End-of-life wind blade recycling through thermal process
Abstract

Renewable energy production with wind turbines has been rising in the last 30 years and it is a crucial technology, which is necessary for the energy transition. As sustainable as the energy production of wind turbines is, the waste management of the blade material is not. Most of the blades end up on a landfill or get incinerated. There are different types of recycling methods, but the most commonly used is to shred the fibers into little pieces and reusing them for filler material in the concrete industry. This approach does not actually split up the blade material into its components but it is more of a downcycling. In this thesis, a new type of pyrolysis will be looked into, which splits up the blade material into its components namely glass fibers and plastic using molten salt. This process would make the glass fiber industry more sustainable by introducing a recycled glass fiber with minimal loss in quality. In a first step, the blade material will be examined more closely with a thermogravimetric analysis to find out what kind of plastic it is and what temperature would be necessary to pyrolyze it. This information will be used to conduct an experiment in a molten salt solution and determine the necessary reaction time and temperature. This data will be used to compare the costs of this method with shredding the material and the conventional pyrolysis.

From the thermogravimetric analysis, it was possible to determine that the type of plastic used in this turbine was made out of epoxy. The maximum degradation of this material occurred at 380 °C. Not many experiments could be conducted in order to find the optimal conditions for the pyrolysis process due to difficulties with the furnace. Nevertheless, one sample was successfully pyrolyzed at a temperature of 400 °C with a residence time of 15 minutes. With the current market conditions in the recycled glass fibers industry, this product would be too expensive and the demand would be too little. However, the market is expected to grow in the next couple years due to rising interests in circular economy and governments introducing regulations. Nevertheless, it is necessary to increase the efficiency of the molten salt pyrolysis in order to be applicable to a bigger scale. More experiments should be conducted with cheaper molten salt in order to sink the costs of the process.
Acknowledgements

First and foremost, I would like to express my sincere gratitude to my supervisor, Wujun Wang, for his invaluable guidance and assistance throughout my master thesis. His ability to remain calm and navigate through difficulties has been a true source of inspiration throughout this journey. Despite undergoing considerable stress, his assistance remained unwavering.

I extend my heartfelt gratitude to Liselotte Alden, whose valuable insights and feedback greatly contributed to the refinement of this report. Her dedication to thorough review and constructive suggestions were instrumental in enhancing the quality and clarity of my work.

I am grateful to Dr. Fei Ye for providing me with the opportunity to conduct my research at Kungliga Tekniska Högskolan, and for all of the resources and support he provided.

I hold a profound appreciation for the dedicated laboratory technicians Leif and Emil from KTH and Alina from UU who played an indispensable role in the execution of my experiments. Their tireless efforts to troubleshoot technical issues were invaluable, enabling me to overcome challenges and progress in my research endeavours.

I would also like to thank my friends and family for their love and support during this process. Their willingness to engage in meaningful conversations and challenge my assumptions have not only enriched my academic journey but have also broadened my horizons. Without them, this journey would not have been possible.
## List of Acronyms

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>GFRP</td>
<td>glass fiber reinforced plastic</td>
</tr>
<tr>
<td>CFRP</td>
<td>carbon fiber reinforced plastic</td>
</tr>
<tr>
<td>rCF</td>
<td>recycled carbon fiber</td>
</tr>
<tr>
<td>TGA</td>
<td>Thermogravimetric Analysis</td>
</tr>
<tr>
<td>PVC</td>
<td>Polyvinylchlorid</td>
</tr>
</tbody>
</table>
Contents

List of Figures vii
List of Tables ix

1 Introduction 1
  1.1 Material of the blade . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 3

2 Background 7
  2.1 Mechanical . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 7
  2.2 Thermal . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 8
    2.2.1 Pyrolysis . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 8
    2.2.2 Fluidized Bed . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 9
    2.2.3 Microwave Pyrolysis . . . . . . . . . . . . . . . . . . . . . . . . . . 9
  2.3 Chemical . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 10
  2.4 Comparison and Summary . . . . . . . . . . . . . . . . . . . . . . . . . . . 10
    2.4.1 Commercially applied recycling . . . . . . . . . . . . . . . . . . . . 13
  2.5 Research Question . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 15

3 Methodology 17
  3.1 Samples . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 17
  3.2 Part 1: Thermogravimetric analysis . . . . . . . . . . . . . . . . . . . . . . 19
  3.3 Part 2: Molten Salt Pyrolysis . . . . . . . . . . . . . . . . . . . . . . . . . 21
    3.3.1 Molten Salt . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 24
  3.4 Techno-economical analysis . . . . . . . . . . . . . . . . . . . . . . . . . . 27

4 Results 28
  4.1 Part 1: Thermogravimetric Analysis . . . . . . . . . . . . . . . . . . . . . . 28
  4.2 Part 2: Molten Salt Pyrolysis . . . . . . . . . . . . . . . . . . . . . . . . . 32
  4.3 Techno-economical analysis . . . . . . . . . . . . . . . . . . . . . . . . . . 36

5 Discussion 38
  5.1 Part 1: Thermogravimetric Analysis . . . . . . . . . . . . . . . . . . . . . . 38
    5.1.1 Probe 1 . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 38
    5.1.2 Probe 2 . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 39
    5.1.3 Probe 3 . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 39
    5.1.4 Probe 4 . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 43
    5.1.5 Probe 5 . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 43

© Uppsala University Kerstin Benz
5.1.6 Probe 6 ......................................................... 44
5.1.7 Probe 7 ......................................................... 44
5.2 Part 2: Molten Salt Pyrolysis .............................. 45
5.3 Techno-economical analysis ............................... 46

6 Conclusion ....................................................... 48

Bibliography ...................................................... 51
List of Figures

