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Abstract

The wind industry has been growing steadily over the past decade due to an increasing focus on developing renewable energy. A wind turbine has a designed lifetime of 20 to 30 years where almost 90% of the turbine can be recycled at end-of-life (EoL). The challenge is the blades, which are made of composites, usually glass fibre-reinforced plastics (GFRP) or carbon fibre-reinforced plastics (CFRP). The common practice for many years has been to landfill the decommissioned blades, gaining no benefit from the material. Due to the steady development of new wind farms, the waste problem is expected to increase and there is therefore a necessity for new solutions.

The European Union (EU) plans to become climate neutral by 2050, where a transition to a circular economy is one of the prerequisites for the EU to reach its goals. Circular economy is an economic system of closed loops, meaning that raw materials, components, and products lose their value as little as possible. In a circular economy, waste is considered a design flaw, and the possible waste should be treated as a resource.

In this thesis, the wind turbine blade supply chain and the current possibilities for handling wind turbine blade waste was investigated. Then the possibility for a circular economy for wind turbine blades were investigated. By using circular economy strategies from the building sector and the Ellen MacArthur Foundation's definition of circular economy, action that can lead towards a circular economy for wind turbine blades were proposed. A circular economy framework for wind turbine blades was also made.

The different EoL-options for wind turbine blades (reuse, repurposing and recycling) were investigated. The market for direct reuse of wind turbine components has been active for over a decade and is the best option as it keeps the blade for its original purpose. Reusing the blades will further contribute to production of clean energy. Repurposed blades have been demonstrated for use in bridges, playground, and urban furniture. The lifetime of the repurposed applications can be up to 60 years and the best environmental benefit is achieved where it substitutes steel and concrete. For recycling, three methods have reached a Technological Readiness Level (TRL) of 9: mechanical recycling, co-processing, and pyrolysis. The recycled material has not been reintroduced into new wind turbine blades by any of these methods. The most promising alternative to these methods is solvolysis, which enables the recovery of long fibres and has possibilities for using the recovered material in new wind turbine blades. In addition, the design phase for turbine blades was investigated. One of the major developments is the change from thermoset to thermoplastic resin systems, which enables easier recycling through solvolysis. The next step towards a circular economy for wind turbine blades will be to use recycled fibres in the design of new blades.

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Abbreviations

For simplification, abbreviations have been used throughout the thesis. The explanation and corresponding first time occurrence for each abbreviation is presented in Table 0.1 below, sorted in alphabetical order.

Table 0.1: List of abbreviations used in the thesis with explanation and page of first occurrence.

Abbreviation	Explanation	Page
AEP	Annual Energy Production	28
CEAP	Circular Economy Action Plan	3
CF	Carbon Fibre	14
CFRP	Carbon Fibre Reinforced Plastic	5
EoL	End-of-Life	5
EPR	Extended Producer Responsibility	47
ESM	Erosion Safe Mode	28
GF	Glass fibre	14
GFRP	Glass Fibre Reinforced Plastic	6
GHG	Greenhouse Gas	1
HTP	High Temperature Pressure Solvolysis	15
HVPF	High Voltage Pulse Fragmentation	15
IEA	International Energy Agency	1
LEE	Leading Edge Erosion	9
LTP	Low Temperature Pressure Solvolysis	15
NVE	The Norwegian Water Resources and Energy Directorate	5
O&M	Operation and Maintenance	5
PET	Polyethylene Terephthalate	8
PVC	Polyvinyl Chloride	8
SAN	Styrene Acrylonitrile	8
TRL	Technology Readiness Level	16

1 Introduction

Over the last decades, the climate crisis with the global challenges of agreeing on a global reduction scheme of GHG (greenhouse gas) emissions has been one of the major problems the world has been facing. In the struggle towards a carbon neutral society the world must undergo some major changes, primarily in the way energy is produced and consumed. As of 2021 over half of the world's electricity production is by fossil fuels. The shift to green energy resources is therefore seen as one of the most important actions in reaching carbon neutrality and meeting the requirements of the Paris Agreement.

The European Union (EU) has agreed on a set of policy initiatives called the European Green Deal, with the aim of making the EU climate neutral by 2050. In the EU, production and use of energy accounts for around 75% of the EU's total GHG emissions and the transition to green energy is one of the major forces of action (European Commission, 2021). The EU Taxonomy was launched in order to create a common classification system for sustainable activities to enable the EU to reach the objectives of the Green Deal (European Commission, 2020). The taxonomy lists six environmental objectives for sustainable economic activities: climate change mitigation, climate change adaptation, water & marine resources, circular economy transition, pollution prevention & control and biodiversity & ecosystem protection. To be regarded as environmentally sustainable, activities must make a substantial contribution to at least one of the objectives, while at the same time not harming any other significantly.

One of the environmental objectives is the transition to a circular economy. A circular economy is an economic system of closed loops. This means that raw materials, components, and products lose their value as little as possible, where renewable energy resources and system thinking is central. One of the major goals when it comes to material usage is to reduce the quantities of virgin material and waste generation.

To meet the goals, the EU is investing heavily in renewable energy, especially wind energy. As of 2019, 13.3% of the electricity produced in the EU was produced by wind. In 2019 IEA projected that by 2050 wind energy, onshore and offshore wind combined, will account for around 40% of EU's total electricity demand (Birol, 2019). One of the remaining problems in the wind industry to meet the goals of the European Green Deal, is the waste management of redundant wind turbines. As of today, up to 90% of the turbines are recyclable, but the wind turbine blades remain a challenge. The turbine blades are made of composite materials and are challenging to recycle. The result is that many of the decommissioned wind turbine blades are either incinerated for energy recovery or directly placed in landfills.

The wind energy industry in Europe led by WindEurope is committed to transition to a circular economy and the industry has recognized the use of landfills as a waste of valuable resources. By 2025 it is predicted that wind turbine blades will contribute 10% of the total thermoset composite waste. To accelerate the transition to a circular economy the wind industry has called for an Europe-wide ban on landfilling for decommissioned turbine blades by 2025 (WindEurope, 2020b). The turbine blades must therefore be managed alternatively, such as repair, reuse, recycling, or energy recovery of the decommissioned blades.

1.1 Scope and limitations

This thesis was proposed by Professor C. Ratnayake at UiS under the project title "Wind turbine supply chain evaluation". The scope was further defined to the evaluation of the wind turbine blade supply chain and the possibility for a circular economy.

The main objective of the thesis is to investigate the potential for a circular economy for wind turbine blades. To investigate this, two major research questions are shall be answered:

1. **What is the current situation of recycling and reuse of wind turbine blades?**
2. **What are the possibilities for a circular economy for wind turbine blades with today's available technologies?**

The current situation of manufacturing, recycling methods and opportunities for reuse has been investigated to answer research question 1. To answer research question 2, the wind turbine blade supply chain is evaluated in terms of circular economy. In addition, an investigation is performed of what can be done to achieve a circular economy or higher circularity with current technologies.

The limitations of this thesis are:

1. The available time, as the thesis was written in a 5-month period. This limits the depth of investigation into the theme.
2. The information available on circular economy for wind turbine blades. This is a relatively new problem and has only been focused on in recent years, limiting the knowledge base.

2 Framework and knowledge base

This chapter describes relevant theory and concepts for the thesis. This includes the concept and characteristics of a circular economy. Wind turbine blade waste estimations, blade materials, repair methods and waste treatment methods for wind turbine blades are also presented.

2.1 Circular economy

Circular economy is an economic system of closed loops, meaning that raw materials, components, and products lose their value as little as possible. The Ellen MacArthur Foundation defines a circular economy as: "A systems solution framework that tackles global challenges like climate change, biodiversity loss, waste and pollution. It is based on the three principles, driven by design: eliminate waste and pollution, circulate products and materials (at their highest value), and regenerate nature." Design is key for the implementation of a circular economy. Products should be designed to be reused, repaired or remanufactured, as well as treating waste as a design flaw, not an inevitable by-product of the things we make (Ellen MacArthur Foundation, n.d.).

Through the European Green Deal the European Commission introduced the new circular economy action plan (CEAP) in March 2020, which is one of the main building blocks of the Green Deal. The action plan will guide the EU in the transition to a circular economy, reduce the pressure on natural resources, and create sustainable growth. Transition to a circular economy is one of the prerequisites for the EU to achieve the goal of climate neutrality by 2050. The CEAP has six overall objectives (European Commission, 2022):

- Making sustainable products the norm in the EU
- Empowering consumers and public buyers
- Focusing on the sectors that use most resources and where the potential for circularity is high.
- Ensuring less waste
- Making circularity work for people, regions, and cities
- Lead global efforts on circular economy

2.1.1 Strategies for circular economy

Kubbinga et al. (2018) list 7 general strategies for a circular economy. Three of them focus on optimizing material use and four on the business model. The seven strategies are presented in Table 2.1.

Table 2.1: General strategies for a circular economy obtained from "A Framework for Circular Buildings" (Kubbinga et al., 2018).

Strategy	Description
Prioritize regenerative resources	Renewable, reusable and non-toxic resources are utilized as materials and energy.
Preserve and extend what's already made	Maintain, repair and upgrade while resources are in-use to maximize lifetime. Enable a second life through take-back strategies when applicable.
Use waste as a resource	Utilize waste streams as a source of secondary resources and recover waste for reuse and recycling.
Rethink the business model	Consider opportunities to create greater value and align incentives that build on the interaction between products and service.
Design for the future	Account for the systems perspective during the design process, to use the right materials, to design for an appropriate lifetime and design to extend future use.
Incorporate digital technology	Track and optimize resource use and strengthen connections between supply chain actors through digital, online platforms and technologies that provide insights.
Collaborate to create joint value	Work together throughout the supply chain, internally within organisations and with the public sector to increase transparency to create joint value.

2.2 Wind turbine blade waste

The lifetime of a wind turbine usually spans from 20 to 30 years. As the development of wind farms is growing steadily, it brings up the question of the magnitude of future wind turbine blade waste. A study by Liu & Barlow (2017) estimated that by 2050 the total wind turbine blade waste would be 43 million tonnes in a scenario with moderate lifespan and growth rate of wind turbines. Europe will account for 25% of the waste, which is estimated to reach around 500,000 tonnes per year by 2050. Liu & Barlow also took the waste from manufacturing and O&M (operation and maintenance) into consideration, predicting the total waste before end-of-life (EoL) to be between 15.6% to 45%, with a median of 25.1%, of the total weight of the blade. Another study looking exclusively at turbine blade waste after EoL in Europe estimated annual waste to be 325,000 tonnes by 2050 (Lichtenegger et al., 2020).

The development of offshore wind turbines enables the usage of larger turbine blades. An increasing trend of using CFRP (carbon fibre reinforced plastics) in wind turbine blades has been observed for larger blades as the requirements for strength increases. Lefeuvre et al. (2019) estimates the combined production and EoL waste of CFRP from the wind power sector to generate 483,000 tonnes of waste globally by 2050. Europe will account for the highest amount of CFRP waste, accounting for 190,000 tonnes. The study was based on CFRP accounting for approximately 6% of the total blade mass.

The Nordic Council proposed in November 2021 an initiative for a common strategy for waste handling of turbine blades for all Nordic countries (Damsgaard, 2021). Denmark was the pioneer of the Nordic countries to build wind power and by 2030 it is estimated that Denmark will have to decommission around 3000 wind turbines. In Norway, most of the wind farms have been built after 2010, and as concessions usually last for 25 years, these turbines will not be decommissioned within the next decade. As of February 2022, there are 1305 turbines in production in Norway according to NVE (NVE, n.d.). The blade waste from these turbines is estimated to be about 60,000 tonnes in total (Stavanger Aftenblad, 2021).

2.3 Wind turbine blade materials

There are several material criteria set for a wind turbine blade; high stiffness to maintain aerodynamic performance, low density to reduce gravitational forces and long-fatigue life to reduce material degradation (Brøndsted et al., 2005). To meet these requirements, wind turbine blades are usually made of composite materials, typically GFRP (glass fibre reinforced plastics) and CFRP. The blade is made up by two faces supported by a spar or shear web. In Figure 2.1 a cross-section of a simplified wind turbine blade is presented.

2.3.1 Fibre materials

The fibres give the composite its strength and stiffness. They are not usable by themselves, and their good properties are exploited through the use in composite. Glass fibre is by far the most widely used fibre, but in recent years carbon fibres have been increasingly used as the blades become larger (Brøndsted et al., 2005). The stiffness, tensile and compressive strength increase proportionally with increasing the volume content of fibres. Typically, glass/epoxy composites used in wind turbine blades contain up to 75wt% glass fibres (Mishnaevsky et al., 2017).

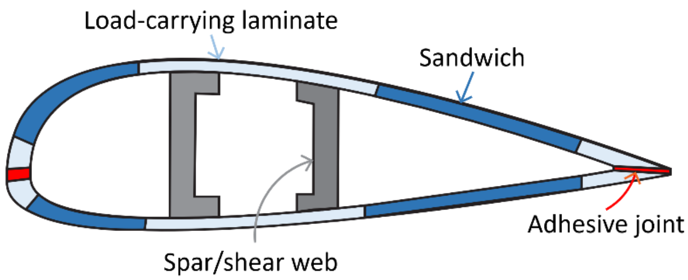

Figure 2.1: Cross-section of a wind turbine blade. Figure inspiration from (Brøndsted et al., 2005; Mishnaevsky et al., 2017).

The E-glass (electrical glass) fibre is the most commonly used reinforcement in composites. Glass fibres have a good combination of properties with a moderate stiffness, high strength and moderate density (Brøndsted et al., 2005). Carbon fibres show higher stiffness and lower density than glass fibres, allowing for thinner, stiffer, and lighter blades. Some of the drawbacks of carbon fibres are that they have lower damage tolerance, compressive and ultimate strength and are much more expensive than glass fibres (Mishnaevsky et al., 2017).

The largest wind turbines today are made of hybrid composites. The two largest blades as of spring 2022, the 107 m long LM Wind Power's Haliade-X 12 MW blade and the 108 m long Siemens Gamesa B108 blade, are both made of carbon/glass hybrid composites (Kellner, 2019; Siemens Gamesa, 2021a). The incorporation of glass fibres in carbon fibre composites improves the impact properties and tensile strain of the composite. Typically, carbon fibres with moderate to low stiffness and relatively high failure strain are used to make the carbon fibres able to share the loads and deform like glass fibres (Brøndsted et al., 2005). A study by Mishnaevsky & Dai (2014) showed that in some cases carbon/glass hybrids can show lower strength and elongation to failure compared with a pure glass fibre composite.

Natural fibres can also be used in composites and have been investigated for use in wind turbine blades. Advantages of natural fibres such as sisal, flax and hemp are low cost, availability and environmental benefits (Kalagi et al., 2018). One of the disadvantages of using natural fibres in composites is the brittleness of the fibres, which can easily lead to delamination. Several studies have been performed on the use of natural fibres, and composites with bamboo and flax have shown promising results for use in smaller wind turbines (Holmes et al., 2009; Thomas & Ramachandra, 2018).

2.3.2 Matrix materials

The main purpose of the matrix materials is to bind the fibres together to create a functioning composite. Typical matrix materials used to make wind turbine blades are thermosets or thermoplastics. Thermosets are the most commonly used matrix material, representing 80% of the market (Mishnaevsky et al., 2017). Of the thermosets, the most used are polyesters, epoxies and vinylesters. In the first composite wind turbine blades, the blade was made of glass fibres combined with polyester (Brøndsted et al., 2005). In recent years, with the development of larger wind turbines, epoxy resins have become the most common matrix material (Mishnaevsky et al., 2017).

Thermoplastics have had an increasing focus in recent years, mainly because of its advantage of being recyclable (Mishnaevsky et al., 2017). Thermoplastics can be reshaped upon melting, have higher fracture toughness, longer elongation at fracture, possibilities for automatic processing and longer shelf life of raw materials than thermosets. Some disadvantages of thermoplastics are the requirement for high processing temperature and the difficulties in manufacturing larger structures due to the higher viscosity. Thermosets also have better fatigue behaviour compared to thermoplastics (Mishnaevsky et al., 2017).

Prabharakan et al. (2011) did a study on the pros and cons of thermoplastics and listed eight major challenges the wind industry needed to resolve to enable the use of thermoplastics in future blades. The primary challenges are the high temperature processing and enabling of manufacturing larger blades of lengths over 40 meters. The larger energy consumption associated with the high temperature processing will also increase the overall cost of the blade.

