. The phosphorous powder and mercury can be used for manufacturing new lamps and crushed glass can be mixed and melted with new one for various applications (Recolight, n.d.). Considering the size of wind turbines there can be high amounts of lighting equipment that needs to be collected and handled according to the WEEE Directive for safety, waste reduction and sustainable resource use.

During recycling it is useful to separate not only different materials but also same materials with various characteristics in order to maintain their maximum value. For example, the plastics used in electronic and electrical equipment can vary, resulting in mixed recycled plastics production which is suitable for only low-grade applications (Dalrymple & Wright, 2007). By keeping the materials in a product as homogenous and pure as possible, the easier and cheaper it is to recycle and salvage cleaner secondary materials that can be used in more various applications. Developing technologies that can separate all sorts of different materials can be expensive and in the end make recycling economically not feasible. In addition it might not even be possible to separate some substances making it impossible to recycle them efficiently.

Disposal

Despite all efforts there will still be parts of electrical and electronic equipment that cannot be reused or recycled and get disposed by landfill or incineration. When WEEE is landfilled some contaminants, for example mercury, polybrominated diphenylethers (PBDEs) from plastics, lead and cadmium, can leach into the soil and groundwater, thus it is landfilled in hazardous waste sites. When they end up in regular landfills, the toxic substances oppose a threat to the environment and health (Brookie, 2013; McCann & Wittmann, 2015). For this reason, it is important to regulate landfilling to make sure, that parts that have to be disposed do not contain toxic materials and are handled by specialists in a controlled environment. Same requirements apply to incineration. If some parts need to be incinerated it has to be done in specific facilities, for example in cement kilns where it can substitute oil (McCann & Wittmann, 2015).

What else could be done?

As mentioned previously, safe and separate collection of WEEE is crucial for proper waste management. A possibility to achieve this is well organized collaboration between wind turbine owners, transportation companies and recycling facilities. WEEE collection from wind farms has to be done in a way, that the parts do not get extra damages during dismantling and transportation. This ensures higher chances of salvaging parts and materials or even reusing the appliances. In addition an efficient collection plan for WEEE makes it more certain that the appliances end up in a waste treatment facility with relevant competence and technology instead of in a landfill.

Summary of Chapter 6

Why recycling guidelines?

- helps identify problematic waste handling areas
- explains how turbine parts are handled
- gives a startingpoint for improvement

How do they help?

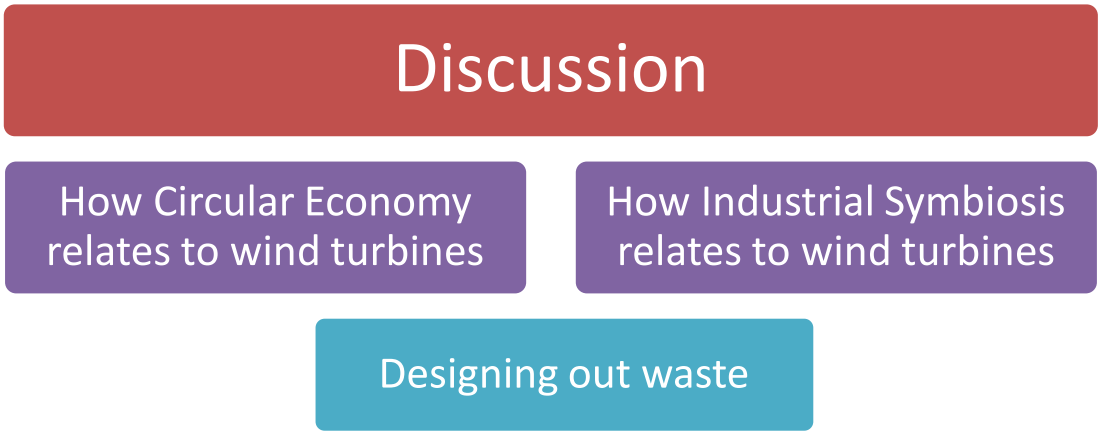
- by knowing the specifics behind each material and part changes are easier to make
- way of communicating information between parties
- directs attention to end-of-life phase early in the products life cycle
- brings attention to potential collaboration between different stakeholders

To whom are they helpful?

- suppliers
- customers
- recyclers
- manufacturers
- installation and dismantling crew
- designers

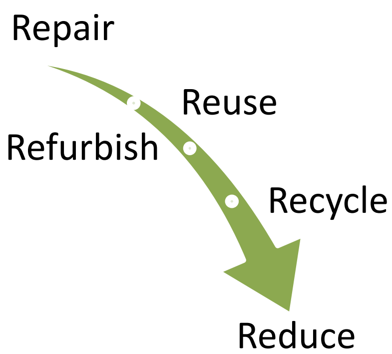
7. Discussion

This chapter will mainly analyse how the chosen theories, circular economy and industrial symbiosis, can help manage waste that derives from wind turbines. In addition the importance of designing out waste is discussed as well. The aim is to give a better understanding on how they are connected, what can be the challenges and possibilities.



7.1 Circular Economy and Wind Turbines

Circular economy gives five R's to follow in order to close material loops and keep them in circulation. Those R's being: **R**educe; **R**epair (maintenance); **R**euse; **R**efurbish and **R**ecycle. All of these steps should be followed in this order, meaning that reducing used materials and waste quantities is the overall aim that can be achieved by prolonging the lifespan through improved design and designing out waste, maintenance and repairing measures. According to the concept of circular economy, when a product cannot be maintained anymore the next step is to reuse it, followed by refurbishment and recycling is considered the last measure. Each of these steps requires more processing and in most cases more energy and resources as well, compared to the previous step (Ellen MacArthur Foundation, 2013).



Re-thinking can be considered as the sixth "R" for circular economy. This means that everything should be reconsidered. Starting from consumer habits and trying to influence it being less wasteful and thinking about a products end of life stage already in the designing phase with the aim to design out waste (Ellen MacArthur Foundation, 2013). All stages from raw material extraction to end-of-life have to be re-thought in order to improve waste management.

7.1.1 Reduce

Figure 19 illustrates annually installed wind capacity in the world, from year 1997 to 2014. As seen, every year additional MWs get installed and the amounts, with one exception – year 2013, grow annually as well. In order to produce more energy supplementary turbines need to be installed or old ones replaced with new ones with bigger output.