Figure 1.1 Global trends for installed capacity for wind energy [27] . . . . . . . . 1
Figure 1.2 Demonstration of the material composition of a wind turbine [70] . . 3
Figure 1.3 Fibers reinforced with plastic. [39] ........................................ 4
Figure 1.4 Schema of the section of the blade. [44] ................................. 5
Figure 1.5 Schema of the production of the blade. [37] ............................. 6

Figure 2.1 Depolymerization, which can be conducted by pyrolysis, is the the process of converting polymers to monomers [21] .......................... 9
Figure 2.2 Types of recycling of wind turbine blades [28] .......................... 11
Figure 2.3 Energy required depending on the different types of recycling. The two values represent the upper limit and lower limit range [54] ............. 12
Figure 2.4 The concept of the pyrolysis applied on wind blades by ReFiber [55] 14

Figure 3.1 Probes taken from the wind turbine blade and from which part they are coming from (Photo taken by the author) ......................... 18
Figure 3.2 Closer picture of the different samples (Photo taken by the author) 18
Figure 3.3 Closer picture of the different samples (Photo taken by the author) 18
Figure 3.4 Closer picture of the different samples from the dust (Photo taken by the author) ................................................................. 19
Figure 3.5 TGA machine that was used for the process in the laboratory (Photo taken by the author) ............................................................... 20
Figure 3.6 TGA results of Glass Fiber Reinforced plastic at different heating rates [53] ................................................................. 21
Figure 3.7 Furnace used to conduct the experiments [64] .......................... 22
Figure 3.8 Scheme of the reactor (Image created by the author) ................ 22
Figure 3.9 Furnace used to conduct the second experiment [31] ................ 24
Figure 3.10 Diagramm of the Methodology followed in the experiment (created by the author) ................................................................. 24

Figure 4.1 Result of the TG analysis from Sample 1 (Graph created by the author) 28
Figure 4.2 Result of the TG analysis from Sample 2 (Graph created by the author) 29
Figure 4.3 Result of the TG analysis from Sample 3 (Graph created by the author) 30
Figure 4.4 Result of the TG analysis from Sample 4 (Graph created by the author) 30
Figure 4.5 Result of the TG analysis from Sample 5 (Graph created by the author) 31
Figure 4.6 Result of the TG analysis from Sample 6 (Graph created by the author) 31
Figure 4.7 Result of the TG analysis from Sample 7 (Graph created by the author) 32
Figure 4.8 Closer picture after conducting the pyrolysis at 400 °C (Photo taken by the author) .......................................................... 34

Figure 4.9 Closer picture after conducting the pyrolysis at 400 °C (Photo taken by the author) .......................................................... 34

Figure 4.10 Closer picture after conducting the pyrolysis at 450 °C (Photo taken by the author) .......................................................... 35

Figure 4.11 Closer picture after conducting the pyrolysis at 450 °C (Photo taken by the author) .......................................................... 35

Figure 5.1 Mass loss of different polyester compositions [29] ...................... 40

Figure 5.2 Result of the TG analysis of the different acrylate samples conducted by Stolov et al. [66] ................................................. 41

Figure 5.3 Result of the TG analysis of epoxy resin with different heating rates conducted by Bao et al. [3] ........................................ 42

Figure 5.4 Result of the TG analysis of polyurethane conducted by Filip et al. [19] 42

Figure 5.5 TGA of epoxy resin samples type S and ST and composite materials conducted by Saidova et al. [58] ............................. 44

Figure 5.6 Cross-section of the blade and indication where the tested sample could come from (Image adapted from [80], modified by the author) .... 45
List of Tables

Table 2.1 Comparison of the different types of Recycling ........................................... 13
Table 3.1 Collection of the different values for different molten salts ......................... 26
Table 3.2 Energy required per recycling method [20] ................................................... 27
Table 4.1 Comparison of the different types of Recycling ........................................... 32
Table 4.2 Process of Pyrolysis at 400 °C ................................................................. 33
Table 4.3 Process of Pyrolysis at 450 °C ................................................................. 34
Table 4.4 Weight percentage left after the pyrolysis .................................................... 36
Table 5.1 Results of the TG analysis from Shi et al. [62] .............................................. 39
Table 5.2 Mass percentages of various components in the formulations [29] ............... 40
Table 5.3 Calculated costs and selling price for the different processes not consider-
ing the machinery and the working hours (calculated for 1 blade with a
weight of 12'474 kg) ................................................................................................. 46
1 Introduction

Over the last few decades, more and more wind turbines have been deployed in Europe but also all over the world (see Figure 1.1). Just alone in the year 2017, more than 50 GW of capacity have been installed all over the world, which added up to a total cumulative capacity of 540 GW [8]. And just four years later, in the year 2021, the added global capacity was almost doubled with 94 GW. This resulted to a global capacity of 837 GW in 2021. Over half of these new installations in 2021 were done in China. [24]

Wind turbines are considered a renewable energy source since they are not emitting any greenhouse gases while operating and they are functioning just with the strength of wind. They are not depleting any type of resources that are not renewable. However, for an energy carrier to be fully renewable, the production and waste management of the materials need to be considered as well.