A study by Murray et al. (2021) structurally compared a thermoset and a thermoplastic blade. Where the thermoset was epoxy, and the thermoplastic was a resin called Elium. This thermoplastic could be polymerized at room temperature, without requiring post-cure heating and thus reduced the energy consumption. The major differences between the two blades were that the thermoplastic blade had more structural damping and was more flexible than the epoxy blade.

2.3.3 Core materials

To ensure high strength, low weight and good stability, a sandwich structure is common in the design of a wind turbine blade. The sandwich structure is made up by two high-strength composite laminates that are separated by a core. This is done to increase stiffness and stability due to the fibre's relatively low thickness (Bannister, 2014). The sandwich structure is primarily designed against elastic buckling (Mishnaevsky et al., 2017). Typical core materials for wind turbine blades are balsa wood, PVC (polyvinyl chloride), SAN (styrene acrylonitrile) and PET (polyethylene terephthalate) foams. In modern wind turbines, multiple core materials are used to optimize weight and material cost, which varies depending on the manufacturer (Bannister, 2014).

Balsa wood has for many years been one of the most commonly used core materials as it is inexpensive, renewable and have high strength (Sloan, 2010). As a natural wood product, balsa may have large variation in density, strength, and stiffness. Balsa also absorbs resin during manufacturing which increases the blade weight (Banerjee, 2010). Modern treatment of balsa reduces the resin uptake, but it is still relatively high compared to foams (Bannister, 2014). Due to this, balsa is widely used in the root section of the blade where high strength and high shear modulus is required, and is more important than weight (Bannister, 2014). One of the disadvantages with balsa wood is the production, which is closely linked to social problems and deforestation. This is further presented in Chapter 4.

Further out on the blade the loads are lower, but the strains are higher. The thickness of the sandwich structure is then more important and a core with lower shear modulus can be used (Bannister, 2014). Structural foams, such as PVC and SAN, are lighter, have lower resin uptake and are more consistent than balsa and are thus used in the outboard regions of the blade. PVC and SAN foams can carry less load, are more expensive, and must be twice as thick as balsa to match the strength and stiffness (Banerjee, 2010).

In recent years, the use of PET foams has increased as it is cheaper, have longer fatigue life and is recyclable (Mohan, 2017; Sloan, 2010). PET does have some disadvantages when it comes to strength, stiffness and weight when compared to SAN and PVC (Banerjee, 2010; Bannister, 2014). However, because of its low price and consistency in properties compared to balsa, it is gaining acceptance in the market (Banerjee, 2014). One of the drivers of the use of PET foam is that it is a thermoplastic, which makes it recyclable. PET foam can also be made of recycled material, typically PET bottles (Sloan, 2010).

2.4 Repair methods for wind turbine blades

To ensure the blades will serve their designed lifetime, repair and maintenance is necessary. For a typical wind turbine, the blades require repair after two to five years (Bech et al., 2018). Blade repair is quite expensive and O&M costs can make up 25% of the total levelized cost per kWh produced over the lifetime for the wind turbine (Stephenson, 2011). Some of the main causes for wind turbine blade damage during their lifetime are manufacturing defects; transportation, assembly and installation damage; lightning strikes; environmental wear, rain, sand and contaminants caused erosion, bird impacts, leading and trailing edge erosion, fatigue, moisture intrusion and mechanical failure (Mishnaevsky, 2019).

Mishnaevsky (2019) classifies the repair techniques according to severity of damage, region of damage and aerodynamic requirements. In terms of severity and kind of damage, the repair techniques are divided into three groups: Erosion repair and protection, non-structural cracks, and structural damage.

2.4.1 Erosion repair and protection

Leading-edge erosion (LEE) is the most common and most expensive of wind turbine blade degradation. LEE is responsible for a reduction of annual energy production by more than 5% (Energy.gov, 2017). Unrepaired LEE can thus lead to a great loss of energy production over time and is therefore at the highest priority when it comes to inspection and repair.

LEE is affected by several variables, such as rain density, rain droplet size, dust, flow velocity and the properties of the coating system such as strength, stiffness, viscosity, and damping (Mishnaevsky, 2019). Surface erosion is realized as coating cracking, debonding, cracks in composite, material loss, and roughening of surfaces. Figure 2.2 shows a surface damaged from leading edge erosion (Belzona Polymerics Ltd., 2014). Protection tapes, protective coatings, epoxy and polyurethan fillers are some solutions for the repair of LEE (Mishnaevsky, 2019). The leading-edge zone always requires a flush repair to meet necessary requirements for aerodynamic performance. While the methods for leading edge protection is sufficient, the lifetime of many coatings are not longer than six to eight years (Mishnaevsky, 2019).

Figure 2.2: Typical blade damage from leading edge erosion (Belzona Polymerics Ltd., 2014).

2.4.2 Non-structural cracks

Non-structural damage are matrix cracks, debonding and minor delamination, while the fibres remain undamaged (Mishnaevsky, 2019). A crack may be a source of moisture intrusion, which can lead to further crack growth. At sub-zero temperatures, the moisture will freeze and expand, which may force crack growth that can damage the fibres (Marsh, 2011). For the repair of surface cracks, a low viscosity resin is injected into the cracks, which fills and seals the crack. To ensure full restoration, an external patch can be applied to the sealed region (Mishnaevsky, 2019).

2.4.3 Structural damage

Structural damage is when the composite fibres in the wind turbine blade are damaged. For structural damage, two repair techniques are typically used: bolted and bonded (Mishnaevsky, 2019). Bolted doublers can be used in heavily loaded laminates to ensure high level of structural restoration. Bolted doublers do not ensure aerodynamically smooth surfaces, which creates stress concentrations at corners and edges. It is still suitable for wind turbine blade repair as it is easy and fast to perform (Katnam et al., 2015).

Still, the blades aerodynamic properties are the most critical, and thus flush repair is the most common structural repair technique. There are several bonded repair techniques, such as scarf, stepped scarf and overlap repair. Both scarf and stepped scarf repair ensures an aerodynamic smooth surface. Scarf repairs are preferred for strength-critical applications. Structural flush repairs are performed by forming a joint between the repair area and the repair patch. Patches are applied by wet lay-up and usually made of the same fabric as the parent structure (Mishnaevsky, 2019).

One of the problems with bonded repair techniques are the requirement to control both curing temperature and time for the composite repair. For wet resin systems the temperature needs to be above 15°C and cured for at least 24 hours (Marsh, 2011). This has led to development of methods that use various heating or radiation effects to control the curing.

2.5 End-of-life options for wind turbine blades

As presented in Chapter 2.2, the composite waste from wind turbine blades is increasing. To meet the incoming waste flow, several studies have been performed on end-of-life options for wind turbine blades. The different methods are sorted by the principles of circular economy in a hierarchy, presented in Figure 2.3, called the waste hierarchy.

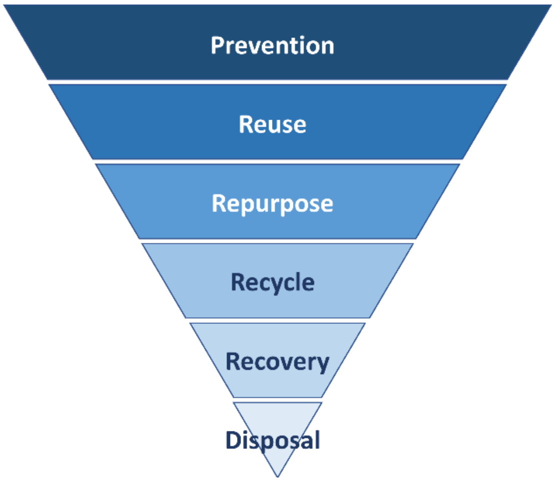

Figure 2.3: The waste hierarchy, sorted from most to least favourable option from top to bottom.

2.5.1 Disposal

Disposal or landfilling of the waste is considered to be the least favoured option. However, it has for many years been the preferred solution for blade waste, as it has been the most cost-efficient method (Ramirez-Tejeda et al., 2017). Landfilling of composites have been banned by several European countries, specifically Austria, Germany, Finland, and the Netherlands, due to the high content of organic material. The wood and organic material in the blades will eventually degrade and potentially release methane and other organic compounds into the environment. Other concerns of landfilling waste is the lost value of the unrecovered materials and space availability (Ramirez-Tejeda et al., 2017).

2.5.2 Energy recovery

As the wind turbine blades are made of polymers and other organic materials, they can be burned as a source of energy. The fibres are not combustible and are responsible for roughly 60 wt% of a normal composite. These will then be left with the ashes, if not further material recovery is done, and disposed of. In Chapter 2.5.3.2 co-processing is presented, which is a method that utilizes both energy and material recovery. In countries where landfilling of composites is banned due to organic content, incinerating the waste before disposal is a common procedure (Larsen, 2009). Due to 60% of the composite not contributing to the energy recovery, a practical way of incinerating composite waste has been to substitute 10% of municipal waste with composite waste (Pickering, 2006).

2.5.3 Recycling

There are several types of recycling methods for thermoset composite waste. The methods are sorted into mechanical, thermal, and chemical, as shown in Figure 2.4.

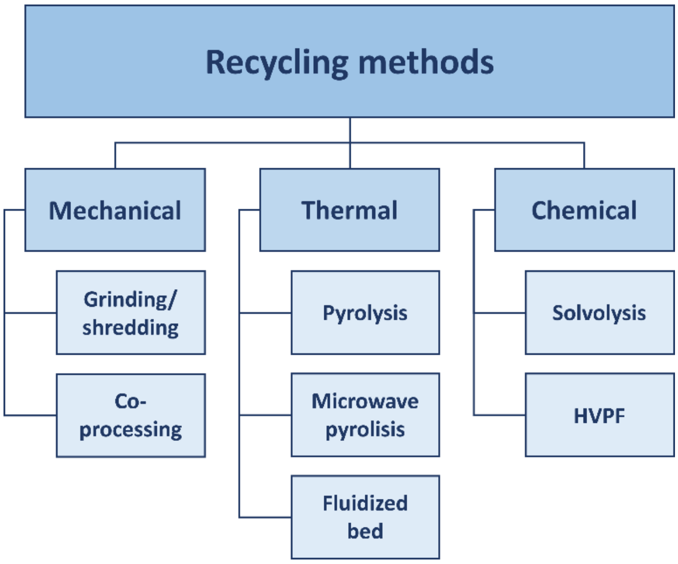

Figure 2.4: Recycling methods for composite waste. The methods are sorted by mechanical, thermal, and chemical.

2.5.3.1 Mechanical

In mechanical recycling, the composite waste is reduced into smaller components by shredding or grinding. Depending on the end product, different machines are used, such as shredders, crushers, mills and grinders (Cherrington et al., 2012). Products are divided into resin-rich and fibre-rich, and can be used as filler and reinforcement, respectively (Fonte & Xydis, 2021). Paulsen & Enevoldsen (2021) divides mechanical recycling into whether the processed product is used to create new products or as a substitute for new raw materials to produce new material, the latter referring to co-processing.

The application of mechanically recycled GFRP has been investigated for integration in new composites or in concrete. A study by Beauson et al. (2016) investigated the use of shredded waste in the production of new polymer composites. The results showed the mechanical properties of the composite waste was drastically reduced by the mechanical recycling. A study on mechanically recycled GFRP in concrete by Ribeiro et al. (2015) proved an improvement of mechanical properties by substituting sand. By replacing 8% of sand, the compressive strength increased by 15.3% and flexural strength by 5%.

A disadvantage with mechanical recycling is that dust is produced in the process and creates a hazardous environment. To control the dust and fibre emissions, it is necessary to have a water fog and to sanitize the area (Jensen & Skelton, 2018).

2.5.3.2 Co-processing

In co-processing, the waste contributes to both material and energy recovery. Inorganic materials replace new raw materials, while organic materials contribute to energy recovery through incineration (Paulsen & Enevoldsen, 2021). The composite waste must be downsized through grinding or shredding before incineration. The shredded composite reduces the need for other fuels in the process, such as coal, due to the organic content (Fonte & Xydis, 2021; Beauson et al., 2022). After incineration the ashes contain the glass fibres which are then used as a source of silica in the clinker matrix (Beauson et al., 2022).

Paulsen & Enevoldsen (2021) concludes in their study that recycling through co-processing is the only economical option at present that can handle large amounts of blade waste. For instance, in Europe, a German cement factory owned by Holcim has a collaboration with the Danish composite manufacturer Fiberline. They have announced that 1000 tonnes of composite waste can replace 150 tonnes of alumina, 200 tonnes of sand, 200 tonnes of limestone and 450 tonnes of coal (Paulsen & Enevoldsen, 2021). The cement factory can process 30,000 tonnes of composite waste every year, whereas 20,000 tonnes originate from wind turbine blades (Beauson et al., 2022).

2.5.3.3 Pyrolysis

Pyrolysis is a thermal process where the composite is heated to elevated temperatures (450-700℃), in absence of oxygen. This separates the polymer matrix into gas, oil, wax, tar, and char, therefore allowing the separation of fibres from the matrix (Fonte & Xydis, 2021). Mechanical downsizing of the composite is needed before pyrolysis takes place. The produced hydrocarbons (gas, oil, etc.) from the matrix can be used for energy recovery for the pyrolysis process (Paulsen & Enevoldsen, 2021).

Polyester decomposes at 400-450℃ and epoxy at 500-550℃, while removal of the matrix materials needs to happen at the lowest possible temperature to avoid weakening of the fibres. At higher temperatures the fibres will degrade, resulting in a residual fibre with poorer properties. This makes it more challenging for recycled fibres to “compete” with virgin fibres. GF (glass fibre) loses 50% of their material properties in pyrolysis at temperatures above 450℃. Maximum temperature for CF (carbon fibre) is considered to be between 500-550℃ before the fibres degrade. Pyrolysis is thus better suited for CF as the fibres are more resistant to high temperatures (Paulsen & Enevoldsen, 2021).

2.5.3.4 Microwave pyrolysis

Microwave pyrolysis is similar to conventional pyrolysis, the main difference is in the way the materials are heated. Microwaves are used to heat the waste material in an inert atmosphere at temperatures between 300 and 600℃. One of the advantages of microwave pyrolysis is that the material is heated throughout at the same temperature. This means that the process can be done at a lower temperature, ensuring less degradation, and thus improved mechanical properties for the recycled fibres (Paulsen & Enevoldsen, 2021).

2.5.3.5 Fluidized bed

Fluidized bed is a thermal process where composite waste, shredded into particles, are heated up to 450-550℃ on a layer of silica sand. The silica sand is fluidized by a flow of hot oxygen rich air. This oxidizes and decomposes the polymer matrix. The fibres are carried by the air stream and separated from other fillers using a cyclone (Jensen & Skelton, 2018; Fonte & Xydis, 2021).

A study by Kennerly et al. (1998) showed that the strength of recovered fibres from fluidized bed would be reduced by 50% but could still substitute 50% of virgin fibres in dough mould composites without significant effect on mechanical properties.

2.5.3.6 Solvolysis

Solvolysis is a chemical process where solvents break down the resins. It is separated into whether the solvolysis is below or near super critical temperature and pressure, for short it is divided into HTP (High Temperature Pressure) and LTP (Low Temperature Pressure). LTP solvolysis means that the temperature is under 200℃, and the pressure at 1 bar or lower (Jensen & Skelton, 2018; Paulsen & Enevoldsen, 2021). Nitric acid, ammonia and glycol are reactive solvents used for decomposition of the polymer matrix under such circumstances. The result is fibres without resin, an inorganic leftover, and the organic decomposition material.

For HTP, under supercritical conditions, the properties of the solvents change, which results in improved solvolysis properties. Ethanol and water are the most commonly used solvents at supercritical conditions. Solvolysis using water as solvent is called hydrolysis. Of the two, ethanol has a lower critical pressure and temperature, making it increasingly interesting as a solvent (Jensen & Skelton, 2018). In a similar way of thermal recycling, the fibres recycled from solvolysis show a decrease in mechanical properties (Beauson et al., 2022). It is shown that ethanol can dissolve thermoset plastics, thus making the use of ethanol viable for recycling blades containing epoxy and polyester as resin (Jensen & Skelton, 2018). Together with pyrolysis, solvolysis could be the best method and most likely establish a commercialized route for recycling wind turbine blade waste containing CF (Fonte & Xydis, 2021; Paulsen & Enevoldsen, 2021).

2.5.3.7 High Voltage Pulse Fragmentation (HVPF)

High voltage pulse fragmentation (HVPF) disintegrates the material using repetitive pulse electric discharges within a dielectric liquid, usually water. HVPF works when high voltages (>100kV) are applied, then the breakdown strength of the solid materials are lower than the dielectric liquid. The high pressure and temperature generated by the discharges induces internal mechanical stresses which exceeds the tensile strength, leading to material disintegration (Mativenga et al., 2016). HVPF solutions are, as of 2016, available at lab and pilot scale. Leißner et al. (2018) concludes that HVPF will be a useful alternative at an industrial scale if a machine is developed to handle waste at a scale of 1 tonne/hour.