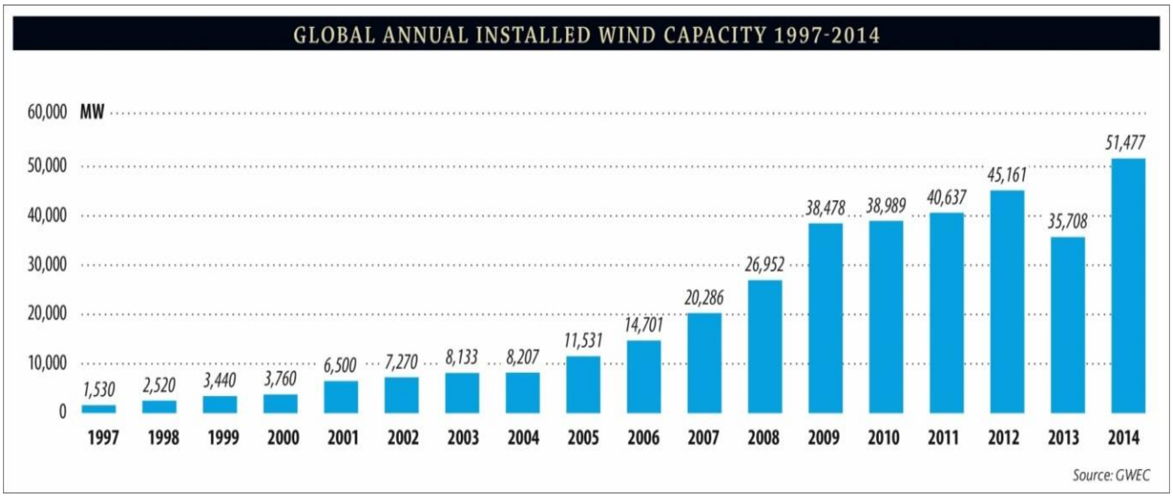


Figure 19: Global annual installed wind capacity (Global Wind Energy Council, n.d.)

The EU has set a target to source 20% of final energy consumption from renewable sources, meaning that wind energy will become even more important (Global Wind Energy Council, n.d.). With a lifespan of 20 – 30 years for wind turbines, the time when wind farms need to be decommissioned or repowered is not far thus preparing for it should start already now (Wind Measurement International, n.d.). For these reasons it is important to figure out ways how to reduce the negative impacts deriving from increasing wind energy industry. It is considered a “green” energy source but extracting raw materials to build turbines, the installation process, maintenance through the entire life span and waste in end-of-life phase can have potentially negative impacts on the environment.

Depending on the size of the wind turbine, it can weigh around 300 tonnes and its production requires large amounts of materials. According to a research by Sànchez, et al (2014) by mass 90% of a turbine is recyclable but the remaining 10% would still be at least 15 tonnes of waste materials. Material efficiency describes the ratio between material input and output and due to production losses inputs are usually larger than outputs. Meaning that in order to produce a 300 tonne turbine it requires more than 300 tonnes of materials. Achieving material efficiency helps reduce the need for materials and waste quantities due to fewer losses. Measures to reduce overall material input are following (Garcia Sànchez, et al., 2014):

- Design towards material efficient products, for example light-weight products. In addition design with the aim to decrease the need for maintenance and increase the easiness of reuse and recycling
- Minimize waste quantities during production processes, for example with the help of new processes or best available technology

- Increase life cycle performance, for example through designing products that are easier to repair, upgrade or remanufacture
- Material substitution for more sustainable ones

In order to reduce the amount of materials needed for wind turbines and waste quantities other R’s from the circular economy play an important role.

7.1.2 Repair and maintenance

Regular maintenance is necessary in order to ensure that a wind turbine can run at its maximum capacity. With monitoring and reparation measures it is possible to expand a turbines life span which is in accordance with circular economy since the materials are used longer and in a more optimal way. Relevant maintenance aspects for offshore wind farms, different maintenance measures and obstacles are explained in chapter 4.3.

Improving maintenance methods is important in order to make sure that low operation and maintenance costs can be achieved. In addition maintaining wind turbines at their operational phase play a role in product recovery through remanufacturing at the end-of-use phase. Regular preventive maintenance can help avoid or slow down functional obsolescence with a result in lower remanufacturing costs. A wind turbine without regular preventive maintenance can require after end-of-use around three extra months for remanufacturing and be around 33% more expensive. With new technological solutions it would be useful to estimate whether it is possible to switch some out-of-date parts out. The technology in a turbine can become outdated after its lifespan, increasing the remanufacturing costs and at the same time decreasing the attractiveness of it (Ortegon, et al., 2014).

Usually, the original equipment manufacturer provides a two year maintenance contract, covering all the costs for corrective and preventive maintenance. It is estimated that preventive maintenance for one turbine per year costs around 10 000 €, depending on the competence of the technicians and local labour markets. With system failures, for example gearbox failures, additional costs should be expected. Turbine sub-systems with the most frequent failures are the electrical system, control system, hydraulics and rotor blades. The gearbox, generator, drive train and rotor blades failures cause the longest downtime. With a failure there are two solutions, either repair or replace (Ortegon, et al., 2014).

7.1.3 Reuse

Turbines in a wind farm can be replaced with new, more powerful, quieter and technologically more evolved models. The “old” wind turbines might have not reached their end-of-life yet being fully functional and due to that can be reused and sold as second hand turbines. For example, in 2001 in Denmark, 1480 turbines with 100 kW were replaced with turbines three times as powerful. The turbines were substituted to take advantage of the possibility to produce more energy not because the old ones were not functional. Repowering was encouraged since the smaller aging turbines were occupying the prime wind sites (Walton & Parker, 2008).

From Europe at the moment, biggest second hand turbine providers are Germany, Denmark, the Netherlands, the UK and Italy (Dutchwind, n.d.). The turbines are sold both to other European countries and abroad, majority goes to Eastern Europe or Latin America. The advantage of buying second hand turbines relies mostly on its lower price; in addition the waiting time for new turbines can be around two years, making it faster to purchase a reused turbine. The main challenge with reusing wind turbines is limited knowledge on the length and quality of its functioning, which can effect whether banks and institutions are willing to invest, leaving the market to be driven more by private investors who can afford it without loans or financial support (Daubney, 2013).