During the period when a wind turbine is used, the wind blade will degrade due to weather conditions like rain, wind and heat. Especially the blades need to withstand a high amount of load throughout their lifetime. This means that the material condition changes and the standards that are necessary for the material to be used for the purpose
of a wind turbine cannot be met anymore as from a certain point in time. In this case, the turbine cannot be operated anymore, since the efficiency will decrease due to cracks in the material or other types of instabilities which can be caused by the coating material, which acts as a protective layer, coming off due to rain, UV, sand or dust [32]. When it is not possible to use the turbine for longer, the end of the lifetime of the turbine is reached. It is said, that the lifetime of a wind turbine blade is around 20 to 25 years and the blades produced in China have a lifetime of around 15 years. [8]

When the end of the lifetime of a component or the entire wind turbine is reached, there are four possible options for what will be done with the wind turbine. It can either be refurbished, repowered, repaired or decommissioned. In the case of refurbishment, the components that are still intact will be kept and the rest will be exchanged. When a turbine is repowered, the whole turbine will be exchanged but it will be kept in the same wind park, but the exact location might shift, since a bigger wind turbine could be installed which might need more distance from the existing wind turbines. [43] In case of decommissioning, the pieces will be disassembled, which means the generator, wind blades and the tower will be separated and the waste needs to be disposed of. Almost all parts of the turbine could be reused, refurbished or recycled and usually, the process will be decided based on the cost of the processes. Due to economic reasons, it is not common to reuse or refurbish the rotor blades, so most of them are being disposed of in landfills. [8]

Following the upward trend of deployments of wind turbines around 1990, these installations are reaching the end of their lifetime now [78]. In Denmark alone, an expected number of 6000-7000 wind turbines need to be replaced in the next seven to eight years [78]. On a global scale, it was expected that 59'000 tons of blade material would reach the end of their lifetime and had to be replaced in 2022 [8]. Since the blades are very difficult to recycle, the methods of disposing them have been to deposit them in landfills or incinerate them [8]. This is not very beneficial for the environment in the sense of wasting important resources and also increasing the pollution with gases coming from the incineration. The European Commission was asked by WindEurope to impose a ban on the deposition of wind turbine blades on landfills by 2025 [77]. This is why there is a need for new technologies which are economically feasible. In a press release from 2021, Vattenfall has decided that they will not deposit end-of-life turbine blades in landfills anymore [73]. By 2025, the goal is to have a 50% recycling rate and reach 100% by 2030 [73]. It is crucial, that the waste problem in the wind energy sector needs to be solved and new innovative solutions need to be introduced. It is also clear that economically viable solutions need to be introduced, which is what will be explored in this thesis. When tackling the recycling question, the material composition of the different components becomes important. This needs to be considered in order to determine the recycling processes and also how to reuse the parts. That is why in the next chapter, the focus will be put on the material composition of the wind turbine.
1.1 Material of the blade

The part of the wind turbine that this thesis will be focused on is the wind turbine blade which is made out of composite materials. The generator and the tower are mostly made out of metals which are currently easier to recycle. It is possible to recycle around 90% of a wind turbine, which are the foundation, the tower, the components of the gearbox and the generator [43].

A wind turbine is composed of 89.1% steel, 5.8% fiber glass reinforced plastic (GFRP), 1.6% copper, 1.3% concrete (cement, water, aggregates and steel reinforcement), 1.1% adhesives, 0.8% aluminum (see Figure 1.2) [43]. Depending on the turbine model, the composition of the different materials can vary. The turbine composition mentioned in the study by Mello et al. [43] differs in the steel composition from the one showed in Figure 1.2. Steel is made out of iron, so this difference could also come from the fact that one source includes the iron in the steel and the other source does not. The blades are mostly made out of glass fiber reinforced plastic, which is basically different layers of glass fibers that are held together with a polymer matrix (see Figure 1.3). The material used for the production of the blade is more expensive than the metal used for the generator and the tower. [44]

![Figure 1.2: Demonstration of the material composition of a wind turbine [70]](image)

The advantages of these fibers are that they can endure high strength but they have a relatively low weight. Depending on the turbine, various types of fibers and plastics are used. There are a lot of different types of fibers, but the material composition depends mostly on the price of the fibers and also on the size of the turbine. [44]
Most used fibers are currently E-glass fibers, which consist of glass, which is made out of borosilicate and is called E-glass, because it has a high electric resistance. Usually, around 65% of the weight of the wind blades is made of the fiber components. Glass fiber is a very resilient material and since the wind turbine blades are getting bigger and bigger with diameters up to over 200 m, the material needs to ensure the stability [48]. The more fibers will be used, the more stiff they are and this means that the tensile and the compression strength is higher. However, when using more than 65% fibers, there will be too many fibers present in the mixture and the matrix will not be able to hold the fibers together and the stability of the material decreases. [44]

An alternative to glass fiber is carbon fiber. Since the material characteristics of carbon fibers are a higher stiffness and lower density when comparing them to glass fibers, it is possible to have thinner and also lighter blades. The disadvantage of this material is the fact that they can be easily damaged and they are also more expensive. There are more materials for the fibers like aramid or basalt fibers, but they are not used on a large scale, which is why they will not be considered in this study. In this study, the focus will be on the glass fiber, since the material provided from Vattenfall is made out of glass fiber reinforced plastic. It is also the material that is currently most used when producing the wind blades. [44]

There are different categories which exist when differentiating types of plastic. One of the categories is made according to how plastic reacts to heat. These two categories are thermoset and thermoplastics. Basically, thermosets get reshaped in the process of heating them and this process cannot be repeated once the material has cooled down and has hardened. When heating this material again, it will burn. Thermoplastics soften and melt when they are heated up and once they cooled down, they can be re-heated and they can be reshaped again. This makes it easier to recycle thermoplastics, but thermosets are more stable. [86]

The matrix of the wind blades are either made out of thermosets or sometimes of thermoplastics. They can occur in the form of polyamides, polyesters, polycarbonates or silicone rubbers and more [57]. Thermosets are polymers that were solidified and cross-linked and this is very difficult to reverse based on the explanation that was given in the last paragraph [57, 21]. This means that chains of polymers are formed that are resistant to heat and mechanically stable [21]. Examples of thermoset materials which are used for the production of wind turbine blades are epoxies or polyesters [44].
case of the material provided, the matrix material used is thermoset, but it is not clear if it is made out of epoxy or polyester.