In a study comparing HVPF to mechanical recycling of GFRP, Mativenga et al. (2016) found that HVPF produced cleaner and longer fibres, with less retained resin content. The recycled fibres were suitable for short fibre applications, such as bulk moulding compound (BMC) and sheet moulding compound (SMC). The downside of HVPF compared to mechanical recycling of GFRP is the high specific energy that is needed, being 2.6 times higher than for mechanical recycling.

2.5.4 Repurpose

Repurpose aims to reuse the blades for other applications, but at a lower value[1] than the original. This involves reshaping the blades for use in structural or semi-structural applications. The GENVIND consortium studied different applications where wind turbine blades could be repurposed (Jensen & Skelton, 2018). Some of the applications considered were bridges, playgrounds, and urban furniture. Repurposing extends the life of the composite material and thus reduces the environmental impact of the products lifecycle.

A study from the GENVIND project showed that if 5% of the yearly production of urban furniture in the Netherlands used decommissioned wind turbine blades, the annual wind turbine waste would be removed from the waste stream (Jensen & Skelton, 2018). The study also showed that the cost was comparable to furniture made from other materials.

2.5.5 Reuse

According to the waste hierarchy, the second-best option for components at EoL is to reuse them. By reuse it is meant as true reuse, using the turbine blade for its original function. In this thesis, this definition is used.

Reuse of a wind turbine or parts of it demand the right decommissioning strategy as the components need to be in a proper condition. Another issue with reuse of wind turbine blades is their size. The blades must be transported in one piece from the old to the new location. Reuse of older generation wind turbine blades seems more technically and economically feasible since the blades are relatively small and may have significant residual life compared to newer blades (Beauson et al., 2022). Newer blades are often designed to match a specific lifetime and save material, thus reducing residual life and making them more difficult to reuse.

2.5.6 Technology Readiness Level (TRL)

Technology readiness level (TRL) is a defined scale used to estimate and evaluate different technology's maturity. The maturity of the technologies is ranked within levels from 1 to 9, where a TRL of 1-4 is at lab scale, 5-7 pilot scale and 8-9 at a commercial scale (Paulsen & Enevoldsen, 2021). Paulsen & Enevoldsen (2021) made an overview of the different recycling method's TRL score by comparing five different studies, using the European waste hierarchy, and through communication with the industry. TRL for the recycling methods are presented in Table 2.2.

[1] Value refers to the waste hierarchy. The higher the value, the better the material's properties are utilized, and often the criteria to the material properties are higher.

Table 2.2: TRL score for the different recycling methods for composite waste presented in this thesis. Gathered from Paulsen & Enevoldsen (2021).

Recycling method	Mechanical	Co-processing	Pyrolysis	Microwave pyrolysis	Fluidized bed	Solvolysis	HVPF
TRL score	9	8-9	7	4	4/5	5/6	5
Waste management score	Low	Middle	High	Middle/High	Middle/High	High	Middle
Predicted needed investment	Low	Low/Middle	Low/Middle	High	Middle	High	High
Machining options	GF+CF	GF	CF+GF	CF+GF	CF+GF	CF+GF	CF+GF

3 Research methodology

This methodology chapter is divided into a description of the methods used for Chapter 2 “Framework and knowledge base” and Chapter 4 “Wind turbine blade supply chain”.

3.1 Framework and knowledge base

The theory in Chapter 2 was based on 32 studies, which are presented in Table 3.1. The research method that the studies used and the topic in this thesis they covered is also presented.

Table 3.1: Research articles reviewed in Chapter 2. A total of 32 articles were reviewed.

Author	Year	Covered topic	Research method
Kubbinga et al.	2018	Circular economy	Literature review
Ellen MacArthur Foundation	n.d.	Circular economy	Literature review
Liu & Barlow	2017	WTB waste	Case study
Lichtenegger et al.	2020	WTB waste	Case study
Lefeuvre et al.	2019	WTB waste	Case study
Brøndsted et al.	2005	WTB materials	Literature review
Mishnaevsky et al.	2017	WTB materials	Literature review
Mishnaevsky & Dai	2014	WTB materials	Experiment
Kalagi et al.	2018	WTB materials	Literature review
Prabharakan et al.	2011	WTB materials	Literature review
Murray et al.	2021	WTB materials	Experiment
Bannister	2014	WTB materials	Literature review
Banerjee	2010	WTB materials	Literature review
Mohan	2017	WTB materials	Experiment
Bech et al.	2018	WTB repair	Experiment
Mishnaevsky	2019	WTB repair	Literature review
Marsh	2011	WTB repair	Literature review
Katnam et al.	2015	WTB repair	Literature review
Stephenson	2011	WTB repair	Literature review
Ramirez-Tejeda et al.	2017	EoL-options	Literature review
Larsen	2009	EoL-options	Literature review
Pickering	2006	EoL-options	Literature review
Fonte & Xydis	2021	EoL-options	Case study
Paulsen & Enevoldsen	2021	EoL-options	Literature review
Cherrington et al.	2012	EoL-options	Literature review
Beauson et al.	2016	EoL-options	Experiment
Jensen & Skelton	2018	EoL-options	Literature review
Beauson et al.	2022	EoL-options	Literature review
Ribeiro et al.	2015	EoL-options	Experiment
Kennerly et al.	1998	EoL-options	Experiment
Mativenga et al.	2016	EoL-options	Experiment
Leißner et al.	2018	EoL-options	Experiment

Figure 3.1 shows the distribution of research articles covering each topic. As seen in this figure some of the topics had many more references than others, especially EoL-options as this needed to cover many different themes.

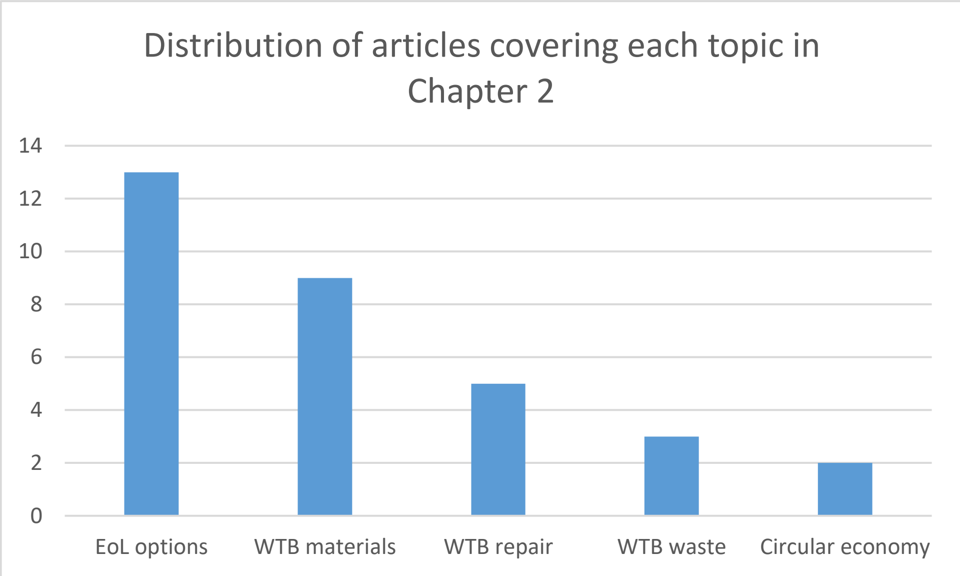

Figure 3.1: Distribution of research articles covering each topic in Chapter 2.

Figure 3.2 shows the distribution of the used research method in the reviewed literature. As observed from the figure, literature review is the most used research method in the reviewed literature.

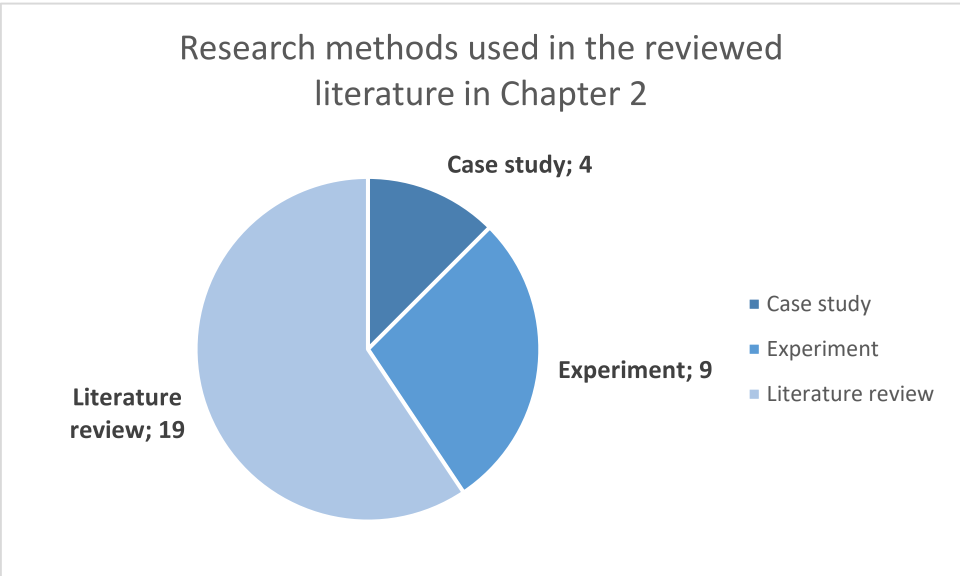

Figure 3.2: Research methods used in the reviewed literature in Chapter 2.

3.2 Supply chain evaluation

The wind turbine supply chain, as proposed in Figure 3.3, was investigated in order to answer Research question 1 and 2. Each step was investigated individually and is presented in Chapter 4. The supply chain in Figure 3.3 is a representation of what the wind turbine blade supply chain could look like.

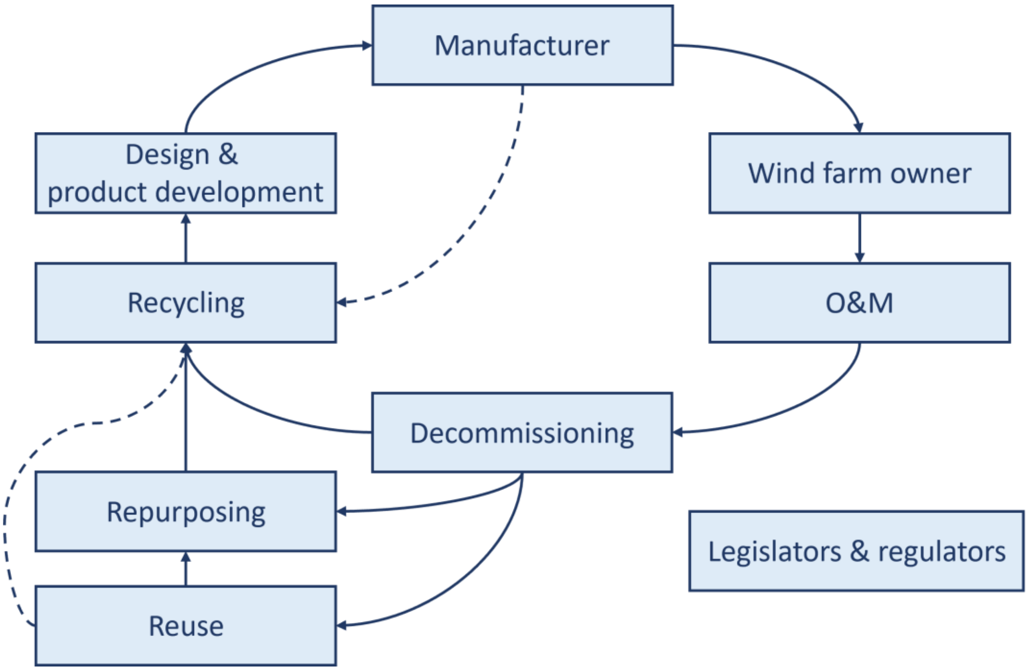

Figure 3.3: Representation of a possible supply chain for wind turbine blades.

To evaluate the supply chain, more literature was reviewed, as well as conducting interviews and mail correspondence with relevant companies. In Figure 3.4 the distribution of literature covering the different parts of the supply chain is presented.

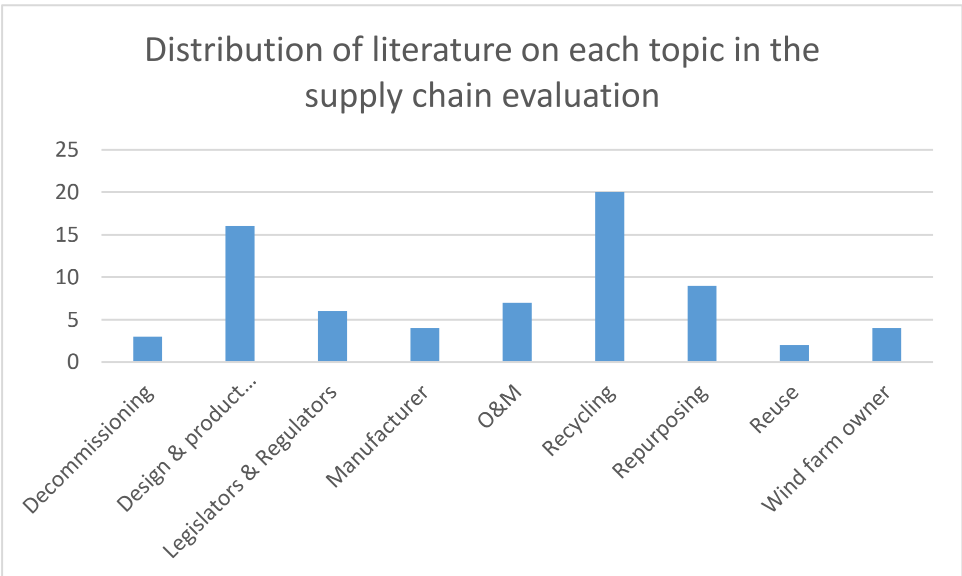

Figure 3.4: Distribution of reviewed literature on each topic in the supply chain. A total of 71 sources were used in the supply chain evaluation.

The reviewed literature used in studying the wind turbine supply chain consisted of journal and conference papers, master's theses, reports, news and magazine articles, and company websites. Interviews were done with Simon Loginov from Gjenkraft the 28th of April and with Charles Göbbels from Reprocover the 12th of May. The interviewees were given the opportunity to do a citation check. In Figure 3.5, the different types of literature that was reviewed are presented.

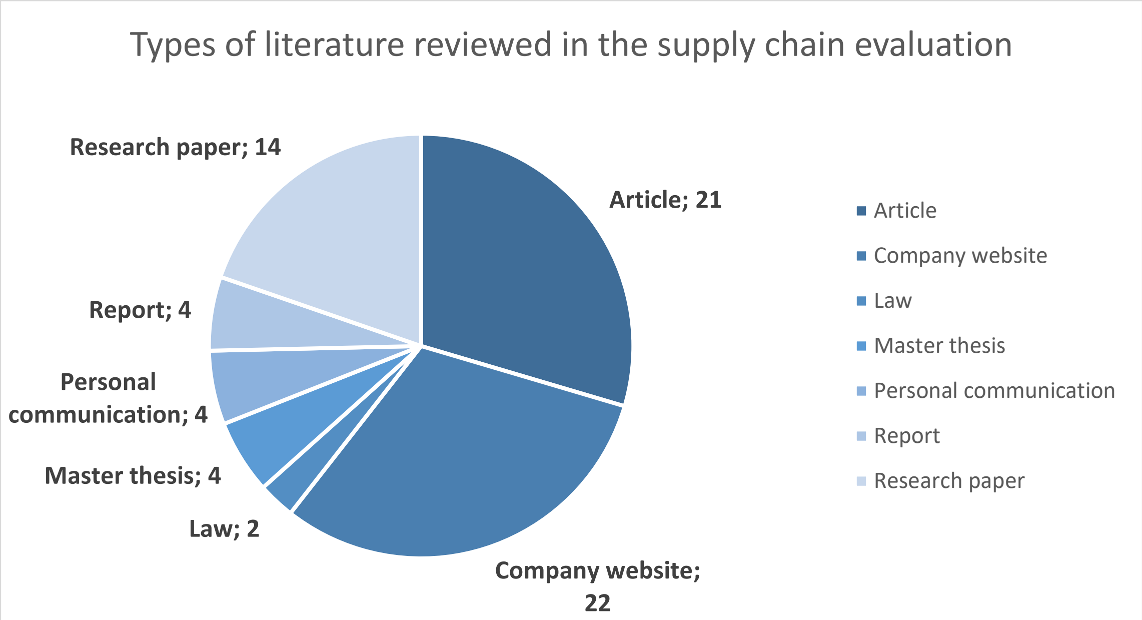

Figure 3.5: Types of literature reviewed in the supply chain evaluation.