7.1.4 Refurbish

Refurbishment and remanufacturing are processes where used products are restored; in most cases it requires replacing bigger parts. Related to wind turbine industry remanufacturing is the more used term with the intention that the product's functionality is restored to "as new" quality (Circular Economy Toolkit, n.d.). Remanufacturing a wind turbine means that it gets taken into pieces and rebuilt with the outcome of looking and running like new. At the same time their price can be around half of a new one (Boythorpe Wind Energy, n.d.). Usually the refurbishment covers (Repowering Solutions, n.d.; Ortegon, et al., 2013):

- Gearbox – installation of new bearings and seals
- Generator – installation of new bearings, units are rewound and reinsulated
- Rotor – gets balanced
- Blades – get repaired, new coating and balanced
- Tower – inspection for cracks and re-coating
- Bed plate and nacelle – inspection for damages, repairing and coating

Repowering projects open up opportunities for remanufacturing. When neither reuse nor remanufacturing is done, the turbines get usually sold for scrap materials. In most cases decommissioning costs exceed the salvage value, making it financially not beneficial. Therefor remanufacturing might increase the value of an end-of-life wind turbine (Ortegon, et al., 2013).

In other industries, for example automotive industry, environmental benefits deriving from remanufacturing have been identified. As an example energy savings around 68 – 83% and CO_2 emission reductions by 73 – 87% have been achieved, in addition costs have been reduced around 50%. Wind turbines have related features to other, widely remanufactured products, meaning that this industry could gain similar benefits from remanufacturing process. Some of the characteristics being: high manufacturing costs; need for periodic replacement for worn out parts; high functional and material value (Ortegon, et al., 2013).

The challenges with wind turbine remanufacturing are related with the need for pre-dismantling on the site since they are not mobile and there is still uncertainty on how to handle the blades safely. In addition uncertainty about the reliability of a remanufactured wind turbine remains. Generally they are given a warranty for 2-5 years, are sold with half of the price of a new turbine and have a life expectancy of 10-15 years (Ortegon, et al., 2013).

How an end-of-life wind turbine gets disassembled, reprocessed and reassembled affect the quality of a remanufactured wind turbine. Due to that the manufacturers are one of the main drivers that can have an impact on the quality through designing for end-of-life solutions. New wind turbines should be designed for disassembly and remanufacturing, which help to reduce the duration of the dismantling process and its complexity. In addition the likelihood of damaging the parts during these activities decreases, resulting in higher remanufacturing potential (Ortegon, et al., 2013).

7.1.5 Recycling

Most of the wind turbine mass comes from the tower, blades and gearbox, and the main materials are steel and fibreglass. Due to the demand and technological availability for recycling, some materials for example steel and aluminium have a higher scrap value. These types of commodity materials do not require a lot of efforts since there are already efficient ways to recover them and a market for demand and supply. Other turbine parts, like blades, which are made out of composite materials and generators that use permanent magnets made out of rare earth elements, need more efforts and attention. A direct-drive turbine can need around 600 kg of magnet material per MW, with around 30% of it being rare earth elements, which is a relatively high amount of material that should be handled properly. When the blades are not reused or remanufactured, they are recycled in three scenarios: grinding, pyrolysis and thermal recycling (Ortegon, et al., 2013; Shaw & Constantinides, 2012).

Blade recycling is considered to be a challenge and estimations describe that around 10 kg of blade material is required for 1 kW installed power. Since both the size of the turbines and their quantity is getting bigger with years, it is assessed, that per year around 225 000 tonnes of blade material needs to be recycled worldwide by year 2034. Blades are difficult to recycle due to the characteristics of the composite material and in addition they cannot be remoulded like thermoplastics (Toncelli, 2014).

So far landfilling has been banned in Germany and that can also be the future requirement in other European countries. Glass fibre reinforced polymers have a low heating value and therefor incineration is not considered to be the optimal solution. Recycling is a better alternative, but relevant markets are not developed enough, processing costs are high and the quality of recyclates is low, resulting in few established recycling processes. The outcome of recycling blades is fibres with lower quality and strength than virgin materials that are in most cases used as fillers, for example in plastic lumber or as reinforcement for polyester and epoxy (Toncelli, 2014). Recycled fibreglass can also be used for concrete, architectural cladding panels, in concrete products like roof-tiles; pre-cast paving slabs and wall elements; concrete paving blocks (Bre, 2009).

Another recycling option is co-processing, when the composites are used in cement kilns. It is supposedly cost effective and reduces the negative environmental impacts related to cement production. The composites are both used as raw materials and alternative fuel; it replaces fossil fuels like coal, petroleum and gas (EuCIA, 2011).

7.2 Industrial symbiosis in wind turbine industry

In general, industrial symbiosis is seen as collaboration between industries or companies, where wastes or by-products from one are used as a raw material by others. In addition to that, industrial symbiosis can also be about sharing knowledge and ideas for an improved outcome. One example of that could be the GenVind project where in addition to other parties, competitive wind power companies like Siemens Wind Power, Vestas and LM Wind Power work together with the purpose to develop technologies for sustainable plastic composite recycling. Wind turbine blades are considered to be the most complex part of a turbine to recycle and with this collaboration there is potential for better solutions. Ideas, knowledge and experience are shared in order to improve not only the wind turbine industry but also waste management and optimize resource use. End-of-life blades that are considered to be waste can be resources for example for furniture or building material manufacturers. Recycled plastic composites could be used for reinforcement in concrete; in noise barriers or building panels (GenVind, n.d.). By informing and including potential partners it is possible to achieve an even wider industrial symbiosis network because every member can potentially have some by-products or waste that could be used by someone new. Partnership is one of the key elements to get businesses to see each other as not only competitors but also as potential for new ways of collaboration.

When considering the more traditional way of industrial symbiosis wind turbine manufacturers should analyze their production processes to determine whether there is potential for new ways of collaboration. For example, when producing turbine blades there could be some excess heat or material leftovers that could be used somewhere else. Instead of “heating the air outdoors” heating costs could be decreased by using heat coming from the production facilities in office areas or close by buildings. Another possibility would be an opposite solution – getting excess heat from someone else to use in blade manufacturing. In this case the proximity of different industries is important. This applies to the production of not only blades but every wind turbine part and not only to heat but also materials, waste, services, water and energy. In order for industrial symbiosis to work there needs to be a clear overview of one’s production processes and communication with other companies to build new business relations.

There is also the possibility of symbiotic or collaborative relationship for industries with close proximity to use wind power for their electricity needs. Shared systems can help decrease energy costs and in addition provide a more “green” source of electricity. Depending on the location of companies, their power needs, whether it pays off and if it even is possible to put up wind turbines. In areas with several industries and relevant location (enough space and wind) it should be investigated how this could be done. Investing together into wind turbines that provide energy can help reduce the pressure from general energy prices. In addition it can be a way to show that efforts towards more environmental friendly solutions are made and that can be used for marketing or image building (Dong, et al., 2002).