Currently, the most used technique to assemble wind blades is the resin infusion technology. In this technique, the glass fiber layers are stacked on top of each other and a protective film is added on top and as an outer layer. These layers are put in a vacuum bag and double adhesive tape is used so no air will reach the materials [15]. Vacuum pressure is applied and liquid plastic will be injected into this bag and through a distribution medium, which has been added before to the layers, the liquid plastic will be injected to connect the glass fibers. The plastic, which serves as the matrix to hold the glass fibers together, can be in the form of thermoset or thermoplastic (see Figure 1.5) [15]. After this process, the material will be heated to dry the plastic. This is done in a big mold, so the material of the blade will already be in the right shape. The blade consists of two sides which are sealed together with adhesive joints (see Figure 1.4). The flapwise bending is the part exposed to the wind pressure and is being kept stable by an internal web. The edgewise bending is more exposed to gravitational force and torque load. [44]
This report is split into background, methodology, results, discussion and conclusion. In the background (see Section 2), the current status of the recycling will be explained and in which area more research is necessary. In the methodology (see Section 3), the materials used in the laboratory and also the process of the experiment are described. The results of the experiments are presented in the chapter "results" (see Section 4) and these results will be analyzed and discussed in the discussion (see Section 5).
2 Background

As stated in the previous section, the thermoset polymers need to be cross-linked in the process of producing a wind turbine blade. Therefore, it is difficult to recycle them since it is not possible to re-melt them or remold them. What happens when trying to re-melt them is that the heat necessary to melt them leads to a degradation of the polymers and the material could be contaminated with other polymers or plasticizers. [21] The GFRP is not a very expensive material nor is it made out of a rare material, so until now it has not been economically viable to recycle the fibers whereas disposing them in landfills is comparably cheap. [28]

In most cases, the wind turbine blades were either disposed of in landfills or incinerated. In the future, manufacturers need to focus on new ways of treating the wind turbine blades other than disposing them in landfills. Some technologies have been introduced in order to recycle these materials. The different types of recycling can be differentiated into three categories which are mechanical, thermal and chemical. The implementation of these recycling methods will depend on the cost and energy consumption of the recycling process, the quality of the recycled fibers and the overall sustainability of the process. There also needs to be a market for the recycled materials of the GFRP, so it needs to be ensured that the recycled materials can be sold to a company that will reuse them. [28]

2.1 Mechanical

The goal of mechanical recycling is to break down the blade into smaller pieces. This can be done by either milling the material in small powder or shredding and crushing the blade. The material that comes out of these processes could be used as raw materials for concrete. The main advantage of using mechanical recycling technologies is that it is not very expensive. Plus, it is also easy to process a bigger volume of material. But there is also a downside to this type of recycling since the mechanical quality is decreasing when it is being shredded. This also has an impact on how the recycled material can be used. Since the steadiness of the fibers decreases with mechanical recycling, they cannot be reused for building turbine blades not least because of safety reasons. [84]

When the process of mechanically treating the wind turbine blades is fulfilled, the fiber can be reused for producing new composite material or using them in order to produce a filler material which is used for concrete [28]. The product of mechanically treating the wind blades can be in the form of a powder, aggregates and fiber clusters [80]. This material is able to replace sand used for the concrete production which can increase the properties of the produced concrete [80]. When using the recycled material in concrete
production, the mechanical quality of the glass fibers still needs to be intact, since the concrete needs to be able to withhold impacts in the form of weight or weather [4]. If the intention of using the glass fibers after the recycling is to produce concrete, the strength of the fibers needs to be checked and eventually some treatment is necessary in order to fulfill the material requirements [54]. Currently, this process is the one that is most in use and its simplicity make it very applicable to the large scale. Nevertheless, the GFRP is not actually recycled back into its components. The process is technically more sustainable than disposing of them in landfills. On the other hand, the separation of components is a more resource-efficient approach.

2.2 Thermal

With this type of recycling, the material will be exposed to heat and the bonds between the polymers are removed. The thermal process includes either pyrolysis, fluidized bed recycling and also microwave pyrolysis. In the paper from Chen et al. several recycling approaches are compared. The matrix will be converted into small molecules under the influence of using inert gas heat. The products that are gained from this process are a share of gas, oil and char and the separated glass fibers. This processes are not necessary when the blade is made out of thermoplastics, since thermoplastic can be melted more easily. [8]

2.2.1 Pyrolysis

Pyrolysis is defined as the process of extracting the resin matrix by decomposing it. Like it was mentioned in section 1.1, thermoset is complicated to melt and this is why pyrolysis needs to be conducted at a high temperature [86]. In comparison to thermoplastic, thermoset is made out of cross-linked polymers, which can be seen in Figure 2.1 [86]. It shows the process of a pyrolysis of thermoset on a polymer scale. When using pyrolysis, it is an advantage that it is not very complicated and also not very expensive. There is also no need for a chemical solvent and the energy of the process can be recovered by using the waste heat. [28]

In comparison with chemical recycling, there is no need to use a chemical solvent with the pyrolysis. It can be said that compared to the other methods, the pyrolysis can retrieve most of the recycled fibers considering the required energy (see Figure 2.3). This is the reason why the focus of this thesis will be mainly on pyrolysis. It can also be said that recently, the focus in a lot of papers has been put on research on how to reuse the fibers that are retrieved from pyrolysis. There are some points that need to be considered though when using pyrolysis. On the surface of the fiber, there will be some solid residues after conducting pyrolysis. Also, the quality of the product of the pyrolysis depends on process parameters like the temperature and also on the material of the fibers [72]. In some studies, scientists have tried to produce hydrogen or different types of catalysts out of the pyrolysis products [84].
According to Jani et al., the recycled glass fibers can be used for plastic production, more specifically it can be applied in order to produce a matrix for low-density polyethylene (LDPE). This means that the polyethylene will become more stable when comparing it with newly produced LDPE made purely from plastic, since the glass fiber increases the stability of the material. [28]