4 Wind turbine blade supply chain

In this chapter the wind turbine supply chain shown in Figure 3.3 is evaluated. Each step is investigated individually.

4.1 Design & product development

The design and product development processes are usually done by the manufacturer. In this subchapter, new design concepts from the top manufacturers in Europe over the last few years are presented. Projects, research consortiums and developments in materials are also presented.

In September 2021 Siemens Gamesa announced the launch of their first RecyclabeBlade, a blade that can be fully recycled at the end of the wind turbine's lifecycle. The blade is 81 metres long and is made with the same manufacturing process as a standard blade, the change being a new resin. At EoL, the fibres can be separated from the matrix by solvolysis, more specifically immersion in a heated mild acidic solution. Siemens Gamesa states that the process protects the properties of the fibres and therefore allows for use in new applications. The RecyclableBlade is a step towards Siemens Gamesa's target of fully recyclable turbines by 2040 (Mason, 2021b; Siemens Gamesa, 2021c).

LM Wind Power, a subsidiary of GE Renewable Energy, also announced their first prototype of a 100% recyclable wind turbine made during the ZEBRA project in March 2022. The blade is presented in Figure 4.1. The blade is 62 metres long and made with a thermoplastic resin called Elium, made by Arkema, chosen for the key benefit of recyclability. The composite can be recycled similarly to the RecyclableBlade by chemical recycling (assumed to be solvolysis), separating the fibres by depolymerizing the resin (Durakovic, 2022; GE, 2022).

Figure 4.1: The first prototype of the 100% recyclable ZEBRA blade made by LM Wind Power. Photo credit ZEBRA consortium (GE, 2022).

Vestas is a leading part of the CETEC project, which also aims at making fully recyclable wind turbine blades. Unlike the RecyclableBlade and the ZEBRA blade, through the CETEC project Vestas wants to address recycling of epoxy resin, a thermoset. Instead of changing the resin, Vestas is looking into developing the recycling process, establishing a circular pathway for epoxy resins. Vestas says the epoxy is broken up into base components through a novel chemcycling process. The base components can then be used in the manufacturing of new blades (Durakovic, 2021).

4.1.1 Projects and consortiums

To achieve a circular economy, the industry led by wind turbine manufacturers have started projects and consortiums regarding the matter. The subject getting most attention at the time is EoL-options for wind turbine blades to manage the amount of waste in the coming years. In Table 4.1 a list of projects and consortiums are listed.

Table 4.1: Ongoing and closed projects and consortiums in the wind industry regarding wind turbine blades.

Project	Description	Status
CETEC	Building on the DreamWind project. Aims to enable circularity for thermoset composite, CETEC (Circular Economy for Thermosets Epoxy Composites). Collaboration between Aarhus University, DTU, Olin and Vestas.	2021 - Active
DecomBlades	The aim of the DecomBlades consortium is to establish sustainable value chains to handle EoL wind turbine blades. Looking into aspects from decommissioning to re-processing and recycling into new applications. Collaboration between 10 partners, for instance, Vestas, Siemens Gamesa and LM Wind Power.	2021 - Active
DreamWind	Research project on development of new composite materials. Focus on high strength materials for future use in wind turbine blades, facilitating disassembly and reuse of the blade. Collaboration between Aarhus University, DTU and Vestas.	2016 - 2020
ECOBULK	Aims at promoting re-use, refurbishment and recycle of products and parts of composite products in the automotive, furniture and building sectors.	2017 - 2021
EROSION	The aim of EROSION was to enable longer lifetime of wind turbine blades at multi-MW machines. Vestas is one of the partners.	2017 - 2021
EURECOMP	The aim of the EURECOMP project was to develop the solvolysis process to recycle fibre-reinforced thermoset composites.	2010 - 2012
FiberEUse	Large scale demonstration of new circular economy value chains based on the reuse of end-of-life fibre reinforced composites. Siemens Gamesa is one of the partners.	2017 - 2021
GENVIND Innovation Consortium	Enabling technologies for sustainable recycling of plastic composites and demonstrating how composite waste can be used in new products, components, and structures.	2012 - 2016
LIFE BRIO project	Project led by Iberdrola aimed to create a new sustainable system for the management and recycling of decommissioned wind turbine blades.	2014 - 2017
REACT	In the REACT project, new recycling solutions for composite materials were identified and tested with the aim of using the recycled material in new applications.	2003 - 2005
ZEBRA	The ZEBRA (Zero wastE Blade ReseArch) project aims to demonstrate in full-scale a thermoplastic wind turbine blade, with eco-design to recycling. Led by Jules Verne Institute, LM Wind Power is one of the partners.	2020 - Active

4.1.2 Material developments

Current status and developments in wind turbine blade materials are in this thesis divided into fibre, matrix and core materials.

4.1.2.1 Fibre materials

As wind turbine blades get bigger, the use of carbon fibre has increased in recent years. Carbon fibre contributes to reducing the overall weight while increasing the stiffness. As of 2019, roughly 25% of wind turbine blades were manufactured with carbon fibre spar caps (CompositesWorld, 2019). This trend is increasing but still, most of the blades are made entirely with glass fibres. When cost compared to performance is taken into consideration, substituting carbon fibre for glass fibre can be beneficial when manufacturing spar caps for blades longer than 55 meters. Today, a typical offshore wind turbine is 6 to 9 MW and has blades that are 65 to 80 meters long (Mason, 2021c).

4.1.2.2 Matrix materials

For the matrix materials, the manufacturers have started to change the resin systems from thermosets to thermoplastics. The typical wind turbine blades consist of a thermoset composite, where the matrix material is epoxy or polyester. Vestas use an epoxy resin for most of their blades, while LM Wind Power use a polyester resin (LM Wind Power, 2022; Vestas, 2021). Siemens Gamesa use either epoxy or polyester depending on the blade (Siemens Gamesa, 2022). The change from thermosets to thermoplastic resin system is mostly due to the recyclability of the thermoplastic resin.

One of the thermoplastic resins that have gained attention is the Elium resin made by Arkema. The Elium resin is recyclable by depolymerization or dissolution. Several studies have been performed on the use of the resin system compared to thermoset resins. Pinto et al. (2021) concludes that Elium is capable of replacing conventional thermoset resins. Elium had similar properties compared to a thermoset counterpart, with a trend of less impact damage. Another study showed that compared to an epoxy blade, the Elium was similar in static and fatigue performance, and had an increased damping, reducing operational loads (Murray et al., 2021). The resin system was DNV certified in March 2022 (Krüger, 2022).

4.1.2.3 Core materials

Balsa wood has been widely used as core material in wind turbine blades but has decreased in recent years. One of the reasons is uncertainties in the supply. The demand for balsa wood increased significantly in 2018, and many of the suppliers were not able to meet the quantity of orders (Badia, 2021). Ecuador is the largest exporter of balsa wood with 75% of the global market. Not only has the demand led to instability in the supply chain, but also deforestation of the Amazon. China, the biggest manufacturer of wind turbines, has due to the shortage started looking into growing the balsa wood domestically, reducing the amount of imported wood (Radtke, 2022).

Due to the balsa shortage, wind turbine blade manufacturers have started to change the composition of the blade. LM Wind Power has since 2017 produced blades with PET foam core, substituting some of the balsa. As of 2020, 60% of the core material in LM blades is PET foam and 79% of the foam is from recycled PET (Korsgaard, 2021). The analysis firm Wood Mackenzie estimates that by 2025 PET will account for about 60% of the global share of core materials for wind turbine blades (Radtke, 2022).

4.2 Manufacturer

The manufacturer is the designer and the producer of a wind turbine blade. In addition, the manufacturers are often in charge of service and maintenance of turbines in operation. In Table 4.2, a list of the largest wind turbine manufacturers by new capacity installed in 2021 are presented. The Danish manufacturer Vestas is the world's largest manufacturer and stands for around 15% of the total new installed capacity globally in 2021 of 99.2 GW (Henze, 2022).

Table 4.2: Top ten wind turbine manufacturers sorted by capacity installed in 2021. Statistics gathered from BloombergNEF's "2021 Global Wind Turbine Market Shares" report (Henze, 2022).

Company	Location	Total capacity (GW)
Vestas	Denmark	15.20
Goldwind	China	12.04
Siemens Gamesa	Spain	8.64
Envision	China	8.46
GE	U.S.	8.30
Windey	China	7.71
MingYang	China	7.53
Nordex	Germany	6.80
Shanghai Electric	China	5.34
Dongfang Electric	China	3.37

In Europe, majority of the market is shared between five different companies: Vestas, Siemens Gamesa, GE, Nordex and Enercon. In the BloombergNEF 2020 report, the onshore wind market share in Europe was Vestas 31%, Siemens Gamesa 20%, GE 18%, Nordex 16% and Enercon 12% (ENERCON, n.d.).

4.2.1 Manufacturing waste

In recent years there has been an increased focus on reducing manufacturing waste and aiming for zero-waste blades. Some of the top wind turbine blade producers (Vestas, LM Wind Power and Siemens Gamesa), have all committed to produce zero-waste blades by 2040 (LM Wind Power by 2030). LM Wind Power states around 20-25% of the initial material in the manufacturing process does not go into the final product and that one third of their operational carbon footprint comes from waste disposal (LM Wind Power, n.d.). Analysis of the manufacturing of blades made of glass fibre and epoxy resin showed that in-process waste was between 12 and 30% of the finished blade weight (Liu & Barlow, 2017). Vestas aims to reduce manufacturing waste being landfilled or incinerated to less than 1%, and waste incinerated with energy recovery by 5% by 2030 (25% landfilled, 12% incinerated and 11% incinerated with energy recovery as of today) (Vestas, 2021). LM Wind Power aims for no excess manufacturing material being sent to landfills or incineration without energy recovery by 2030.

4.3 Wind farm owner

The wind farm owner or developer has a crucial role in how a wind farm will turn out. The developers buy or lease land, install, operate and maintain the wind turbines during the licenced period. Most importantly, the developers finance the wind farm. Location of the wind farms can affect if the project is going to turn a profit. Wind resources, environmental concerns and available infrastructure are some of the factors that wind farm developers need to consider (Butterfield, 2022; Daniels, 2008).

The Norwegian company Statkraft has developed onshore wind power for 20 years and is the leading producer in Northern Europe with 63 wind farms (Statkraft, n.d.). In the offshore wind market, the Danish company Ørsted is the largest developer, with approximately 30% of the global offshore wind power capacity, excluding China (Ørsted, 2022).

4.4 Operation and maintenance

One of the highest prioritized strategies for a circular economy is preserving what is already made and extending the lifetime of products. By maintaining the turbines and keeping them producing the environmental impact is highly reduced. As mentioned in Chapter 2.4, leading edge erosion (LEE) is the main maintenance problem for wind turbine blades. LEE lowers the aerodynamic performance of the wind turbine blade and results in lower annual energy production (AEP). As a result, the industry and researchers are primarily focusing on this topic when it comes to O&M.

4.4.1 Life extension techniques and strategies

There are three common strategies to mitigate LEE; prevention and avoidance, prediction and repair, and protection (Mishnaevsky et al., 2021). The leading-edge lifetime highly depends on environmental conditions and is shown to be a larger problem offshore than onshore. It is speculated that this is due to rough weather at sea and high tip speeds. Offshore wind turbines are generally larger than onshore, which results in higher nominal tip speeds (Bech et al., 2018).

A study by Liu et al. (2019) showed that a life extension of 10 years could reduce the net environmental impact to 53% compared to landfilling at EoL, thus being the best EoL-option for wind turbine blades. Means and mitigations to achieve life extension are described in the following sub-sections.

4.4.1.1 Prevention and avoidance

A research project by DTU called EROSION aimed to enable longer lifetime of wind turbine blades at multi-MW machines, mainly by researching how to avoid erosion at leading edges. The project began on April 1st 2017 and ran to December 31st 2021. One of the proposed strategies, called erosion safe mode (ESM), is to reduce the tip speed during heavy rain conditions (Mishnaevsky et al., 2021). The strategy was proposed by Bech et al. (2018), investigating five different control strategies carried out on a Vestas V52 turbine. The results showed that with no reduction in tip speed, the loss of AEP could be significant, with up to 3.5% compared to an erosion-free reference case. The expected leading-edge lifetime for a blade where no tip speed reduction is done would be 1.6 years, whereas the most erosion safe strategy would result in an expected lifetime of 107 years. The results also showed that by slightly reducing the blade tip speed during the harshest rain intensities (meaning only 10.6 hours per year in the simulation), the expected leading-edge lifetime would extend to 10.4 years. Bech et al. (2018) concluded that the lost energy production due to tip speed reduction was marginal compared to the cost of loss of energy production due to eroded blades and cost for maintenance and repair.

A study by Hasager et al. (2021) found that the loss in profit due to LEE could be reduced approximately 70% by using the ESM strategy. Another study from the EROSION project indicated that 88% of the loss in profit due to LEE could be saved by using ESM (Skrzypiński et al., 2020).

4.4.1.2 Prediction and repair

This strategy aims at predicting the intensity of erosion and degradation (predictive maintenance) and then repairing at regular intervals. Repair is usually done by placing protective tapes or coatings on the eroded areas. Another method is condition-based maintenance, where maintenance is performed based on indicators and monitoring, so that maintenance can be scheduled when needed, not before, nor too late.

4.4.1.3 Protection

There are several types of protection used to increase the lifetime and to avoid LEE. These can be coatings, tapes, or shields.

One of the most commonly applied products is ELLE (Ever Lasting Leading Edge), an erosion shield developed by Polytech. This is a robust, while still flexible polyurethane shell. Polytech states, as the name of the product indicates, that the protection will last the lifetime of the turbine (Polytech, n.d.). ELLE has been tested on a demonstration turbine for three years (as of 2019) and rain erosion tested for 100 hours with no visible erosion in any of the cases (Herring et al., 2019).

Another erosion shield solution is Armour Edge, which is made of blended acrylonitrile styrene acrylate with polycarbonate. Since the coating is a thermoplastic, large pits will not occur as the material erode, providing a more preferable aerodynamic performance (Herring et al., 2019). Armour Edge states that the lifetime of their product has been extensively rain erosion tested and should provide protection against LEE for more than 20 years (Armour Edge, n.d.).

One of the solutions for LEE protection that has gained attention the recent years is electroformed metallic shields. Metals have higher impedance than typical gelcoats and can therefore reflect a large amount of the impact energy from the rain droplets. This allows the metallic shield to have better rain erosion performance at high tip speeds compared to polymeric materials. A rain erosion test by Herring et al. (2019) of a nickel alloy showed that there was no surface degradation after 85 hours while at a rotational speed of 173 m/s. This corresponds to an estimated lifetime of over 30 years at tip speeds of 120 m/s. An example of a provider for a solution for leading edge protection with electroformed metallic shields is GalvanoPro, which use electroformed nickel-cobalt.

4.5 Decommissioning

The decommissioning strategies presented in this chapter are mostly derived from WindEurope's guidance document "Decommissioning of Onshore Wind Turbines" (WindEurope, 2020a). The dismantling of a wind turbine is dependent on whether the turbine is going to be further used in its entirety or partially, or if it's going to be disposed of.

Dismantling by crane is the most common method. The dismantling is done in steps, and the individual parts are carefully disassembled. This ensures the integrity of the components and enables further use. Depending on whether the wind turbine is being reused or not, cutting equipment is present at the site to section the blades into more easily transportable pieces. The sectioned pieces can then be transported to a waste management company. If the blades are being reused, there are higher requirements in terms of transport. By transporting the blades as a whole, there are stricter requirements to the vehicle and road transport. The transport will in that case usually exceed legal weights and dimensions for road transport, thus escorts are usually required.

Controlled felling or controlled demolition is a disassembly strategy where the turbine is turned over and falls to the ground. The felling is usually done by hydraulic equipment or by explosives. This method has been widely used internationally and has also been used in Norway, where the method was used when decommissioning the Hundhammerfjellet wind farm (Bjerkomp, 2020). The method is characterized as being cheap, fast, and effective but may damage both the composites and the surrounding environment. This may make the blades unable to be repurposed, and the blades are therefore sent to recycling, incineration, or landfilling. In most cases, this method is avoided and dismantling by crane is applied. An example of this is when an offshore test turbine operated by SSE Renewables in Ayrshire, Scotland, was decommissioned, a "suitable method for safely dismantling the turbine by crane could not be established", and controlled felling was identified as the only feasible option (Herald & Hilley, 2019).