7.3 Designing out waste

In order to improve waste management each phase in a products’ life cycle needs to be taken into consideration. Focusing on the waste handling leads to dealing with the result not the cause. Designers are the key stakeholders in developing products that contribute to sustainability. Decisions made during design phase can help reduce resource use, give longer life span to products and make them easier to repair, reuse and recycle. These measures support waste reduction and resource efficiency. In addition WEEE Directive 2012/19/EU emphasizes the importance of eco-design and Directive 2009/125/EC establishes framework for eco-design for energy-related products, meaning that, the relevance of design is recognized on EU level. In addition to regulations, circular economy has a focus on effective design as well.

How can it be done?

First steps in order to reduce waste can be done when choosing materials. For example, using already recycled materials will avoid waste generation and help decrease the need for virgin materials. Lightweight materials can lower waste quantities by mass and be easier to transport and install. Best available technology for manufacturing can help reduce material losses and avoid some waste production. In addition it is useful to know the composition of materials that are used to avoid hazardous substances, keep the materials as pure as possible and find suppliers that support responsible sourcing. Using homogenous materials that do not contain toxic substances makes it easier and cheaper to reuse and later recycle a product.

Design decisions should include repair, reuse and recycling possibilities for a product. Modular design can be helpful because it makes disassembly easier and faster, it allows broken parts to be replaced or repaired more conveniently thus increasing the chances of keeping a product in circulation. When it is difficult to separate parts and materials it is more likely that the entire product gets disposed and materials will not be salvaged. For this reason the way how parts in a product are connected and attached should be considered as well. For example, if there are screws, it is better to keep them the same size if possible, in order to make disassembly, repairing and recycling easier because less different tools are required. Even small additions like marking the potentially hazardous parts can improve the recycling process since it saves time for the recyclers if they know what they are dealing with.

A good example of a company who puts effort into managing their waste better is Maersk. Maersk uses a product passport for their vessel that is continually updated throughout the lifespan of the ship. They list the material composition of the main parts with the purpose to improve the recycling (Maersk, 2014). The shipping industry, like wind turbine industry, is dependent on resources that are finite. Even with materials that already have high recycling rates it is important to make sure that they do not get mixed with others that can affect the recycling potential and quality. Wind turbine industry could learn from Maersk's experience and try to implement a similar system for their turbines to maximize the recycling potential.

Design phase is the key stage in achieving a more efficient waste management. Measures can be taken that decrease the need of materials and waste deriving from the production. Circular economy principles can be taken as a stepping stone when making design decisions in order to make the products more easily maintainable, reusable, and recyclable and keep them longer in circulation and avoiding waste generation. In addition industrial symbiosis potential should be taken into consideration. There might be possibilities to develop cooperation with other industries or companies, to cut back on some costs and decrease the negative impact on the environment. When these aspects are considered already in the design phase some relevant chances can be made in order to improve waste generation and management throughout the entire lifecycle of a product.

Summary of Chapter 7

Circular Economy and Wind Turbines

Reduce

- Design towards material efficient products
- Increase life cycle performance
- Material substitution for more sustainable ones
- Minimize waste quantities during production processes

Repair and Maintain

- With monitoring and reparation measures it is possible to expand a turbines life span

Reuse

- Lower price
- Less waiting time for purchase
- Environmental benefits

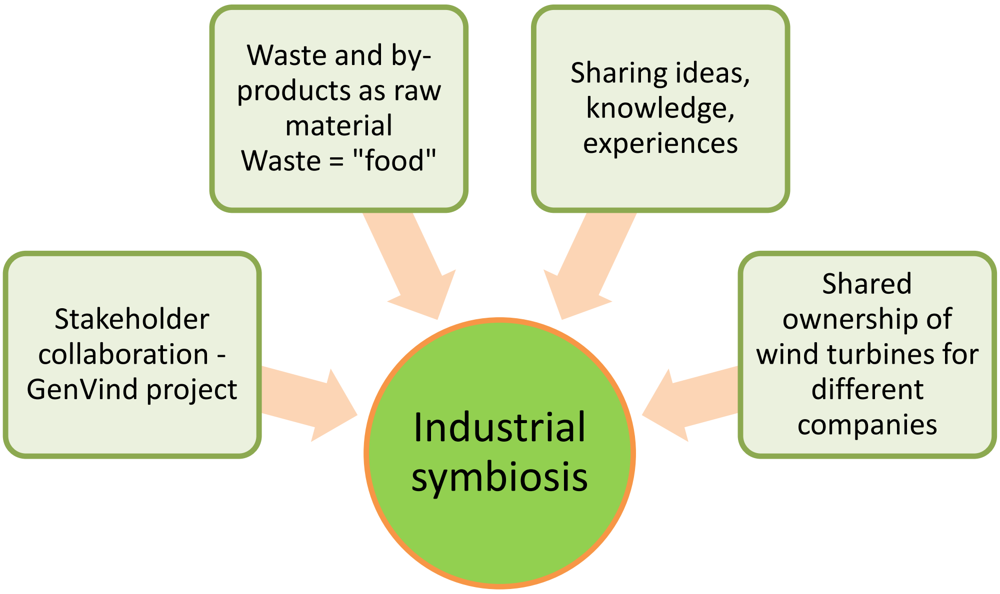
Refurbish

- Functionality is restored to “as new” quality
- Lower price

Recycle

- The majority of the wind turbine parts are recyclable
- Fibre glass is not easy and non-profitable to recycle

Industrial Symbiosis and Wind Turbines



8. Conclusion

With increasing human population the consumption and need for resources and energy grows as well. Using renewable sources is a way to satisfy the needs for energy and simultaneously decrease the use of some finite natural resources like fossil fuels. Currently wind energy is the fastest growing renewable energy source and in order to build turbines and wind farms, materials like steel, fibreglass, copper and iron, amongst others, are required. After the lifespan of 20 – 30 years a wind turbine has reached its end-of-service life and after that wind farms get repowered or decommissioned.

The goal of this thesis is to analyse and answer the main question: *How are the end-of-service wind turbines managed today and how could it be improved?* To answer this question the waste management of end-of-service life wind turbines is investigated in three aspects with relevant sub-questions.

To get an understanding on the current situation the first sub-question has to be answered. *How are the materials in end-of-service wind turbines handled today?* The main materials used for wind turbines are steel, iron cast, glass fibre and copper. With metals the common practice is recycling and it is already well-developed, meaning that, these materials are not considered problematic. The challenges with wind turbine waste management are mostly related to the blades, which consist of composite materials that are difficult to recycle thus resulting in higher chances of disposal.