Figure 2.1: Depolymerization, which can be conducted by pyrolysis, is the process of converting polymers to monomers [21]

2.2.2 Fluidized Bed

In the fluidized bed recycling process, the composite matrix is decomposed with an airflow under high temperatures. Compared to the pyrolysis, there will not be any char left on the fiber surface after the fluidized bed pyrolysis [72]. The issue with this process is that the recovered fibers have relatively poor mechanical properties. Studies have shown that this degradation can decrease the strength of around 25% to 50% [72]. Plus, it can occur that the fibers can break in this process [8]. This material can be used for producing bulk molding compounds. This compound has a consistency like a dough and can be used for producing different types of material like electrical equipment or headlamps used for cars [28].

2.2.3 Microwave Pyrolysis

When using the microwave pyrolysis, the resin matrix will be decomposed by microwave radiation in an inert environment [8]. The plastic, which the matrix is composed of, will be turned into oil and gas [1]. The advantages of this process are the limited amount of equipment that needs to be used and it is quite a quick process [8]. The products of the microwave pyrolysis can be used to produce recycled glass fibers, but for different applications than a wind turbine blade [28]. In multiple studies, the quality of the recycled fibers after the microwave pyrolysis was almost at the same level than
the virgin fibers. Nevertheless, it is quite complicated to scale up this process in order to commercially recycle wind turbine blades [5].

2.3 Chemical

The chemical process uses chemical decomposition to change the blade material into other materials that can be recycled [8].

The advantage of this more complex process is that it is possible to separate the fibers from the matrix completely and the products are clean fibers. This means that the length of fiber can be kept and also there is not much degradation of the material. It needs to be considered that this process requests chemicals that can be hazardous for the people using it and also for the environment [84]. Plus, depending on the chemicals that were used, the properties of the material can change. It is also not as easy to scale up this method as for example the mechanical process. [72]

The most used processes in this category are solvolysis and supercritical fluid. A supercritical fluid is a fluid, which is in a state where the temperature and pressure are above what would be the critical temperature and critical pressure for this specific fluid. This has the effect that this fluid has a good solubility and mass transfer properties, which means it can be used to decompose polymers. The products of this process are in a gaseous, liquid and solid form. In most cases, water or alcohol can be used as a fluid. The recovered fibers that are obtained in this process have a clean surface and have a good strength. On the other hand, the process needs a lot of energy to create the required high temperature and high pressure. [8]

When conducting solvolysis, water or alcohol will be used at high pressure and temperatures (200-370 °C and 100-250 bar), which are not the same as the supercritical conditions that are mentioned above. The water or alcohol have the characteristics in this environment that they can act as both solvent and reactant. The plastic matrix will be degraded into smaller pieces and the glass fibers are separated from the matrix. [42]

In comparison with the supercritical fluid, where the polymer will be dissolved, in the solvolysis, the polymer matrix is split into smaller pieces. When testing the method of solvolysis, the reactants that were used were mostly toxic for the environment, which is a disadvantage for this method [8]. Nevertheless, it is possible to use reactants (e.g. water) that are not toxic.

2.4 Comparison and Summary

The different types of recycling can be seen in an overview in Figure 2.2. The three headers are the mechanical, thermal and chemical recycling and the different types are listed in each category.
Figure 2.2: Types of recycling of wind turbine blades [28]

To determine which type of recycling is the best one, many different characteristics of the processes need to be considered. What can be compared is the extent of the mechanical deterioration, the cost, the reusability of the recycled products or, as it is shown in Figure 2.3, the energy consumption. It is evident from that Figure that the highest energy consumption occurs with the chemical recycling processes and the lowest one with the mechanical recycling processes [54]. Until recently, the cheapest method has been the deposition in landfills. But, policies have been implemented in order to prevent these harmful landfills. This means that not only the economic aspect should be taken into consideration but also current policies and the environmental aspect of these different methods. Considering that the mechanical recycling has the most negative impact on the mechanical quality of the glass fiber, the best trade-off can be achieved with the thermal recycling. This assumption is supported by the fact that the energy consumption for the thermal recycling is not much higher than for the mechanical recycling. When comparing the different thermal processes to recycle a wind turbine blade (see Table 2.1), the fluidized process uses more energy but the recyclate is of a smaller value than the products that were produced with the pyrolysis. The microwave pyrolysis seems to be cheaper in comparison with the conventional pyrolysis. As previously stated, scaling up microwave pyrolysis, which is essential for processing wind turbine blades, presents considerable challenges. What stands out in this Table is that the value of the recyclate produced with a mechanical recycling process is much higher compared to the pyrolysis and the price and the energy consumption to recycle is much lower. This underlines the statement that currently, the most viable recycling solution is to mechanically treat the blades. This stems from the fact that there has not been a lot of research yet looking into how the thermal and chemical processes could be improved, since it is even less economically viable than shredding or grinding the material. Plus, the market for selling the mechanically treated fiber, which is mostly the concrete industry, seems to be more advanced at this point than with the other methods. While the method in question
serves as an effective way to downcycle the material, it is important to recognize that alternative approaches place a stronger emphasis on component separation. It should also be considered that using the GFRP in the cement production means that the cement mixed with the shredded GFRP also needs to be recycled at some point. This is even more complex than just recycling cement and GFRP by itself. The thermal and chemical recycling play a pivotal role in enhancing the circular economy. Looking ahead, it is anticipated that companies will increasingly prioritize the regeneration of these materials, leading to the introduction of specific policies aimed at supporting such sustainable practices.