4.6 Reuse

Reuse of the wind turbine blades is the best option according to the waste hierarchy and should therefore be aimed for. There are several companies which specialize in selling refurbished turbines and components, some shown in Table 4.3. The market for reuse of wind turbines has been active since the early 2000s and the largest resellers are located in the pioneering countries in terms of developing wind energy in Europe.

Table 4.3: European companies reselling turbines and turbine components.

Company	Location
Green-Ener-Tech	Denmark
Repowering Solutions	Spain
Enerpower	Ireland
Spares in Motion	Netherlands
DutchWind	Netherlands
Windbrokers	Netherlands

Wind-turbine.com	Germany

Reuse of wind turbines are a viable option for wind turbines where the wind farms are repowered before end of the wind turbine blade lifetime. In Norway, sale of used wind turbines has been a tried-out practice. In an example from 2014, five of the turbines at Mehuken were sold after 13 years in operation (Bjerkomp, 2020). In some cases used wind turbines are sold to developing countries, where second-hand turbines could contribute to a green energy transition and avoid a lot of CO_2 emissions (Ankersmit & Disse, 2021).

4.7 Repurposing

By using the wind turbine blades as they are and repurpose them in other applications, the lifetime of the material can be extended for many years. Nagle et al. (2022) estimated that the lifetime of secondary life wind turbine blade applications could be up to 60 years. In a 60-year time, it is likely that the recycling technology for GFRP is developed, hence the secondary applications can be recycled with the material being recovered at a higher value than at present. There have been several projects where decommissioned wind turbine blades have been used in different applications, such as bike shelters and in playgrounds. A list of repurposing projects is presented in Table 4.4. Figures of some of the applications are presented in Appendix A.

Table 4.4: Repurposing solutions for decommissioned wind turbine blades.

Application	Developer	Status
Culverts	Re-Wind	Concept
Powerline poles	Re-Wind	Concept
Bridge	Re-Wind	Under installation in Cork, Ireland as of Feb. 2022
	Superuse Studios (GENVIND)	Planned location in Aalborg, Denmark.
	Anmet	Installed in Szprotawa, Poland in October 2021.
	Stijn Speksnijder	Concept
Playground	Superuse Studios	Installed in Rotterdam, Netherlands in 2009 and Terneuzen, Netherlands in 2017.
Bike shelter	Superuse Studios	Installed in Almere, Netherlands in 2014.
	Siemens Gamesa	Installed in Aalborg, Denmark in 2020.
Farm applications (Feed bunks, cattle & grain partition walls)	Re-Wind Network	Concept
Roof	Re-Wind	Concept
Barriers	Re-Wind	Concept
Fencing	Re-Wind	Concept
Urban furniture	Superuse Studios	Installed in Rotterdam, Netherlands in 2012.
	Anmet	Sold in Poland and Germany.
Household furniture	Wigh Design (GENVIND)	Concept
Signpost	Superuse Studios	Installed in Maastricht, Netherlands in 2014.
Planters	Re-Wind	Concept
Artificial reefs	Behzad Rahnama	Concept

Nagle et al. (2022) found that substitution of steel provided the most positive environmental performance, followed by substitution of concrete. One of the most researched repurposing applications is the use of blades in bridges, where the blade in most cases substitutes steel beams. The first bridge made from wind turbine blades was installed in Szprotawa, Poland in October 2021 by Anmet, a polish recycling company. The bridge was made by two blades connected by the root in the middle, with a span of 23 meter (Burchardt, 2022). A photo of the bridge is shown in Figure A.4 in Appendix A. Anmet also produces furniture from decommissioned wind turbine blades, which is mostly sold in Poland and Germany (A. Adamcio-Wilczynska, personal communication, 6 April 2022).

Bridges made of wind turbine blades have also been designed by Stijn Speksnijder, Superuse Studios and Re-Wind Network, where the Re-Wind Network's bridge is under installation in Cork, Ireland.

Superuse Studios have used decommissioned wind turbine blades in several of their projects. Their first project was the Wikado playground in Rotterdam, Netherlands. Five turbine blades were used, one of them used as a whole. The ecological footprint was fifty times smaller than a comparable standard playground, where it also won the 2009 European Environmental Design Award (Guzzo, 2019). The properties of the wind turbine blades made it an excellent material choice for a playground as it is weather and wind resistant and have a strong and rigid structure. Superuse Studios have also designed urban furniture and bike shelters using wind turbine blades, both installed in the Netherlands. Photos of repurposing solutions made by Superuse Studios are shown in Figure A.1, Figure A.2 and Figure A.3 in Appendix A.

The GENVIND consortium was a Danish innovation project aimed to identify and develop new and existing strategies for recycling of composites, also including how waste could be reused in secondary applications (Jensen & Skelton, 2018). During the project a bridge was designed by Superuse Studios and planned to be installed in Aalborg, Denmark. The project presented some limitations of repurposing as the application requires testing of the blade, cutting to meet design, transport, and the construction, and showed that gaining experience on the topic is crucial for future implementation of similar concepts. Other secondary applications researched in the GENVIND project was furniture and hybrid materials. Household furniture was designed by Wigh Design and the project showed that the strength, weight, and durability of the material could be utilized to create objects of high value.

The Re-Wind Network is a research project in collaboration between City University of New York, Georgia Institute of Technology, University College Cork, and Queen's University Belfast, which seeks to find alternative methods to unsustainable disposal methods for wind turbine blades. During the project, several new alternatives for repurposing have been presented, such as power poles and farm applications. Different sized blades can be used for different transmission lines depending on height and voltage. The blades are suited for angle poles and dead-end poles due to their large moment carrying capacity and the existing grounding cable in the blade can be used as pole ground. Alshannaq et al. (2022) did a structural analysis of the proposed concept and mechanical testing indicated that the repurposing of blades into transmission poles is feasible. Figure A.8, A.9 and A.10 in Appendix A shows the bridge, feeding bunk and power pole designs made by the Re-Wind Network.

Another concept presented by the Re-Wind Network is repurposing into farm applications, such as feed bunks, cattle, and grain partitions. One of the reasons behind this concept is that the wind farms are often built on or near conventional farms, reducing the cost of transport for the decommissioned blades. The design concept uses the whole blade, where the tip is used for cattle partitions, the middle for grain partitions and feed bunks, and root sections can be used as culverts. These applications mostly substitute steel and reinforced concrete.

In 2020 Siemens Gamesa installed a bike shelter made by a decommissioned turbine blade in Aalborg, Denmark. This was a part of the DecomBlades consortium and the research projects FiberEUse and DigiPrime, which all seek to promote a circular economy (Iotkovska, 2021). The bike shelter is shown in Figure A.7 in Appendix A.

The use of decommissioned turbine blades to create artificial reefs has been studied by Rahnama (2011). By creating artificial reefs it will support marine life, have a smaller environmental impact compared to incineration and landfill, while still a fast and simple method (Rahnama, 2011). It needs to be further investigated to determine the actual environmental and ecological effect, e.g., related to the issue of microplastics.

4.8 Recycling

The recycling methods that have been investigated was chosen according to their TRL presented in Table 2.2 in Chapter 2.5.6. Mechanical recycling, co-processing and pyrolysis are the three technologies having the highest TRL, 9, 8/9 and 7, respectively. In WindEurope's report "Accelerating wind turbine blade waste recycling" from 2020, all the methods mentioned above was given a TRL of 9. In addition to these, solvolysis is also presented due to the increasing focus on this recycling method in the industry. The predicted environmental impact of the different recycling methods is also presented.

4.8.1 Mechanical recycling

Mechanical recycling refers to downsizing the blades by shredding, grinding, or milling and using the downsized composite in new products. There are several companies using recycled composites in new products. In Table 4.5, some companies that make new products using mechanically recycled composites are presented. Pictures of some of the products are shown in Appendix B.

Table 4.5: Mechanical recycling companies/projects and their products made from recycled material.

Company	Location	Application
FiberEUse	Europe	Ski
		Bathroom furniture (bathtub, stools, etc.)
		Bricks
		Filler material in additive manufacturing
EcoFiber Recycling	Norway	Bench
		Boats
		Reinforced concrete
Miljøskærm	Denmark	Noise barriers
Reprocover	Belgium	Level crossings (railway)
		Cable troughs
		Covers
MCR	France	Reinforced concrete
		Reinforced asfalt
ECO-WOLF	USA	Spray-up equipment
Extreme Eco Solutions	Netherlands	Pavement & wall tiles
Conenor	Finland	Boards
		Benches
		Raincovers

EcoFiber Recycling was the first company in Norway to recycle composite waste, mainly old fibreglass boats. The recovered fibres can be used in several new products and have been used in reinforced concrete, benches, and in new boats (Svendsen, n.d.). A boat with 30% recycled material was made in 2018 in cooperation with Siddis Plast AS (Nissen-Lie, 2018). The benches are part of a project called SKOG, where the recovered fibres are combined with plastic and wood chips and made into profiles which can be used to make furniture (EcoFiber, n.d.). A picture of the SKOG bench is presented in Figure B.1 in Appendix B. Ecofiber is still looking for downstream solutions for their recovered fibres, as the earlier solutions were not commercially viable. A new product is currently being worked on and Ecofiber aims to have prototypes ready next year. The demand for waste will then increase and wind turbine blade waste is seen as one of the possibilities. As of today the recovered materials are incinerated for energy recovery (O. E. Kvelland, personal communication, 13 May 2022).

Reprocover is a Belgium based company making products from recycled thermoset composites for railways, roads, and urban development. Their most popular product is cable troughs, for cable protection alongside railways or similar. The cable trough is shown in Figure B.2 in Appendix B. On average the composition of their new products consists of 85% recycled granulate and 15% virgin material, depending on the product requirements. Reprocover started to process wind turbine blade waste in 2020 and processes 20 to 50 tonnes per year and aims to upscale this towards 1000 tonnes per year. One issue with recycling the wind turbine blades is that there are lack of specific internation legal requirement for the crushing process when it comes to e.g., dust and noise pollution. The blades are coarsely crushed at site and further crushed into fine granulate off-site. Reprocover has also previously developed railroad ties or sleepers made of recycled composite, but found that this was not competitive due to significantly lower cost of concrete sleepers (G. Charles, personal communication, 12 May 2022).

Finland is one of the European countries with a ban on landfilling of composites. The Finish company Conenor, which specializes in extrusion technology, has started using recycled thermoset FRP in some of their products, like decking boards and other building materials. As a part of the ECOBULK project, Conenor utilized wind turbine blade waste for manufacturing of grandstand benches and rain covers at the KymiRing near Kouvala, Finland (Conenor, n.d.; Kyheröinen, 2020).

The Danish company Miljøskærm has since 2015 produced noise barriers using recycled fibreglass. A photo of one of their noise barriers is presented in Figure B.3 in Appendix B. Miljøskærm has experience with recycling wind turbine blade waste and is currently using it in their products. A life-cycle analysis of the noise barriers showed that Miljøskærm's product reduced CO_2-emissions by 60% and energy consumption by 40% compared to a noise barrier made from virgin materials (Miljøskærm, 2021).

4.8.2 Co-processing

Bjerkomp (2020) concludes with co-processing being the best available option for recycling of wind turbine blades from Norwegian wind farms. The process is already commercialized, and processing of wind turbine blade waste has already been experienced. One of the companies is Geocycle, a subsidiary of Holcim, which has several locations in Europe where co-processing cement plants are operational. Geocycle currently offers co-processing solutions for wind turbine blades in Germany and is looking into the possibility of extending to other parts of Europe (Geocycle, 2021).

In the U.S., GE Renewable Energy announced in 2020 a multi-year contract with Veolia for decommissioned wind turbine blades owned by GE in U.S.-based wind farms. The blades are shredded and used in Veolia's cement kiln co-processing facility in Missouri. Using wind turbine blade waste in the cement production enables a 27% net reduction in CO_2 emissions compared to traditional cement manufacturing (Nehls, 2020).

4.8.3 Pyrolysis

Pyrolysis has TRL 7 by Paulsen & Enevoldsen (2021) and TRL 9 by WindEurope (Schmid et al., 2020). Pyrolysis is more often used for recycling carbon fibres than glass fibres as the high temperatures degenerates the glass fibres. The carbon fibres will still experience a degradation in mechanical properties, but the high value of carbon fibres still makes the process economically viable. In Table 4.6, a list of companies using pyrolysis to recycle composite waste are presented. Products made of their recovered fibres are also presented. Pictures of some of the products are shown in Appendix B.

Table 4.6: Pyrolysis recycling companies and their applications for recycled fibres.

Company	Location	Application
Gjenkraft	Norway	Ski
		Climbing holds
		Insulation materials
carboNXT	Germany	Car bumpers
		Bicycle
		Kiteboard
		Covers
Gen 2 Carbon	UK	Nonwoven fibre mats

The Norwegian company Gjenkraft uses pyrolysis to recycle wind turbine blades. In the pyrolysis process, the material output is 54.7% recycled fibres, 23.8% synthetic gas, 10.5% light fuel oil, 9.5% carbon, and 1.5% metals (stainless steel, bronze, and aluminium). Millfiber is the product name of the recovered carbon and glass fibres, and these fibres are used in production of alpine skis, climbing holds and various insulating materials. The alpine skis are made of recovered carbon fibres and are made by EVI skis. An example of skis made by EVI using Millfiber is Norrøna's "Lofoten woodcore 104". The carbon fibres are at approximately 95% of virgin strength, while the glass fibres will degenerate. One of the solutions to this is to grind the glass fibres to micro-silica which can be used in products such as processors and 3D-printing fillers but also to synthesise new glass fibres. The recovered glass fibres has been used in production of climbing holds and have showed to improve the strength. The glass fibres are also used in production of insulation materials and glass fibre foam which can be used to substitute concrete (S. Loginov, personal communication, 28 April 2022).

Gjenkraft is still developing the technology and methods to improve their process. One of the problems is to separate the glass and carbon fibres, where a method is under development. Also, a technology for synthesising the gas and oil products from the pyrolysis process into monomers and polymers is under development in cooperation with BASF and Future Materials (S. Loginov, personal communication, 28 April 2022).

CarboNXT is a Germany based pyrolysis company, recycling carbon fibres and producing new products from recovered fibres. The recovered fibres are sold as e.g., milled, chopped, nonwoven fabrics and moulding compounds. Most of their products are towards the automotive industry, like anti-corrosion covers, engine covers, bumpers, and weight-reducing interior. CarboNXT has also designed other products, such as a bicycle, kiteboard and hockey masks (carboNXT, n.d.). The bicycle was made in cooperation with STEVENS Bikes and is presented in Figure B.6 in Appendix B (STEVENS, 2012).

Gen 2 Carbon makes nonwoven fibre mats out of recycled carbon fibres. These mats come in two types: 100% recycled carbon fibre and combination of carbon and thermoplastic fibres. The materials have been used in the automotive and rail industry, and Gen 2 Carbon also says their products can be used in wind turbine structures. The carbon fibre fabrics can be processed using resin infusion and are thus suitable for wind turbine blades (Gen2Carbon, n.d.).

4.8.4 Solvolysis

Solvolysis or chemical recycling is the method that three of the largest manufacturers (Vestas, Siemens Gamesa and LM Wind Power) are focusing on when it comes to recycling their blades and in the aim of making 100% recyclable blades. A study by Liu et al. (2022) shows that chemical recycling gives the highest value of recovered fibres, both for carbon and glass fibres. Solvolysis is also the only method where 100% of the fibres can be recovered. The study concludes that solvolysis is still at lab scale but is the most promising recycling method for wind turbine blades. In WindEurope's report "Accelerating Wind Turbine Blade Circularity" (Schmid et al., 2020), solvolysis is considered economically viable for carbon fibres but not for glass fibres due to the high processing cost relative to the value of the recovered fibres.

The technology is still not commercialized for wind turbine blade waste, but some companies have tried to use solvolysis to recycle fibre-reinforced composite. The U.S.-based company Adherent Technologies Inc. has developed a solvolysis process for recovering of carbon fibres. The company states that the recovered fibres retain 95% of virgin fibre strength. Adherent Technologies Inc. says that the process is suitable for all fibre-reinforced composites but has so far only reclaimed carbon fibre due to economic reasons (Adherent Technologies, 2022).