To find improvement ways it was investigated, *how could material loops be closed for sustainable resource use?* With the problem of resource exploitation through wasteful consumption ways, the concept of circular economy can be of help. Circular economy emphasizes the need for closing material loops which means that products and materials are kept in the circulation as long as possible instead of disposal. Through preventive maintenance and reparation, reusing, remanufacturing and recycling the quantities of waste and virgin materials are reduced. It is important to take these aspects into consideration already in the design phase, since decisions made at that time affect the effectiveness of handling the waste at the end-of-life phase.

In addition to circular economy the concept of industrial symbiosis can be useful for better waste management and help close material loops. Traditional industrial symbiosis is considered as companies or industries exchanging their waste or by-products, but it can also be through sharing ideas and information. Again, the quantities of waste and the need for virgin materials are reduced when industries find collaboration ways and use waste from one as a resource for other. Communication and dialogue between companies is the key for better chances to discover the potential of industrial symbiosis.

The third and final aspect to answer the main research question is to figure out *how to communicate waste management related information between stakeholders?* There are different parties that play a role during the life cycle of a wind turbine from manufacturing and installation to decommissioning and recycling. Siemens Wind Power has already recycling guidelines for some of their turbine parts and this report has one for WEEE and the cables as well. It would be useful to have a similar document with all the relevant information on the exact material composite, reuse, recycling and disposal options and recommendations for improvements for every part in a wind turbine. These guidelines could be used as a stepping point to identify problematic areas, communicate information to customers, designers, suppliers, government organisations, recycling companies and other interested parties. Having an easily understandable information sheet can decrease the problems deriving from the lack of communications and helps figure out how to improve the way end-of-service wind turbines are handled today.

To answers how end-of-service wind turbine management could be improved the key lies in circular economy. It helps to emphasize the importance of design choices, realize that waste can be seen as a resource and helps identify measures to keep materials and products in circulation for longer. Industrial symbiosis is helpful as well, by introducing additional collaboration ways for waste reduction and sustainable resource use. In order to communicate relevant information between stakeholders, developing recycling guidelines for all the parts of a wind turbine is recommended.

9. Bibliography

4C Offshore, 2015. *Support Structures for Offshore Wind Turbines.* [Online] Available at: http://www.4coffshore.com/windfarms/support-structures-for-offshore-wind-turbines-aid268.html
[Accessed 12 February 2015].

American Iron and Steel Institution, n.d. *Steel Works.* [Online] Available at: http://www.steel.org/Sustainability/Steel%20Recycling.aspx
[Accessed 08 March 2015].

American Wind Energy Association, 2013. *Anatomy of a Wind Turbine.* [Online] Available at: http://www.awea.org/Resources/Content.aspx?ItemNumber=5083
[Accessed 10 February 2015].

Ancona, D. & McVeigh, J., 2011. *Wind Turbine - Materials and Manufacturing Fact Sheet.* [Online]
Available at: http://www.perihq.com/documents/windturbine-materialsandmanufacturing_factsheet.pdf
[Accessed 6 March 2015].

Andersen, P. D., Bonou, A., Beauson, J. & Brøndsted, P., 2014. *Recycling of Wind Turbines,* Copenhagen: DTU.

Arnold Magnetic Technologies, 2012. *The Important Role of Dysprosium in Modern Permanent Magnets ,* s.l.: Arnold Magnetic Technologies.

Ashihara, S. et al., 2008. *Recycling of Insulation of 600V XLPE Cable Using Supercritical Alcohol.* [Online]
Available at:
http://ieeexplore.ieee.org.zorac.aub.aau.dk/stamp/stamp.jsp?tp=&arnumber=4664473
[Accessed 23 April 2015].

Barnes, Z., 2011. *Offshore wind: Opportunities for the composites industry.* [Online]
Available at:
http://www.bvgassociates.co.uk/Portals/0/BVG%20Composites%20presentation%20ZHB%20110504.pdf
[Accessed 3 March 2015].

BBC, 2013. *What to do with the world's unwanted wind turbines?.* [Online] Available at: http://www.bbc.com/news/uk-scotland-highlands-islands-23048093
[Accessed 4 March 2015].

Binnemans, K. et al., 2013. Recycling of rare earths: a critical review. *Journal of Cleaner Production,* Volume 51, pp. 1-22.

BlueScope Steel, n.d.. *Recycling in the Steel Industry.* [Online]
Available at:
https://www.bluescopesteel.com/media/10558/Recycling%20in%20the%20Steel%20I

ndustry.pdf
[Accessed 6 March 2015].

Borealis, n.d.. *Recycling plastic from cable waste.* [Online] Available at: http://www.borealisgroup.com/Global/Polyolefins/Energy%20Infrastructure/Cables/medium-voltage-mv-cables/recycling-plastic-from-cable-waste.pdf
[Accessed 23 April 2015].

Boythorpe Wind Energy, n.d.. *Refurbished wind turbines.* [Online] Available at: http://www.boythorpewindenergy.co.uk/refurbished-wind-turbines/
[Accessed 10 April 2015].

Bre, 2009. *Applications of glass reinforced plastic (GFR) waste in concrete composites.* [Online] Available at: http://www.bre.co.uk/filelibrary/pdf/rpts/BeAware_GRP_Waste_in_Concrete_Briefing_Document__D3.9.2.pdf
[Accessed 14 April 2015].

Brookie, A., 2013. *Guide to Starting Collection & Recycling For Lighting Equipment.* [Online]
Available at: http://www.ecreee.org/sites/default/files/event-att/philips-andrew-lignting-cr.pdf
[Accessed 21 May 2015].

Business Recycling, 2013. *Why Recycle?.* [Online] Available at: http://businessrecycling.com.au/recycle/iron-steel
[Accessed 15 March 2015].

Cabrera-Cruz, R. B. E. et al., 2014. Perspectives of Waste Electrical and Electronic Equipment in Tampico, Mexico. *Journal of Environmental Protection,* Volume 5, pp. 1266-1276.

Cherrington, R. et al., 2012. Producer responsibility: Defining the incentive for recycling composite wind turbine blades in Europe. *Energy Policy,* Issue 47, pp. 13-21.

Circular Economy Toolkit, n.d.. *Introduction - Refurbish/Remanufacture.* [Online] Available at: http://circulareconomytoolkit.org/refurbish-remanufacture.html
[Accessed 10 April 2015].