In this thesis, it will be more thoroughly focused on the thermal processes because the chemical type would require more financial investment. It is more difficult to scale up the chemical process from the lab to the actual blade scale, since a lot more chemicals will be required when processing more volume of blade material.

Figure 2.3: Energy required depending on the different types of recycling. The two values represent the upper limit and lower limit range [54]

© Uppsala University

Kerstin Benz
Table 2.1: Comparison of the different types of Recycling

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional</td>
<td>Landfills</td>
<td>59 [7]</td>
<td>0.26 [34]</td>
<td>0 [35]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Incineration</td>
<td>192.1 [28]</td>
<td>-4.16 [34]</td>
<td>58.7 [35]</td>
<td></td>
</tr>
<tr>
<td>Mechanical</td>
<td>Shredding</td>
<td>101.01 [28]</td>
<td>0.27 [34]</td>
<td>410.6 [35]</td>
<td>Alternative to virgin fibers [28] Cement production [28]</td>
</tr>
<tr>
<td></td>
<td>Grinding</td>
<td>101.01 [28]</td>
<td>0.27 [34]</td>
<td>410.6 [35]</td>
<td>Alternatives to virgin fibers, Cement production [28]</td>
</tr>
<tr>
<td></td>
<td>Microwave</td>
<td>61.7 [35]</td>
<td>10 [34]</td>
<td>240.5 [35]</td>
<td>Create new composites [28]</td>
</tr>
</tbody>
</table>

2.4.1 Commercially applied recycling

Right now, it is not economically viable yet to recycle the entire wind turbines, since the blades are made out of materials that are not very expensive or rare. This is why they are deposited in landfills. Since wind energy is considered a renewable energy source, the whole process of producing the turbines and also the waste management should be environmentally-friendly. Some companies have already implemented some kind of technologies in order to recycle the wind turbine blades. In Summer 2022, the first offshore and onshore wind turbines have been installed, where the blades were manufactured out of materials that can be recycled. The process of producing the blade is still the same (see section 1.1), but what has been changed is the matrix material, also known as the resin. When the blade needs to be recycled, a mildly acidic solution can be used to dissolve the plastic and the glass fibers will be separated from the matrix. Siemens has the goal to be able to use organic materials to produce the blades for example vegetable oil or hemp fibers. For the future, introducing materials like this for the wind turbine blade market would tackle the recycling issue. The costs for the recycling process would decrease drastically. Nevertheless, this does not solve the problem of the recycling of the already installed wind turbines. [63]

A company named ReFiber, established a long time ago, was started with the goal to use pyrolysis commercially in order to recycle wind blades. The blades get chopped into smaller pieces in a first step and then this pieces get heated up to 600 °C in an anaerobic environment (see concept Figure 2.4). The glass fibers are being reused for plastic production. When heating the fibers to a high temperature, they loose around 50% of their strength but the stiffness stays the same as before heating them. [55]

FiberEuse is a project from different countries in the European Union, where companies from countries like Spain, Germany and Finland and many more work together with the goal to recycle GFRP and also carbon fiber reinforced plastic (CFRP). They have three different use cases according to the three different types of recycling which are...
described in the previous section (mechanical, thermal and chemical). As the thermal process, pyrolysis at $<400\,^{\circ}\text{C}$ is used. The goal is to have recycled fibers with almost the same quality as the virgin fibers in order to reuse them for the automotive industry, like manufacturing clutch pedals, or also in the building construction sector, where different types of components, like the roof or gutters, can be produced. It is beneficial for these applications, that the glass fibers can be kept at the longest possible length and not be cut into many small pieces. It is easier to reuse the glass fiber for different applications if they are longer. [18]

The question is how much degradation actually occurs in the process of pyrolysis. Multiple studies have already been conducted in order to find the optimal temperature in the pyrolysis to achieve a high quality of recycled glass or carbon fibers. Depending on the quality of the recycled glass fiber, the application of the product can vary. There has been a lot of research in different types of application of the glass fibers. According to a paper from Yang et al., when using the pyrolysis to recycle the glass fibers, the product can be used for example as insulation material for sound proofing. It is possible to absorb the sound between 100 and 6400 Hz and it can be measured with an absorption coefficient which is at 0.8. This comes close to the value that is achieved by commercial insulators which have an absorption coefficient of about 1. Recycled glass fibers can also have a thermal conductivity of up to 0.041 $\frac{W}{m\cdot K}$. This means that the recycled fibers could also be used as a thermal insulator material for the construction sector. The value of 0.037 $\frac{W}{m\cdot K}$ for commercially produced materials intended for this application closely corresponds to the measurement obtained from using glass fibers. [84]

The most researched potential use of the recycled fibers would be using them in the concrete production. The GFRP can be used as an aggregate in the clinker feedstock [25]. In the cement production, the raw materials like limestones, chalk, clay, etc. get heated up to around 1500 $^\circ\text{C}$ [49]. The mass that comes out of this process is called clinker [49]. The oil that is produced in the process of the pyrolysis could be used in order to power the oven that heats up the mixture of raw materials [25]. This reduces the amount of fossil fuel used in the process of the cement production. More than 10 years ago, Holcim started to use mechanically chopped wind blade material for the production of their cement [60]. In 2008, a trial was set up and they used 68 blades with a length in a range between 20 and 42 metres [60].

---

Figure 2.4: The concept of the pyrolysis applied on wind blades by ReFiber [55]
2.5 Research Question

The research on recycling of GFRP is extensive and consolidated. It mainly focuses on the temperature optimization of different pyrolysis processes (such as the microwave pyrolysis, the pyrolysis conducted in a batch reactor or also in the fluidized bed reactor) and evaluates specific characteristics of the recycled fiber. ([82, 84, 33, 65, 50, 1, 69, 46, 36, 13, 11, 12, 23, 22, 47, 76, 83, 85, 26]).