4.8.5 Environmental impact

Liu et al. (2019) did an eco-audit comparison of different EoL-options for three different types of wind turbine blade: full glass fibre, hybrid and full carbon fibre blade. The benchmark in the analysis was landfilling. In Table 4.7, the optimal EoL-options are presented, excluding life extension, based on environmental impact for the three types of wind turbine blades according to Liu et al. (2019).

Table 4.7: Current and future optimal EoL-options for wind turbine blade waste (Liu et al., 2019).

Blade type	Current best	Future
Glass fibre	Mechanical recycling	Chemical
Hybrid (glass/carbon)	Mechanical recycling	Chemical
Carbon fibre	Fluidized bed	Chemical

Mechanical recycling reduced the net impact to 90% for glass fibre and 87% carbon fibre, while the current best option for carbon fibres, fluidized bed, reduced the net impact to 73%. Chemical recycling, such as solvolysis, was the best EoL-option with the net impact reduced to 86% for glass fibre and to 56% for carbon fibre blades. The study concludes that recycling by chemical recycling is still not technically viable as of 2018 but will be the best option for blades when the technology matures. Pyrolysis was shown to be a viable option for carbon fibre, reducing the net impact to 83%. Recycling of glass fibre blades would increase the net impact to 110%. This is due to the high embodied energy in the carbon fibres compared to the glass fibres.

Bjerkomp (2020) concluded that co-processing was the best option for decommissioned wind turbine blades from Norwegian wind farms, in terms of both cost and environmental impact. This study was based on a Norwegian wind farm and had four different EoL-options: landfilling, incineration, co-processing and reuse. Because of transport costs, reuse was not a viable option economically. In this case, using wind turbine blades in a co-processing gave a negative net CO_2-equivalent emissions of 1099 tonnes. This was mainly due to incineration of the organic components in the blades would substitute fossil fuels. In Bjerkomp's case, co-processing was the only alternative to achieve negative net greenhouse gas emissions.

A life-cycle assessment by Nagle et al. (2020) comparing co-processing and landfilling of decommissioned Irish wind turbine blades showed that substituting Irish blades in a German cement kiln was six times better environmentally than landfilling in Ireland. The study showed that the carbon footprint due to transportation was far less compared to the beneficial impact of raw material substitution. The study also showed that theoretically if the waste was used in an Irish co-processing facility it would be 1007% better than landfilling and 78% better than co-processing in Germany. The data was based on a 10% material substitution rate in the cement kiln.

4.9 Legislators and regulators

The legislators and regulators are the governing bodies which makes the framework for the industry. This can for example be licencing to build wind farms, regulations towards decommissioning and waste handling. The legislators make the laws, while the regulators maintain the law. Relevant issues to regulate for wind farms development can include distance to residential areas, noise limits and tip height restrictions (WindEurope, 2019).

The EU Landfill Directive sets requirements for landfill sites to what waste, the amount of waste, and technical requirements to the waste being landfilled. The Landfill Directive sets restrictions on landfilling of waste suitable for recycling or energy recovery (from 2030) and requirements to reduce the amount of landfilled biodegradable waste (European Commission, 2020). Some wind turbine blades contain balsa wood, which is biodegradable, and plastics. As a part of the European Green Deal Circular economy action plan, EU is taking action against plastic pollution. EU's focus has not been directly towards composite waste but wind industry associations, such as WindEurope, have called for a Europe-wide ban on landfilling of turbine blades (WindEurope, 2021). Four European countries have already banned landfilling and incineration of composite waste: Germany, Austria, Finland and the Netherlands (Schmid et al., 2020). In Norway it is forbidden to landfill biodegradable waste with a carbon content above 10% (Lovdata, 2016).

The governing bodies administrate the licensing hence affect development of wind farms. In Norway the licensing process for developing new onshore wind farms was stopped in April 2019, and was reopened in April 2022 (NVE, 2022).

5 Circular economy for wind turbine blades

To answer research question 2: “What are the possibilities for a circular economy for wind turbine blades with today’s available technology?”, the Ellen MacArthur Foundation’s definition of circular economy and circular economy strategies from the building sector are applied. The strategies are presented in Chapter 2.1 and were gathered from “A Framework for Circular Buildings” by Kubbinga et al. (2018). Of the seven main strategies, six have been taken into consideration. To visualize what may or should be done to achieve a circular economy, a fishbone diagram (Ishikawa diagram) has been used. Normally, fishbone diagrams are used to determine the failure cause(s) or what needs to be put into a specific design. The fishbone diagram is presented in Figure 5.1. Every “bone” is investigated individually.

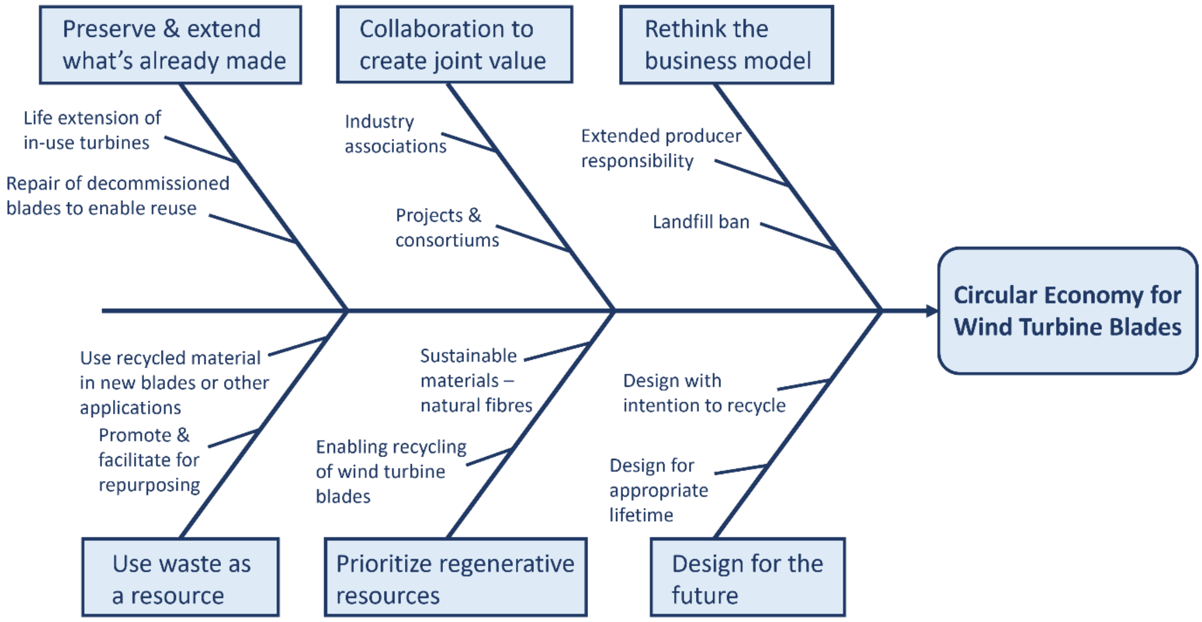

Figure 5.1: Fishbone diagram showing what could be done to achieve a circular economy for wind turbine blades built on circular economy strategies by Kubbinga et al. (2018).

5.1 Preserve & extend what’s already made

While a lot of the focus in the wind industry is on recycling and what to do with wind turbines after EoL, the action contributing most to circular economy factors is the life extension of products, keeping them at the highest possible value for as long as possible. Therefore, life extension of already in-use wind turbines and repair of decommissioned blades to enable reuse in other windfarms are of importance.

5.1.1 Life extension of in-use turbines

Research on EoL-options for wind turbine blades has shown that extending the lifetime of a blade is the best option in terms of environmental impact. Since the manufacturing of the blades consumes high amounts of energy, the longer the blade is operational, the more energy is produced back. Since the use of more energy intensive materials have increased, like carbon fibre, this will be even more important.

The main problem in O&M for wind turbine blades is LEE, which can contribute to significant losses in annual energy production (AEP). Minimizing LEE is important to ensure that the blades can operate through their expected lifetime and also be possible to extend beyond this. Implementation of the erosion safe mode (ESM) developed during the EROSION project should be focused on, as this has shown to reduce the impact of LEE. In addition, research has shown that metallic erosion shields can have an expected LEE lifetime of more than 30 years. By using both ESM and effective erosion shields, life extension of the already in-use blades should be possible.

5.1.2 Repair of decommissioned blades to enable reuse

Repowering is a normal strategy for older wind farms. As technology has developed, the turbines have become larger and can produce more. Therefore, many wind farms are repowering, i.e., changing their old turbines with newer, larger ones. In a circular economy context, it is important to keep these old turbines still producing, if possible, since they may still have residual life. Primarily, the decommissioning strategy should favour reuse. The decommissioning strategy of controlled felling should be avoided, and all turbines should be dismantled with the intention to reuse the blades or other components. Secondly, the blades should be upgraded or repaired to be able to produce for several more years. By using more careful dismantling strategies, the need for repairs can be reduced. However, the blades should be upgraded to avoid for instance LEE.

5.2 Use waste as a resource

Using waste as a resource is the key part of changing the supply chain from linear to circular. The most desired situation is to use the material in the manufacturing of new blades, but also to extend the lifetime of the blade by repurposing it in other applications.

5.2.1 Use recycled material in new blades and other applications

One of the goals to achieve a circular economy for wind turbine blades is to use recycled blade materials in the manufacturing of new blades. As of today, one of the major problems with recycled fibres is the loss of strength by using the current technologies. Recycling facilities cannot usually recycle a blade as a whole and the blades are therefore often sectioned into smaller pieces. This leads to the fibres being shorter than what is demanded for fibres in new blades as virgin fibres often are long. One solution to this is the technology which has been proposed by Siemens Gamesa in their RecyclableBlade. This blade can be recycled as a whole by a solvolysis-like method, where the fibres then can be retrieved and used for new blades.

Substituting all the virgin fibres may not be realistic, while using recycled fibres in less critical parts of the blades could be a step towards achieving a fully circular blade. Gen 2 Carbon states that their recycled carbon fibres can be used in wind turbine blades, which could substitute virgin material.

In recent years, PET foams have been increasingly used as core material in wind turbine blades. PET foams have the advantage that they are made of recycled material. This contributes to reduce the amount of virgin materials that are needed to produce the wind turbine blades and gives the recycled PET a relatively high value function. Recycled PET also degrades when being recycled and can in most cases not be used in the original product.

As of today, most of the recycled material from a wind turbine blade is not viable for use in manufacturing of new wind turbine blades. The recycled material can be used in other applications, where several demonstrations have shown that this a good option. The fibres are energy intensive to produce and therefore inherit a large carbon and energy footprint, especially the carbon fibres. Substituting virgin material in other applications have generally been shown to reduce the carbon footprint of the products.

5.2.2 Promote & facilitate for repurposing

One of the challenges as described in the previous chapter is the degradation of the fibres during the current recycling methods. Repurposing of the blades in other applications can extend the lifetime by as much as 60 years, thus enabling further development of recycling techniques. Repurposing solutions for wind turbine blades have also shown to reduce the carbon footprint of some applications when substituting certain materials such as concrete and steel. Facilitating for repurposing when decommissioning blades could therefore be an option in the long run, where the materials can be recovered in the future when the recycling technologies have developed further.

Several concepts have been tried out for repurposing wind turbine blades, especially the bridge concept has gained a lot of attention. This is a good repurposing solution as the blades have high strength and can substitute carbon intensive materials, like steel and concrete. Many concepts for bridges have been designed by the Re-Wind Network which can be used in different terrains and lengths. Using decommissioned blades in repurposing projects can also contribute to raise awareness of the situation, by showing the communities the possibilities and functional use of waste.

5.3 Prioritize regenerative resources

Usually, this circular economy strategy is weighted towards the use of renewable energy but also the use of sustainable and renewable materials. The wind turbines themselves will contribute to the production of renewable energy in their lifetime and therefore the use of renewable energy resources will not be discussed. The use of sustainable resources in the turbines is something which can decrease the carbon footprint of the turbines when operational, making the energy payback time shorter.

5.3.1 Sustainable materials

The UN defines sustainability as “meeting the needs of the present without compromising the ability of future generations to meet their own needs” (UN, n.d.). This relates to avoiding the depletion of natural resources. For wind turbine blades, the fibres are most commonly glass and carbon fibres, which are not regenerative. Research has been put into using natural fibres in wind turbine blades, which can make the fibres come from renewable resources. There should be more focus on using natural fibres in smaller wind turbines where the strength criteria are relatively lower, where it can substitute glass fibre for instance. The research on natural fibres has increased over the last couple of years, mainly due to the aim of utilizing natural, and thus also renewable fibres in wind turbine blades. Further testing and prototyping of blades should be done to see the full potential of natural fibres.

Of the core materials used in wind turbine blades, it has been common to use balsa wood in the blades, at least in certain areas of the blade. Balsa is a fast-growing tree and is therefore also considered a renewable resource. A problem is related whether the extraction and production processes are sustainable, as well as stability in the supply chain. Currently, most of the balsa wood is gathered from the Amazon rainforest, where Ecuador is the world’s largest producer accounting for 75% of the global market. The high demand for balsa wood has led directly to an increased deforestation of the Ecuadorian rainforests. This has also led to social problems in Ecuador where this has had consequences for indigenous communities. Although a fast-growing, renewable resource with excellent properties for wind turbine blades, the current management of balsa wood is not sustainable. If the industry continues to use balsa wood in the production of wind turbine blades there should be guarantees that the balsa is produced sustainably.

5.3.2 Enabling recycling of wind turbine blades

Some of the materials in a wind turbine blade are degenerated through recycling, making them nonviable for use in new turbine blades. As of today, only three of the recycling technologies for thermoset composites has reached a TRL of commercial scale: mechanical recycling, co-processing, and pyrolysis. Development of other recycling technologies, as well as the already commercialized ones, are key to achieving a circular economy. By enabling the recycling of the blades, the loop can be closed, and a circular supply chain can be created.

One of the most promising technologies is solvolysis. This is due to the possibility of recycling whole blades, recovering long fibres which can be used directly in the production of new blades. This method has been investigated earlier by research projects, like EURECOMP, and in recent time by Siemens Gamesa in their RecyclableBlade and LM Wind Power in the ZEBRA project. The main problem with solvolysis is the high operating cost, which currently makes it economically viable only for recycling carbon fibre. By developing the technology, and lowering the operating cost, this could be the best option for recycling both carbon and glass fibre as it ensures long fibres with relatively low loss in structural properties.

5.4 Collaboration to create joint value

One of the key elements of a circular economy is collaboration. It is important to work together throughout the supply chain and with researchers to be able to achieve a circular economy.

5.4.1 Projects & consortiums

As mentioned in this thesis, there are several research projects and consortiums regarding wind turbine blades. The research projects help accelerating the development, making connections between different parts of the supply chain as well with universities and other researchers. One of the ongoing projects is the DecomBlades consortium, where Vestas, Siemens Gamesa and LM Wind Power are participating. The manufacturers should collaborate across and not only with other parts of the supply chain. They should share experiences to jointly reach their common goals of recyclable blades and no waste for landfill.

Collaboration was also stated to be essential during the conducted interviews, and that it is better for the industry as a whole to share ideas and to create joint value. Instead of being competitors, the companies can collaborate. One example is that the different recycling companies collaborate across technologies, so that the different types of materials can be recovered at the optimal method.

5.4.2 Industry associations

The wind industry associations can also be influential in the transition to a circular economy. WindEurope is the voice of the wind industry in Europe and has over 400 members from the whole wind energy supply chain. WWEA (World Wind Energy Association) is an international association with more than 600 members from around 100 countries, promoting worldwide deployment of wind energy. The industry associations influence larger parts of the supply chain and can support the initiatives for further developments, collaboration, and research across the supply chain.

The wind industry associations should also influence and advise governments and other organisations to raise awareness about the issues in the industry and to promote and accelerate a change towards a circular economy.

5.5 Design for the future

In the design phase, focus should be on designing for a circular economy. Here, two factors are suggested for how to implement a circular economy strategy into the design process:

- Design for an appropriate lifetime
- Design with the intention to recycle

5.5.1 Design for an appropriate lifetime

Currently, blades are designed for a lifetime of 20 to 30 years. Even though the blades are designed for this lifetime, many require regular repairs throughout the lifetime, some even every two to five years. This should be increasingly addressed in the design phase, adding sufficient protection by for example LEE. Repair and maintenance also account for 25% of the total levelized cost per kWh produced over the lifetime of the turbine. Focusing on erosion protection in the design phase will reduce the need for maintenance i.e., lower operating cost, increase the profit, and increase the lifetime of the wind turbine blade. By extending the designed lifetime, the wind turbine blades can produce for longer, exceeding the energy payback time further.