Copper Development Association, n.d. *Recycling of Copper.* [Online] Available at: http://www.copper.org/environment/lifecycle/ukrecyc.html
[Accessed 2015 March 06].

Costa, I. & Ferrão, P., 2010. A case study of industrial symbiosis development using a middle-out approach. *Journal of Cleaner Production,* Issue 18, pp. 984-992.

Dalrymple, I. & Wright, N., 2007. An integrated approach to electronic waste (WEEE) recycling. *Circuit World,* 33(2), pp. 52-58.

Daubney, K., 2013. *Repowering trend enlivens second-hand turbine market.* [Online] Available at: http://www.windpowermonthly.com/article/1183990/repowering-trend-enlivens-second-hand-turbine-market
[Accessed 10 April 2015].

Directive 2012/19/EU, 2012. *Waste electrical and electronic equipment (WEEE).* [Online]
Available at: http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32012L0019&from=EN
[Accessed 5 May 2015].

Dong, J., Gonzalez, J., Memon, L. & Murrow, D. K., 2002. *The Application of Industrial Symbiosis to the Puerto Rico Techno-Economic Corridor.* [Online] Available at: http://is4ie.org/resources/Documents/2002%20PRTEC.pdf
[Accessed 20 April 2015].

Dutchwind, n.d.. *Used wind turbines.* [Online] Available at: http://dutchwind.com/
[Accessed 10 April 2015].

Ecoenergy Ventures, n.d.. *What is the 'Waste Management Hierarchy'?.* [Online] Available at: http://www.ecoenergyventures.com/about/why-waste-to-energy/
[Accessed 19 February 2015].

Eldan Recycling A/S, n.d.. *Cable recycling.* [Online] Available at: http://www.eldan-recycling.com/content/cable-recycling-0
[Accessed 23 April 2015].

Electronics TakeBack Coalition, n.d.. *About Producer Responsibility.* [Online] Available at: http://www.electronicstakeback.com/promote-good-laws/about-producer-responsibility/
[Accessed 6 May 2015].

Ellen MacArthur Foundation, 2013. *The circular model - an overview.* [Online] Available at: http://www.ellenmacarthurfoundation.org/circular-economy/circular-economy/the-circular-model-an-overview
[Accessed 8 April 2015].

Ellen MacArthur Foundation, 2013. *Towards the Circular Economy,* s.l.: Ellen MacArthur Foundation.

Ellen MacArthur Foundation, 2014. *Towards the Circular Economy,* s.l.: Ellen MacArthur Foundation.

Ellen MacArthur Foundation, n.d.. *Kalundborg Symbiosis.* [Online] Available at: http://www.ellenmacarthurfoundation.org/case_studies/kalundborg-symbiosis
[Accessed 3 April 2015].

Energenz, n.d.. *Industrial Symbiosis.* [Online]
Available at: http://www.energenz.com/themes/circular-economy/industrial-symbiosis/
[Accessed 19 February 2015].

Environmental and Energy Study Institute, 2010. *Offshore Wind Energy ,* Washington: EESI.

Environmental Protection Agency, 2014. *Steel.* [Online]
Available at: http://www.epa.gov/epawaste/conserve/materials/steel.htm
[Accessed 14 March 2015].

EuCIA, 2011. *Composites Recycling Made Easy.* [Online]
Available at: http://www.nordic-composite.com/admin/common/getImg2.asp?Fileid=1238
[Accessed 14 April 2015].

European Commission, 2011. *Roadmap to a Resource Efficient Europe.* [Online]
Available at: http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52011DC0571&from=EN
[Accessed 19 February 2015].

European Commission, 2015. *Recast of the RoHS Directive.* [Online]
Available at: http://ec.europa.eu/environment/waste/rohs_eee/index_en.htm
[Accessed 5 May 2015].

European Commission, 2015. *Waste Electrical & Electronic Equipment (WEEE).* [Online]
Available at: http://ec.europa.eu/environment/waste/weee/index_en.htm
[Accessed 5 May 2015].

European Commission, n.d.. *Directive 2008/98/EC on waste (Waste Framework Directive).* [Online]
Available at: http://ec.europa.eu/environment/waste/framework/
[Accessed 19 February 2015].

European Commission, n.d.. *Renewable Energy.* [Online]
Available at: http://ec.europa.eu/energy/en/topics/renewable-energy
[Accessed 21 April 2015].

European Commission, n.d.. *Waste.* [Online]
Available at: http://ec.europa.eu/environment/waste/
[Accessed 29 April 2015].

European Commisssion, 2014. *Towards a circular economy: A zero waste program for Europe.* [Online]
Available at: http://eur-lex.europa.eu/resource.html?uri=cellar:aa88c66d-4553-11e4-a0cb-01aa75ed71a1.0022.03/DOC_1&format=PDF
[Accessed 26 February 2015].

European Wind Energy Assosiation, n.d.. *How a wind turbine works.* [Online] Available at: http://www.ewea.org/wind-energy-basics/how-a-wind-turbine-works/ [Accessed 3 April 2015].

Eurostat, n.d.. *Renewable energy statistics.* [Online] Available at: http://ec.europa.eu/eurostat/statistics-explained/index.php/Renewable_energy_statistics
[Accessed 21 April 2015].

Garcia Sànchez, R., Pehlken, A. & Lewandowski, M., 2014. *On the Sustainability of Wind Energy Regarding Material Usage.* [Online] Available at: http://acta.fih.upt.ro/pdf/2014-1/ACTA-2014-1-06.pdf [Accessed 8 April 2015].

Gardner, P. et al., n.d.. *Wind Energy the Facts - Part I Technology,* s.l.: s.n.

GenVind, n.d.. *Mission.* [Online] Available at: http://genvind.net/Legal/Mission_EN.htm [Accessed 4 March 2015].

Gill, E., 2012. *Danish offshore strategy moves closer to shore.* [Online] Available at: http://www.windpowermonthly.com/article/1161698/danish-offshore-strategy-moves-closer-shore
[Accessed 23 April 2015].

Global Wind Energy Council, 2012. *Wind Power FAQs.* [Online] Available at: http://www.gwec.net/faqs/how-many-wind-turbines-world/ [Accessed 2 April 2015].

Global Wind Energy Council, n.d.. *Global Offshore.* [Online] Available at: http://www.gwec.net/global-figures/global-offshore/ [Accessed 18 May 2015].

Global Wind Energy Council, n.d.. *Global Statistics.* [Online] Available at: http://www.gwec.net/global-figures/graphs/ [Accessed 8 April 2015].