The most relevant characteristics measured are: the tensile strength [MPa], which measures the maximal tensile stress that can be forced on a material before it breaks [75]; and the elongation break [%] ([82, 84, 65, 1, 12, 23, 22, 47, 83]), which concerns ductility a measurement of how much a material can stretch or deform before it breaks, expressed as a percentage of its original size. [51].

From that, extensive studies have been done exploring the degradation level of glass fibers. These levels tend to fall on the range between 50 - 90% of the original fiber strength, depending on the pyrolysis type, material, and the conditions in which the pyrolysis is conducted (e.g. temperature). These characteristics determine what kind of usage the products will have. [50]

As explained in the last section, the most common processes in the industry for wind turbine blades recycling are mechanical processes that reuse the obtained material for concrete production. The popularity of this processes relies on the "impurity" of the glass fiber obtained, and is not reused for their characteristics. In that way it is relevant to look into new ways to recycle the material, where the glass fibers and the matrix can be separated efficiently and where the process is applicable at a large scale. Given the potential for enhanced sustainability when recycling with a thermal or chemical process, it becomes pertinent to explore novel recycling approaches.

This is why a new type of pyrolysis will be introduced in this thesis. Instead of conducting the pyrolysis in an inert environment, it will be conducted in molten salt. Molten salts have a high capacity for storing heat and since the process will be in a liquid environment, there is no need for nitrogen [6]. Since the characteristics of molten salts are also to store heat, it is not necessary to heat the samples all the time, so it is also a less energy intensive process compared to the conventional pyrolysis. Another advantage of using molten salt is that it provides a liquid reaction environment. With the conventional pyrolysis occurring in a gaseous atmosphere, the reaction can be incomplete and that can affect the pyrolysis oil, which could lead to the oil getting oxygenated and it could end up being chemically unstable. [87] This thesis primarily focuses on recycling glass fibers reinforced with thermosets rather than thermoplastics. This is done due to the pyrolysis not being necessary when separating thermoplastic from the glass fibers.

In the pre-trials which were conducted by the supervisor, the temperature for the pyrolysis was set at 450 °C. Under these temperatures, the process produced a lot of smoke. The most common gases created in that pyrolysis process, measured in the literature were: methane, carbon monoxide, carbon dioxide, ethane, ethene, propane, propene, hydrogen, oxygen, nitrogen, butane, butene and butadiene [82, 69, 36, 12, 11, 23, 76]. Methane,
carbon monoxide and also carbon dioxide are greenhouse gases which should be avoided in order to have a sustainable process. To minimize gas emissions from this process, the temperature was set as low as possible in order to have less gaseous emissions but also not too low, so that the reaction still occurs. For that case, it is important to have a molten salt that will have a low melting point. Lower temperatures will also cause less damages to the quality of the glass fibers. According to Cunliffe et al. [11], the result with the lowest gas emissions was obtained in a static bed reactor, when having a temperature of 400 °C and a residence time of 60 minutes. This resulted in a gas yield of 0.6%, an oil yield of 5.1% and a char yield of 94.3% [11]. The intention is to conduct laboratory experiments aimed at reducing the reaction temperature. This implies that the molten salts must also possess a low melting temperature. Several different molten salts have been introduced in different papers, where the melting point and the price have been listed in Table 3.1. The goal is also to make the process as economically feasible as possible, which means minimizing the costs of the molten salt as well.

As a first step, the goal is to find the decomposition temperature of the wind turbine blade material. With this data, it is possible to find the minimum temperature required to melt the thermoset and separate it from the glass fibers. It is important to point out here that the melting temperatures obtained in this process only apply to these specific samples. These values can vary depending on the material used for the wind turbine blade and also the location of the sample in the wind turbine blade.

In a second step, it is also necessary to find the melting point of the molten salt. If the melting point of the molten salt is higher than the decomposition temperature of the thermoset, it is not possible to conduct the experiment in a liquid environment.

In the next step, an actual setup for the molten salt pyrolysis will be created in order to find out if it is actually possible. The goal is to conduct this at the lowest temperature possible in order to reduce the electricity required for the process and make it more affordable. This steps tests the hypothesis: lower reaction temperature will decrease the gaseous output.

Finally, it is important to quantify the costs of this process and find out if it is competitive with the existing recycling methods considering the costs. The research questions can be summarised as:

- What is the decomposition temperature of a specific wind turbine blade material sample?
- Is it possible to conduct a molten salt pyrolysis in order to separate the glass fiber from the thermoset? If yes, what is the required temperature for the process?
- Is the process economically competitive with mechanically treating the fibers or the conventional pyrolysis?
3 Methodology

The experiment was separated into two parts. This includes a more thorough analysis of the material that was obtained from Vattenfall. There is not much knowledge available from Vattenfall concerning what type of material was used when building the specific wind turbine blade, from which the samples come from. The first part includes a thermogravimetric analysis (TGA) which is heating up the sample in an inert environment and tracking the weight change during this process. With this analysis, a curve is obtained showing how much weight is lost throughout the process of heating the material. This gives more information about the decomposition temperature which is an important characteristic of a material. This obtained temperature can be compared to the decomposition temperature of commonly used materials for wind turbine blades. This answers the question of what kind of material the blade is made out of. Furthermore, the decomposition temperature is also necessary for the second part, since it answers the question of how high the temperature of the furnace should be set in order to pyrolyze the plastic matrix.