5.5.2 Design with the intention to recycle

In the development phase, the designers should always prioritize the EoL of the wind turbine blade, and with the highest attention to recycling. Manufacturers have already started to change from thermosets to thermoplastics in some of their blade designs, making the blades more easily recyclable. It should also be decided in the design phase what kind of recycling methods to be used for the specific blade design. The design focus regarding recycling should be towards keeping the materials in a full circle, enabling them to be used in new blades for a second lifetime.

5.6 Rethink the business model

Legislators and regulators can affect the whole supply chain by regulations or incitements. Implementation of new laws or regulations can affect the way the industry is run today and make actors in the wind turbine blade supply chain make choices and support research positively towards a circular economy. One of the primary examples of this is the proposal of a landfill ban of composite waste, which drives the development of other EoL-options, such as repurposing and recycling.

5.6.1 Extended producer responsibility

Extended producer responsibility (EPR) is a policy approach in which producers are given a significant responsibility for the treatment or disposal of post-consumer products (OECD, n.d.). EPR currently exists for other industries, such as for electronic and electrical equipment, and EoL for vehicles. Introducing EPR to the wind industry could provide a higher incentive to address the waste problem. This could lead to changes in product designs, prevention of waste at the source and support public recycling and materials management goals (OECD, n.d.).

Jensen & Skelton (2018) proposed introducing EPR principles for the wind industry, particularly towards the design phase, which could enable closed-loop recycling of wind turbine blades. The turbines should not only be renewable in terms of energy generation but also in terms of material use (Jensen & Skelton, 2018).

Introducing EPR for the wind industry has been debated in some European countries. In France, a report from October 2019 by the Ministry for a Just and Ecological Transition on wind turbine circularity recommended introducing EPR for blades. When a new law on circular economy was adopted on the 10th of February 2020, EPR was introduced for several products, however wind turbine blades were not included as EPR was deemed not to be effective in increasing blade recycling (Schmid et al., 2020). In Germany, EPR has also been discussed. One of the arguments against EPR for wind turbine blades was that an isolated regulation in Germany contradicts with the fundamental idea of the EU internal market. A solution could be to propose EPR for wind turbine blades under an EU directive, as it is today for electronic and electrical equipment under the WEEE directive.

5.6.2 Landfill bans

The wind industry in Europe, led by WindEurope, proposed in June 2021 a landfill ban for wind turbine blades by 2025. This also included decommissioning European blades outside of Europe, ensuring the waste is not landfilled elsewhere. A ban on thermoset composites is already issued in some European countries which have directly led to the development of other alternatives. One example is the cement kiln co-processing facilities in Germany. Issuing a Europe-wide ban will accelerate the developments as countries must find new ways to handle this waste.

In the long run, not only banning landfills but also setting restrictions on incineration should be considered. Since the blades are mostly made of non-regenerative materials it is important to keep these materials in circulation if possible. By incinerating the blade waste, the materials cannot be reintroduced into the supply chain.

One option, which for example is used by wind farm developer Ørsted, is to store the decommissioned blades. Ørsted said, instead of landfilling the blades, they will temporarily store the decommissioned blades until the recycling challenges are solved (Ørsted, 2021). The problem with this is the space required to store the blades if the technology is not developed sufficiently in the following years. This is however considered a better option than landfilling or incinerating the blade waste, as it keeps the recycling opportunity open.

5.7 Circular economy framework for wind turbine blades

To visualize the findings and proposals of this thesis, a circular economy framework for wind turbine blades has been made, shown in Figure 5.2. The bold line shows the preferred pathway for a circular economy for wind turbine blades, with the green boxes being the optimal options, yellow being acceptable, and orange should be avoided.

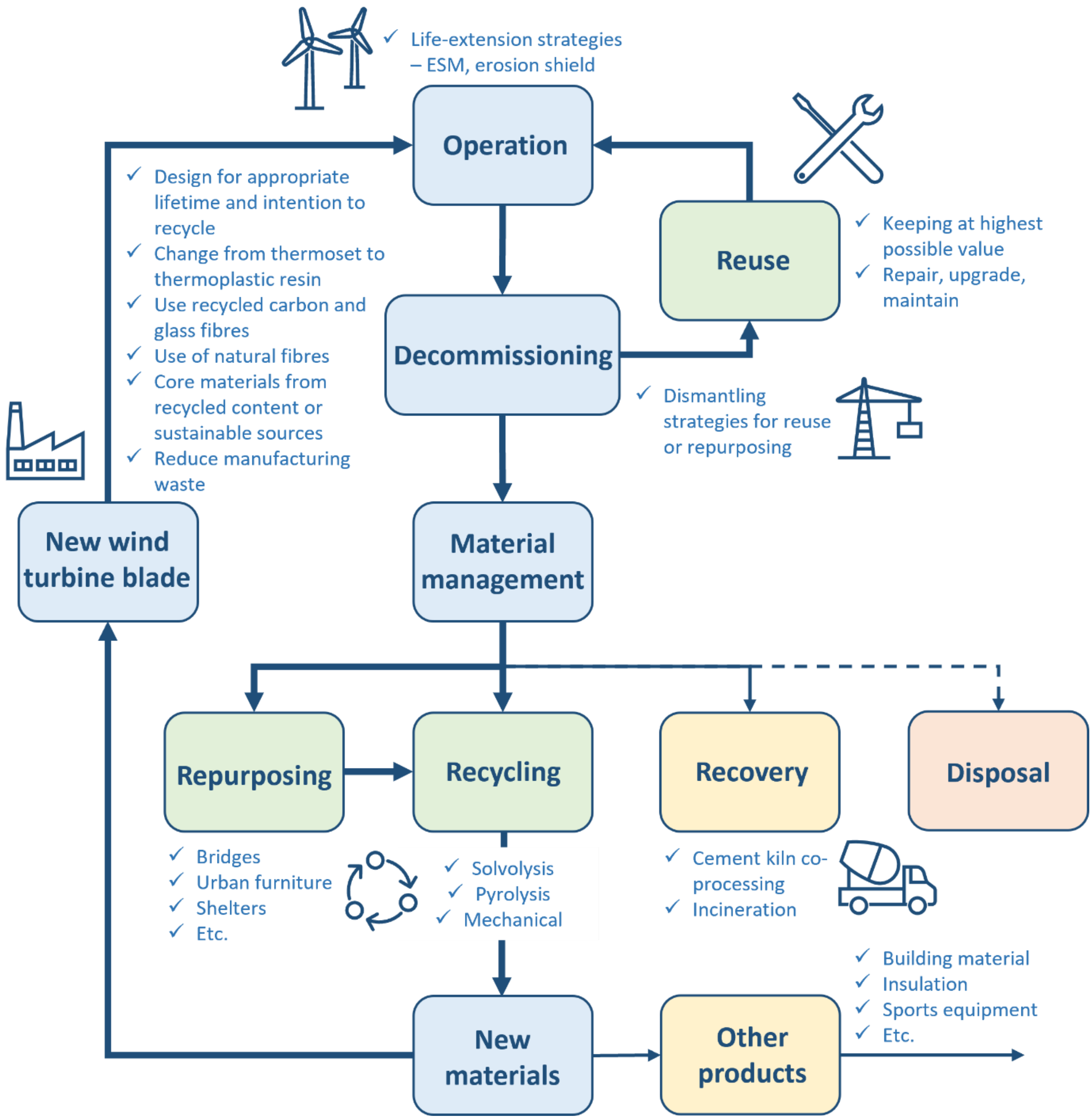

Figure 5.2: Circular economy framework for wind turbine blades.

The optimal route is to enable the recycled materials to be reintroduced into new wind turbine blades. To use the materials in other products is also acceptable, but this means that in most cases the materials are used at a lower value than the original. As of today, the recycling methods are not able to recover the fibres at a high enough value for full circularity for wind turbine blades. The recycling methods in Figure 5.2 are sorted from the most preferred to the least preferred method in terms of value of the recovered fibres.

6 Discussion

The two research questions to be answered in this thesis were: “What is the current situation of recycling and reuse of wind turbine blades?” and “What are the possibilities for a circular economy for wind turbine blades with today’s available technologies?”. Information answering these questions are presented in the previous chapters. Research question 1 gives a status on current technologies and trends in developments. Research question 2 requires coordinated strategies and action at several different levels, from politics and regulations, cooperation across the supply chain, as well as technological development.

This discussion, focus on the technological aspects to be able to achieve a circular economy for wind turbine blades. The discussion is sectioned into three parts: the design and manufacturing phase, the operation and decommissioning phase, and material management.

6.1 Design and manufacturing

Most wind turbine blades are made of thermoset composites, GFRP or CFRP, and have a designed lifetime of 20 to 30 years. To improve the circularity, several actions are proposed in the circular economy framework in Figure 5.2.

The blades should be designed with an intention to recycle. The EoL of the blade should be considered in the design phase and designed with materials that enable the recycling process. One example studied in this thesis are the RecyclableBlade and ZEBRA-blade, where the blades are made with a thermoplastic instead of a thermoset resin. This allows the blades to be recycled by solvolysis at EoL.

Currently, most of the materials used in the manufacturing of a new wind turbine blade are virgin, processed materials. One exception is the use of PET-foam as core material. In recent years the use of PET-foam from recycled PET has increased. Recycled fibres are not reintroduced into new blades. As the recycling methods develop and the materials are recovered at a higher value, the fibres can be reintroduced into the blades. This is particularly relevant in parts of the blade where the criteria may be lower for stiffness or strength. This will enable a circular pathway for at least some of the materials in the blades.

Another option is to use natural materials, which can be used as both fibres and core material. As natural materials are regenerative, they don’t necessarily need to be recycled and reintroduced, as long as they are grown and sourced sustainably. Prioritizing regenerative resources is a good option but should not be at the expense of nature and the environment. Studies have shown that the use of natural fibres is possible for wind turbine blades, at least in smaller blades (Holmes et al., 2009;

Thomas & Ramachandra, 2018). More research and testing are needed before this can be implemented in bigger blades, e.g., on structural stability and degradation. A natural material already used is balsa wood, though the use has decreased in recent years due to unstable supply and high prices. Continued use of balsa wood should only be supplied from sustainable sources to reduce deforestation and social problems associated with the production.

6.2 Operation and decommissioning

One of the key elements of circular economy is to keep the value of the product and the material at the highest possible value for as long as possible. The blades have large amounts of embedded energy from manufacturing and the longer they produce, the more energy efficient they are. Studies have shown that life extension of wind turbine blades is the best environmental option due to the improved energy lifetime efficiency and additional energy produced in these years. One of the issues with life extension of older turbines is that it can be more economical to replace them with new turbines to increase the production efficiency. One of the life extension strategies for wind turbine blades is to use ESM (erosion safe mode). Studies have shown that ESM can extend the erosion lifetime of the blade to up to 107 years and that up to 88% of the loss in profit due to LEE could be avoided (Bech et al., 2018; Skrzypiński et al., 2020). ESM should be implemented for all turbines, especially offshore wind turbines, to reduce the need for repairs and to keep the blades at the highest value, meaning the highest level in the waste hierarchy.

The dismantling method called controlled felling should be avoided. When dismantling, the damage to the material should be minimized to reduce the need for repairs and enable the reuse of the blades in either new wind farms or to be repurposed. This method can be damaging both to the material and the local environment. The dismantling strategy used should be well planned and chosen to make reuse possible. This will again keep the material at highest value and the dismantled turbines can be redistributed and used to produce clean energy elsewhere, like in developing countries. If the turbines are reused in developing countries, it is important is to account for the waste after second lifetime, so that the waste from the reused blades is not for example landfilled.

6.3 Material management

Material management refers to options for the wind turbine blades when they can no longer be used for their original purpose. From the circular economy framework shown in Figure 5.2, there are four possible routes: repurposing, recycling, recovery, and disposal. Disposal is the least favoured option and should be avoided since the material as a resource is not used.

This thesis has identified several demonstrated applications for repurposed wind turbine blades, though the amount going this route is still low. Most of the applications are one-time installations as part of projects and few are commercialized businesses. The exception is the urban furniture produced by Anmet, which is sold in Germany and Poland. In terms of circular economy, repurposing is a good solution since it extends the lifetime of the material further. It also replaces other materials which are then not needed, which can offer a good environmental benefit by reduced resource utilization. The most positive environmental performance is achieved when it substitutes steel or concrete, due to their energy demand in processing. Studies have also estimated that the lifetime of repurposed applications can be up to 60 years, which enables the development of recycling technologies (Nagle et al., 2022). One issue which is rarely addressed with composites, is the degradation of the polymers and thus potential pollution of microplastics. Repurposed applications may be in direct contact with fauna or nature, or erosion products following water streams, which can lead to potential health or environmental issues. This topic should be further investigated before blades are used in such applications.

Of the recycling methods presented in this thesis, three have reached a TRL of 9 or close to 9: mechanical recycling, co-processing, and pyrolysis. In the circular economy framework, co-processing is put into the recovery section. Using wind turbine blades in co-processing has its advantages by for instance reducing the environmental impact of the process. The drawback is that the value potential of the material is significantly reduced, and it cannot be recycled again. Using waste in co-processing should therefore be the last step in the product’s lifecycle. As of today, co-processing is one of the most commonly applied techniques in Europe and is the only economical option for processing large amounts of blade waste.

Mechanical recycling is the most mature of the recycling methods and there are several companies applying this method. As of 2019, mechanical recycling was found to be the environmentally best recycling method for glass fibre blades (Liu et al., 2019). The downside is that the material is highly degraded during the process. From Table 2.2, mechanical recycling has the lowest waste management score of all the recycling methods mentioned in this thesis. The recovered material can still be used and as shown in this thesis it is used in several lower value applications. This is still an acceptable use of the material as it is used in new products and therefore substitute more valuable virgin materials. Even though co-processing is considered a better waste management than mechanical recycling, mechanically recycling composites and using them in new applications will always allow the waste to be recycled through co-processing after the second lifetime.

Pyrolysis has the highest waste management score of the three methods with a TRL of 9. It is the only option of the three which has the potential to start “close the loop” and recycle material that can be reintroduced into new blades. One of the companies presented in this thesis, Gen2Carbon, states that their recovered carbon fibres can be used in new wind turbine blades. The main problem with pyrolysis of wind turbine blades is the large content of glass fibre compared to carbon fibre. The glass fibre will lose 50% of its mechanical properties (Paulsen & Enevoldsen, 2021), while the carbon fibre can be retrieved at 95% of original strength (S. Loginov, personal communication, 28 April 2022). The glass fibre is therefore too degraded to be used in higher value products or reintroduced in new blades but can be used in products as insulation materials. While pyrolysis is not able to fully close the loop, it can start the process by increasing the circularity of carbon fibre in wind turbine blades. The carbon fibre is also more energy intensive to produce and is of a higher value than the glass fibre, thus more important to keep at a higher value for a longer time.

The recycling methods in the circular economy framework are presented in the order of the recovered material’s value. The most promising technology was identified as solvolysis, as this recovered fibres at the highest value. Solvolysis makes wind turbine blades made with a thermoplastic resin recyclable. This lays the foundation for fully recyclable blades when these are being decommissioned. The problem is that these blades will not be decommissioned for another minimum of 20 years. Studies presented in this thesis have estimated the annual blade waste in Europe alone can grow up to 500.000 tonnes by 2050, and where most of these blades are thermoset composites (Liu & Barlow, 2017). Solvolysis has shown to be viable for recycling thermosets like epoxy and polyester, by using ethanol as solvent. One problem is that the processing costs are high and as of today solvolysis is therefore only viable for recycling carbon fibres. Most of the blades are still made of GFRP. Further development of the process and investments in infrastructure could lay the foundations for blade recycling in 20 years, when the thermoplastic blades start to be decommissioned. By further developing and upscaling the process it could also be economically viable for glass fibre.

A combination of demands and economic incentives has shown that administrative pressure can lead to both technological development, establishment of a supply chain, thus reduce the waste and increase recycling. An example, which is similar to turbine blades is the return arrangements for fibreglass boats in Norway. To ensure proper management of the waste, when returning an old fibreglass boat, the owner is given 1000 NOK. The economic incentives led to more of the waste being returned and therefore could be managed properly.

The optimal route for recovered materials is to be reintroduced in the manufacturing of new wind turbine blades. Today, the use of virgin materials is still dominant since the material degrade too much during recycling. Implementation of recycled fibres is the next step in enabling a circular pathway, starting to close the loop for wind turbine blades. Recycled fibres could possibly be used in smaller blades or in less critical parts of larger blades. Today, the recovered material is used in other applications. In this thesis, several products using recycled composite waste have been presented. The material is used in lower value applications and the material will further decrease in value after recycling at the end of its second life. Still, this replaces virgin material and extends the lifetime of the material. Using recycled fibres in other applications is therefore regarded as acceptable however the goal should still be to strive towards reintroducing the materials into new blades.