Greenergy, n.d. *Wind Turbine Tower Internals.* [Online] Available at: http://www.windgreenergy.com/product_in.asp?bigclassid=7 [Accessed 3 March 2015].

Harrell, M. & Bradley, M., 2009. *Data Collection Methods,* Santa Monica: RAND Corporation.

Hart, C., 1998. *Doing a Literature Review: Releasing the Social Science Research Imagination.* London: Sage Publications.

Hatch, G., 2009. *How does the use of permanent magnets make wind turbines more reliable?.* [Online]
Available at: http://www.terramagnetica.com/2009/08/03/how-does-using-permanent-

magnets-make-wind-turbines-more-reliable/
[Accessed 9 March 2015].

Health and Safety Executive, n.d.. *Waste Electrical and Electronic Equipment recycling (WEEE).* [Online]
Available at: http://www.hse.gov.uk/waste/waste-electrical.htm#treatment
[Accessed 19 May 2015].

Hexcel, n.d.. *Nacelle.* [Online]
Available at: http://www.hexcel.com/solutions/wind-energy/wnacelle
[Accessed 3 March 2015].

Iamgold Corporation, 2012. *RARE EARTH ELEMENTS 101.* [Online]
Available at: http://www.iamgold.com/files/REE101_April_2012.pdf
[Accessed 9 March 2015].

Januário, C., Semino, S. & Bell, M., 2007. *Offshore Windfarm Decommissioning: A proposal for guidelines to be included in the European Maritime Policy,* s.l.: s.n.

Joshi, S. V., Drzal, L. T., Mohanty, A. K. & Arora, S., 2004. Are natural fiber composites environmentally superior to glass fiber reinforced composites?. *Composites: Part A,* Issue 35, pp. 371-376.

Kaiser, M. J. & Snyder, B., 2011. Offshore wind decommissioning regulations and workflows in the Outer Continental Shelf United States. *Marine Policy,* 23 January, Volume 36, pp. 113-121.

Kapur, A. & Graedel, T. E., 2004. Industrial Ecology. *Encyclopedia of Energy*, pp. 373-382.

Kasper, A., 2008. *Recycling composites: FAQs.* [Online]
Available at: http://www.reinforcedplastics.com/view/436/recycling-composites-faqs/
[Accessed 5 March 2015].

Larsen, K., 2009. Recycling wind turbine blades. *Renewable Energy Focus,* 9(7), pp. 70-73.

Lee, C., 2014. *Rare earth recycling: Is it worth it?.* [Online]
Available at: http://arstechnica.com/science/2014/03/rare-earth-recycling-is-it-worth-it/
[Accessed 9 March 2015].

Lenntech, n.d.. *Neodymium.* [Online]
Available at: http://www.lenntech.com/periodic/elements/nd.htm
[Accessed 9 March 2015].

Lombardi, R. D., Lyons, D., Shi, H. & Agarwal, A., 2012. Industrial Symbiosis. Testing the Boundaries and Advancing Knowledge. *Journal of Industrial Ecology,* 16(1), pp. 2-7.

Maersk, 2014. *Cradle to Cradle.* [Online]
Available at: http://www.maersk.com/en/hardware/triple-e/the-hard-facts/cradle-to-

cradle
[Accessed 11 May 2015].

Marshall, J., 2014. *Why Rare Earth Recycling Is Rare (And What We Can Do About It).* [Online]
Available at: http://ensia.com/features/why-rare-earth-recycling-is-rare-and-what-we-can-do-about-it/
[Accessed 9 March 2015].

Martinez, E. et al., 2009. Life cycle assessment of a multi-megawatt wind turbine. *Renewable Energy,* Issue 34, pp. 667-673.

McCann, D. & Wittmann, A., 2015. *E-waste Prevention, Take-back System Design and Policy Approaches,* s.l.: Step Green Paper Series .

Mishnaevsky, L., 2011. *Composite Materials in Wind Energy Technology,* Oxford: Eolss Publishers.

Newport Metal Recycling, n.d. *Cast Iron Recycling.* [Online]
Available at: http://www.nmrscrap.com/cast-iron-recycling.html
[Accessed 08 March 2015].

Nexans, n.d.. *Products and solutions.* [Online]
Available at: http://www.nexans.co.uk/eservice/UK-en_GB/navigate_238480/Products_and_solutions.html
[Accessed 23 April 2015].

OCS Renewable Energy EIS, n.d. *Wind Energy Potential on the U.S. Outer Continental Shelf.* [Online]
Available at: http://www.ids-environment.com/Common/Paper/Paper_157/Environment%20-Sample.htm
[Accessed 5 April 2015].

OECD, n.d.. *Extended Producer Responsibility.* [Online]
Available at: http://www.oecd.org/env/tools-evaluation/extendedproducerresponsibility.htm
[Accessed 6 May 2015].

Ortegon, K., Nies, L. F. & Sutherland, J. W., 2013. Preparing for end of service life of wind turbines. *Journal of Cleaner Production,* Issue 39, pp. 191-199.

Ortegon, K., Nies, L. F. & Sutherland, J. W., 2014. The Impact of Maintenance and Technology Change on Remanufacturing as a Recovery Alternative for Used Wind Turbines. *Procedia CIRP,* Issue 15, pp. 182-188.

Pagh Jensen, J., 2015. *Cable data* [Interview] (24 April 2015).

Pagh Jensen, J., 2015. *Materials used by Siemens Wind Power* [Interview] 2015.

Pagh Jensen, J., 2015. *WEEE parts* [Interview] (4 May 2015).

Phakos, C., 2011. *What is the environmental footprint for manufacturing fiberglass windows? Is it safe for workers and the environment?.* [Online] Available at: http://greenhomeguide.com/askapro/question/what-is-the-environmental-footprint-for-manufacturing-fiberglass-windows-i-m-interested-in-fiberglass-because-it-s-supposedly-more-energy-efficient-than-aluminum [Accessed 5 March 2015].

Physics Planet, n.d. *Three Laws of Thermodynamics.* [Online] Available at: http://www.physicsplanet.com/articles/three-laws-of-thermodynamics [Accessed 15 March 2015].

Pickering, S. J., 2006. Recycling technologies for thermoset composite materials—current status. *Composites Part A: Applied Science and Manufacturing,* 37(8), p. 1206–1215.

Rademakers, L. W., Braam, H. & Obdam, T. H., 2011. Operation and maintenance of offshore wind energy systems. In: J. D. Sørensen & J. N. Sørensen , eds. *Wind Energy Systems. Optimising design and construction for safe and reliable operation.* Cambridge: Woodhead Publishing Limited, p. 598.

Ramboll Wind, 2010. *Anholt Offshore Wind Farm.* [Online] Available at: http://www.ens.dk/sites/ens.dk/files/supply/renewable-energy/wind-power/offshore-wind-power/environmental-impacts/project_description.pdf [Accessed 23 April 2015].

Recolight, n.d.. *The Recycling Process.* [Online] Available at: http://www.recolight.co.uk/lighting-producers/how-we-recycle.aspx [Accessed 21 May 2015].

Repowering Solutions, n.d.. *Refurbished wind turbine.* [Online] Available at: http://www.repoweringsolutions.com/english/refurbished_wind_turbines/ [Accessed 10 April 2015].

Resources SchoolScience, n.d. *Extracting Copper.* [Online] Available at: http://resources.schoolscience.co.uk/CDA/11-14/chemistry/copch32pg3.html [Accessed 07 March 2015].

Shaw, S. & Constantinides, S., 2012. *Permanent Magnets: the Demand for Rare Earths.* [Online] Available at: http://www.roskill.com/reports/minor-and-light-metals/news/download-roskills-paper-on-permanent-magnets-the-demand-for-rare-earths [Accessed 18 May 2015].

Shutterstock, n.d.. [Online] Available at: http://ak3.picdn.net/shutterstock/videos/1568092/preview/stock-footage-offshore-wind-farm-seamless-loop.jpg [Accessed 3 March 2015].

Siemens AG, 2011. *New dimensions,* Erlangen: Siemens AG.

Siemens AG, 2011. *Oceans of Opportunities,* Erlangen: Siemens AG.

Siemens, n.d.. *Wind Turbine SWT-3.6-107.* [Online]
Available at: http://www.energy.siemens.com/hq/en/renewable-energy/wind-power/platforms/g4-platform/wind-turbine-swt-3-6-107.htm#content=Technical%20Specification
[Accessed 4 March 2015].

Smith, E., 2008. *Using secondary data in educational and social research.* Berkshire: Open University Press.

Stolpe, M. et al., 2014. *Offshore Wind Energy Developments,* s.l.: s.n.

The European Wind Energy Association, 2015. *Wind in power 2014 European Statistics.* [Online]
Available at: http://www.ewea.org/fileadmin/files/library/publications/statistics/EWEA-Annual-Statistics-2014.pdf
[Accessed 21 April 2015].

The Guardian, 2008. *Timeline: The history of wind power.* [Online]
Available at: http://www.theguardian.com/environment/2008/oct/17/wind-power-renewable-energy
[Accessed 2 April 2015].

The Telegraph, 2011. *World's largest renewable energy projects.* [Online]
Available at:
http://www.telegraph.co.uk/finance/newsbysector/energy/8390731/Worlds-largest-renewable-energy-projects-in-pictures.html?image=7
[Accessed 10 February 2015].

Toncelli, C., 2014. *Reuse of shredded composite in new polymer composite,* Roskilde: DTU Wind Energy.

Tongyu Heavy Industry, n.d. *Main Shaft for WTG.* [Online]
Available at: http://en.tongyuheavy.com/html/chanpinzhizao/cp/zhuzhou/
[Accessed 17 March 2015].

Truttmann, N. & Rechberger, H., 2006. Contribution to resource conservation by reuse of electrical and electronic household appliances. *Resources, Conservation and Recycling,* 48(3), pp. 249-262.

UNEP, 2011. *Recycling Rates of Metals,* Paris: s.n.

Walton, S. & Parker, D., 2008. *The Potential for Remanufacturing of Wind Turbines.* [Online]
Available at: http://www.remanufacturing.org.uk/pdf/story/1p259.pdf?-session=RemanSession:42F949BD0320f33D1DvOug2831AA
[Accessed 10 April 2015].

West, L., n.d. *The Benefits of Metal Recycling.* [Online] Available at: http://environment.about.com/od/recycling/a/metal-recycling.htm [Accessed 08 March 2015].

Wind Energy-The Facts, 2009. *Technology.* [Online] Available at: http://www.wind-energy-the-facts.org/index-2.html [Accessed 9 February 2015].

Wind Measurement International, n.d.. *Operational and Maintenance Costs for Wind Turbines.* [Online]
Available at: http://www.windmeasurementinternational.com/wind-turbines/om-turbines.php
[Accessed 8 April 2015].

Windpower Engineering & Development, 2011. *What types of metals are used in wind turbines?.* [Online]
Available at: http://www.windpowerengineering.com/design/materials/metals/ [Accessed 10 February 2015].

WindPower Monthly, n.d. *Turbine Manufacturers.* [Online] Available at: http://www.windpowermonthly.com/turbine-manufacturers [Accessed 12 February 2015].

Wiser Recycling, n.d.. *WEEE Reuse & Recycling.* [Online] Available at: http://www.wiserrecycling.co.uk/our-processes/weee-reuse/ [Accessed 6 May 2015].

World Steel Association, 2012. *Steel Solutions in the Green Economy,* Brussels: World Steel Association.

WRAP, 2014. *What is industrial symbiosis?.* [Online] Available at: http://www.wrap.org.uk/content/what-industrial-symbiosis [Accessed 19 February 2015].

Wyse, S. E., 2011. *What is the Difference between Qualitative Research and Quantitative Research?.* [Online]
Available at: http://www.snapsurveys.com/blog/what-is-the-difference-between-qualitative-research-and-quantitative-research/
[Accessed 13 May 2015].

Yang, Y. et al., 2012. Recycling of Composite Materials. *Chemical Engineering and Pocessing,* Issue 51, pp. 53-68.

Yellishetty, M., Mudd, G. M., Ranjith, P. G. & Tharumarajah, A., 2011. Environmental life-cycle comparisons of steel production and recycling: sustainability issues, problems and prospects. *Environmental Science & Policy,* Volume 14, pp. 650-663.

Zipp, K., 2012. *Cables 101.* [Online]
Available at: http://www.windpowerengineering.com/design/electrical/cables/cables-101/
[Accessed 3 April 2015].

Zoeteman, B. C., Krikke, H. R. & Venselaar, J., 2010. Handling WEEE waste flows: on the effectiveness of producer responsibility in a globalizing world. *The International Journal of Advanced Manufacturing Technology,* 47(5-8), pp. 415-436.

Cover picture: http://www.triplepundit.com/2009/12/4-factors-shaping-the-wind-energy-industry-in-2009/