6.4 Robustness of the results

As seen from Figure 3.5, the reviewed literature used to evaluate the wind turbine blade supply chain consists of many different types of sources, such as company websites and articles. This information is not necessarily objective as it is information given by the companies themselves, and not peer-reviewed subjected to independent research. It could therefore be questioned whether this type of sourced information is correct or not. Obviously, commercial companies will present information in a way which possibly make their products or projects look favourable. Since the supply chain is under development there is few peer-reviewed scientific articles on the subjects. Information from commercial actors is therefore very valuable in order to investigate the topic for this thesis, and to ensure the most updated knowledge.

7 Conclusion

In this thesis the possibilities for a circular economy for wind turbine blades have been evaluated. In the next decades there will be an increasing amount of decommissioned wind turbines. Therefore, there is a need for solutions, in terms of both technology and capacity. Through evaluation of the supply chain several possible solutions were identified.

Reuse is the best option at EoL, since it keeps the wind turbine blades for the original purpose. To enable reuse, life-extension strategies like ESM and proper erosion protection should be implemented. Reuse of wind turbine blades also contributes to enhanced production of clean energy.

Repurposing is using the blade or parts of the blade for other applications. In this thesis, several concepts have been presented which show good potentials. By repurposing the material, it is kept at a high value and it substitutes the need for other materials. Applications made by repurposed blades are still few, but the possibilities are good, especially within urban furniture and infrastructure like bridges.

Three recycling methods have reached the highest TRL and are commercialized: mechanical recycling, co-processing, and pyrolysis. The recycled material has been used in new products, contributing to enhanced use of the material. The downside of this solution is that the material cannot be reintroduced in new blades due to high degradation of the material during recycling. A promising recycling method is solvolysis, which may allow recycled fibres to be used in new blades.

In terms of circular economy, waste is a design flaw, and the waste problem should therefore be addressed already in the design phase. The design of wind turbine blades has in recent years increasingly focused on making the blades more recyclable. A promising development is the change from thermoset to thermoplastic resins, which makes the blades easier recyclable through solvolysis. There has also been an increase in use of recycled materials, like PET-foam as core materials, but the fibres are still not reintroduced. The next step for designing more circular blades will be to use recycled fibres and introduce natural fibres.

8 Further work

Based on the thesis work some suggestions for further work have been proposed:

- Further investigation of solvolysis of thermoset composites. Since solvolysis is the most promising technology, especially when it comes to the recycling of thermoplastic composites, this method should be further investigated for thermoset composites as this is the main content of the incoming wind turbine blade waste the next 30 years. By developing and investing solvolysis at an early stage, the technology and infrastructure will be ready for application when the thermoplastic blades are subject for decommissioned.
- Structural validation of natural fibres in larger blades. Several studies have been done on natural fibres in smaller blades and have shown promising results. Structural testing and validation of natural fibres can be the next step in achieving regenerative fibre materials for wind turbine blades.
- Structural validation of recycled fibres in blades. Recycled fibres may be viable for use in smaller blades or in parts of larger wind turbine blades.
- Degradation of polymer composites when it comes to pollution and microplastics. When it comes to repurposing, some of the applications are in direct contact with fauna (e.g., feeding bunks) and the surrounding environment. The issue of microplastics is increasing and before blades are repurposed on a larger scale, this topic should be further addressed.

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Appendices

Appendix A – Repurposing solutions

List of figures in Appendix A

Superuse Studios

Figure A.1 shows the Wikado playground in Rotterdam, Netherlands designed by Superuse Studios *(Guzzo, 2019)*.

Figure A.1: Wikado playground in Rotterdam, Netherlands designed by Superuse Studios. Established in 2009. Photo by Denis Guzzo (Guzzo, 2019).

Figure A.2 shows the ReWind Almere bike shelter in Almere, Netherlands designed by Superuse Studios (Guzzo, 2019).

Figure A.2: ReWind Almere bike shelter in Almere, Netherlands designed by Superuse Studios. Established in 2014. Photo by Denis Guzzo (Guzzo, 2019).

Figure A.3 shows the ReWind Willemsplein seating in Rotterdam, Netherlands designed by Superuse Studios (Guzzo, 2019).

Figure A.3: ReWind Willemsplein seating in Rotterdam, Netherlands designed by Superuse Studios. Established in 2012. Photo by Denis Guzzo (Guzzo, 2019).

Anmet

Figure A.4 shows a footbridge in Szprotawa, Poland constructed by Anmet in 2021 (Boryna, 2022).

Figure A.4: Footbridge in Szprotawa, Poland constructed by Anmet in 2021. Photo by Maciej Boryna.(Boryna, 2022)

Figure A.5 shows a bench made out of wood and wind turbine blades, made by Anmet (Anmet, n.d.).

Figure A.5: Bench made out of wood and wind turbine blades, made by Anmet. Photo by Anmet (Anmet, n.d.).

Figure A.6 shows seating made by Anmet (Mason, 2021a).

Figure A.6: Seating made by Anmet. Photo by Anmet (Mason, 2021).

Siemens Gamesa

Figure A.7 shows a bikeshelter made by Siemens Gamesa in 2020 in Aalborg, Denmark (Siemens Gamesa, 2021b)

Figure A.7: Bikeshelter made by Siemens Gamesa in Aalborg, Denmark. Established in 2020. Photo by Siemens Gamesa (Siemens Gamesa, 2021b).

Re-Wind Network

Figure A.8 showes the BladeBridge constructed by the Re-Wind Network in Cork, Ireland (Deeney & Ruane, 2022).

Figure A.8: BladeBridge constructed by the Re-Wind Network in Cork, Ireland. Photo by the Re-Wind Network (Deeney & Ruane, 2022).

Figure A.9 shows an example of one of the farm application concepts made by the Re-Wind Network, showing a feeding bunk for cattle. Obtained from the “Re-Wind Design Catalog Fall 2021” (Re-Wind Network, 2021).

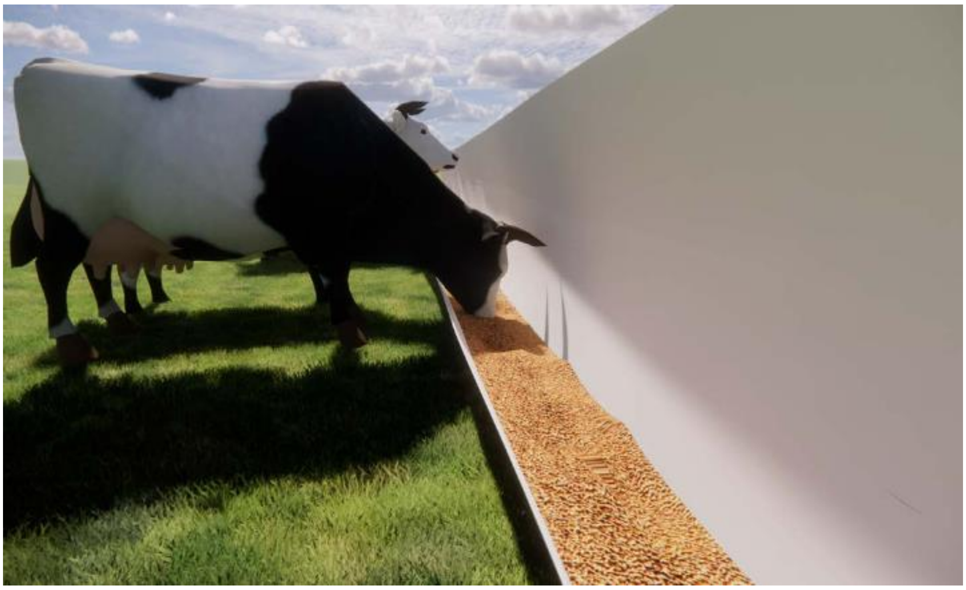

Figure A.9: Example of one of the farm application concepts made by the Re-Wind Network, showing a feeding bunk for cattle. Obtained from the “Re-Wind Design Catalog Fall 2021” (Re-Wind Network, 2021).

Figure A.10 shows a power pole concept made by the Re-Wind Network (Alshannaq et al., 2022).

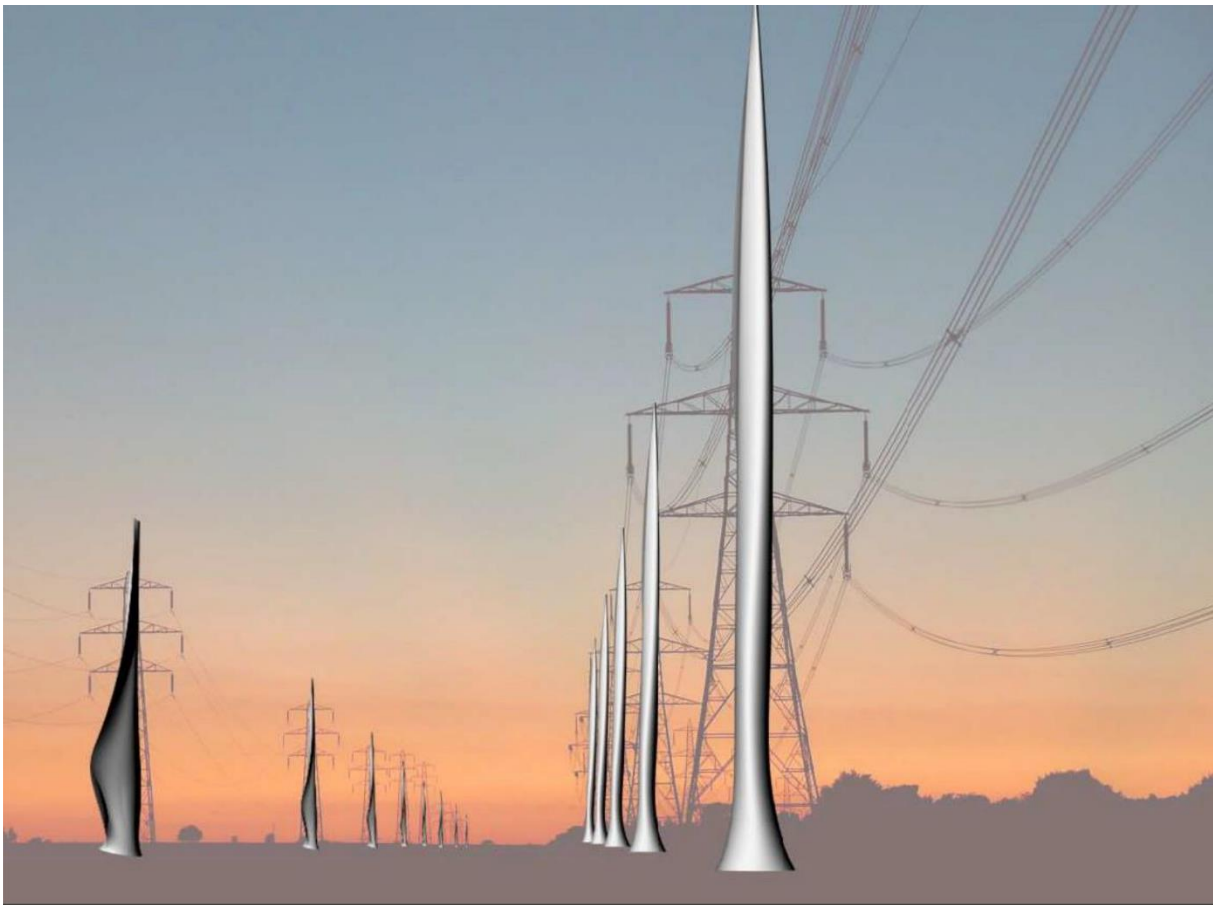

Figure A.10: Power pole concept made by the Re-Wind Network (Alshannaq et al., 2022).

Appendix B – Recycling solutions

List of Figures in Appendix B

Mechanical recycling

Figure B.1 shows the SKOG bench made by EcoFiber Recycling.

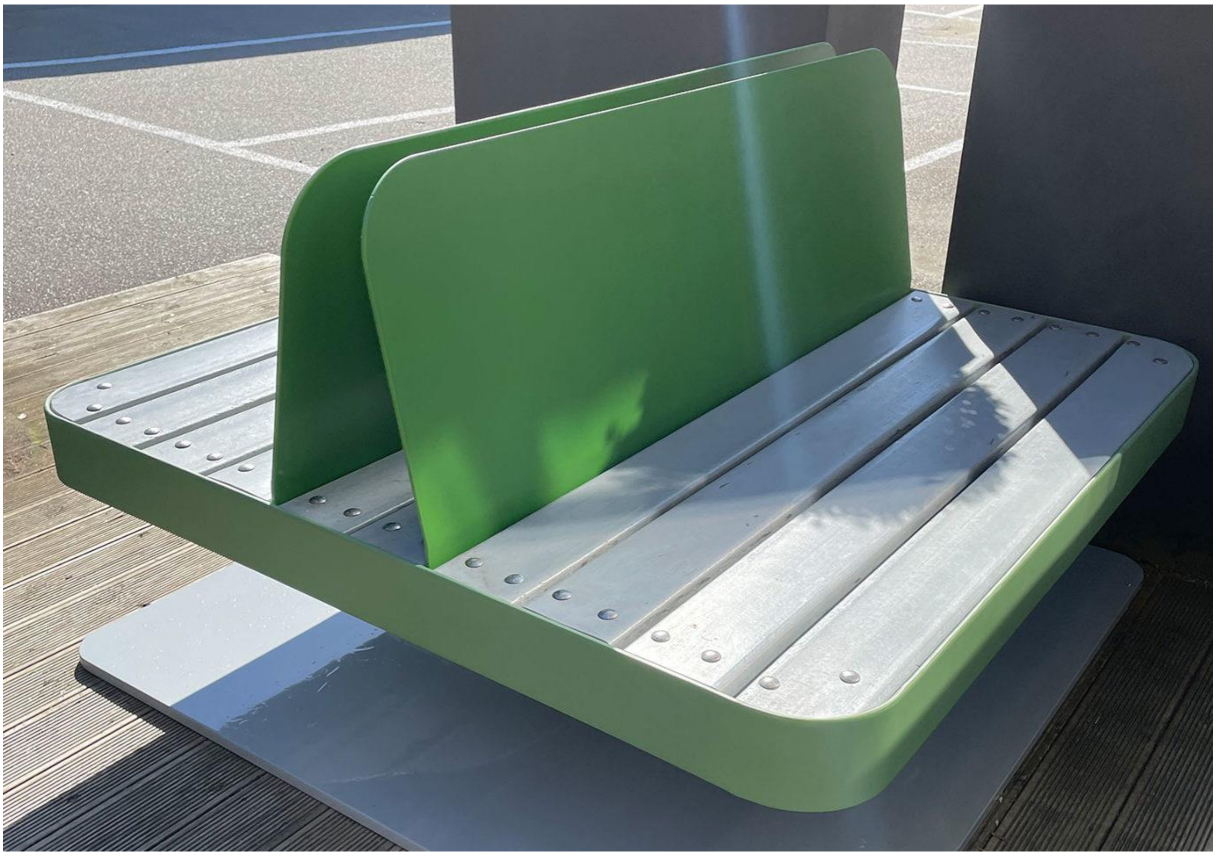

Figure B.1: SKOG bench made by EcoFiber Recycling. Photo by Ecofiber Recycling (Ecofiber, n.d.).

In Figure B.2 the cable trough made by Reprocover is presented.

Figure B.2: Cable trough made by Reprocover. Photo by Reprocover (G. Charles, 2022).

Figure B.3 shows noise barriers made by Miljøskærm.

Figure B.3: Absorbent noise barriers made by Miljøskærm. Photo by Miljøskærm (Miljøskærm, 2021).

Pyrolysis

In Figure B.4 skis made by EVI skis with recovered carbon fibres from Gjenkraft is presented.

Figure B.4: Skis made by Gjenkraft with recovered carbon fibres. Photo by Gjenkraft.

In Figure B.5 a climbing hold made by Gjenkraft is presented.

Figure B.5: Climbing hold made by Gjenkraft. Photo by Gjenkraft.

In Figure B.6 the bicycle made by STEVENS Bikes with recycled carbon fibres from carboNXT is presented. Photo by carboNXT (carboNXT, n.d.).

Figure B.6: Bicycle made with recovered carbon fibres from carboNXT. Photo by carboNXT (carboNXT, n.d.).