In the second part, the pyrolysis with the molten salt was conducted. The findings from the TGA, which are the temperature where the thermoset starts to melt and can be separated from the glass fiber, can be used to find out the temperature at which the pyrolysis should be conducted. The actual setup of the experiment will be discussed in this chapter. Determining whether the process yielded desired outcomes involved visually examining the samples. This chapter contains images and descriptions of the samples captured prior to pyrolysis, while the subsequent chapter 4.2 presents the outcomes obtained after pyrolysis.

3.1 Samples

Scraps of material have been provided by the company in separate bags depending on the location of the wind turbine blade. There were 5 different types of material which are from the inside blade, outside blade, the dust, the longer side and diverse locations. From each bag, one probe was taken except for the bags dust and diverse since there were a lot of different looking pieces in these bags, two samples were taken out of each bag. The probes from dust (see sample 2 in Figure 3.1 and separately in Figures 3.4a and 3.4b) were split into two different probes since they seem to be two different materials. An overview of the samples is visible in Figure 3.1.
Sample 1 consists of a layer of glass fibers reinforced plastic and there is a transparent layer of a hard material on top of the layers of GFRP (see Figure 3.2a). The third sample is thinner and it consists of a thin layer of glass fibers which are layered in two different directions upon another. This can be seen, because the glass fibers go into two different directions. On top of the layer of the glass fibers, there is a thin grey layer (see Figure 3.3).
3.2b). The sample 4 consists of only glass fibers which are layered in one direction (see picture 3.2c). There is some residue of a brown layer on the sample. It looks similar to the layer from sample 1, but it is thinner and less transparent. The sample 5 consists of multiple layers of GFRP which is surrounded by a very hard grey layer (see Figure 3.3a). The sixth sample are glass fibers that are layered in two different directions (see Figure 3.3b).

![Sample 2](image1.png) ![Sample 7](image2.png)

Figure 3.4: Closer picture of the different samples from the dust (Photo taken by the author)

The two samples from the dust (see Figure 3.4) do not contain any glass fibers. The second sample is a very light piece and is made out of a porous brown material (see Figure 3.4a). It still seems to be a very hard material, since it cannot be broken apart by hand and tools are necessary. The sample 7 is made out of a black, dense material that is also quite hard (see Figure 3.4b).

### 3.2 Part 1: Thermogravimetric analysis

The wind blade material was analyzed in a first step with a Thermogravimetric Analysis. The TGA gives further understanding about kinetic parameters for decomposition reactions in different processes. [61] In this case, it can provide information about the used material and their characteristics. It was conducted in order to measure the weight change of a sample at a given time and temperature [68]. The amount of weight change of this analysis is based on the heating rate, the atmosphere, which can either be inert or oxygen-rich, and the temperature. A maximum of 20 mg in powder form can be used as a sample and a thermocouple was used to measure the temperature in the sample.

As a result of this process, a weight percentage curve was generated which shows the weight change depending on the temperature and the amount of residue that was left after the experiment [68]. This curve can be derived and it shows the rate of decomposition. The temperature at which the highest derivative of weight loss occurs is referred as the peak temperature for the process of the decomposition [68]. The questions that can be
Methodology

answered with the TGA are:

• What is the decomposition temperature of the coating and the matrix material?

• The decomposition temperatures can be compared to the literature which would show out of which material each sample is made of

• What is a suitable temperature for the pyrolysis process?

Figure 3.5: TGA machine that was used for the process in the laboratory (Photo taken by the author)

Seven probes were taken (see section 3.1) by filing off the surface of each sample to a fine powder. The goal was to not have any glass fiber in the probes, since the TGA was done to find out more about the decomposition temperature of the matrix material in order to separate it from the glass fibers. The powder was then placed in a small aluminium or ceramic pan in order for it to be measured.

In a similar experiment done with wind blade materials by Cousin [10], the maximal temperature was set at 800 °C and the heating rate was set at 10 °C/min in a nitrogen environment. The heating rate was kept the same as in the experiment conducted by Cousin. After the first test with the material, it was evident that the maximum temperature of 800 °C would be too high, since the decomposition would already occur before that, so a temperature of 700 °C would already be sufficient.

In a study by Qiao et al., the thermogravimetric analysis of GFRP was conducted at different heating rates of 5, 10, 15 and 20 °C/min. From the experiment conducted by Qiao et al., the graph in Figure 3.6 was obtained. According to Figure 3.6, the heating rate does not have a substantial impact on the maximum decomposition temperature. The most mass loss occurs for all the different heating rates in a temperature range between 400 °C and 440 °C. So choosing another heating rate would not have made a big difference in the resulting decomposition temperature. [53]
The residence time was then automatically calculated with the maximum temperature of 700 °C and a heating rate of 10 °C/min, the time to heat up the reactor from 20 to 700 °C would take around 68 minutes. The reaction was established within a nitrogen environment, as an oxygen-free setting is essential for conducting pyrolysis.

![TGA results of Glass Fiber Reinforced plastic at different heating rates](image)

Figure 3.6: TGA results of Glass Fiber Reinforced plastic at different heating rates [53]

### 3.3 Part 2: Molten Salt Pyrolysis

In the second part of the experiment, a more practical process was conducted in order to actually try to separate the thermoset from the glass fiber. With the decomposition temperature, that was determined in the first part (see section 3.2), a molten salt pyrolysis was conducted. The process was conducted in a molten salt bath. The molten salt was chosen according to the melting point, which should be as low as possible and according to the price, which should also be as low as possible (see Table 3.1). When measuring the weight of the sample before and after the process, it could be determined how much of the thermoset has been separated from the glass fiber. In order to determine the economical aspect of the process, the energy consumption of the furnace has been measured in the process as well.

To heat up the molten salt, a SNOL 8.2/1100 heater was used. It has a volume of 8.2 litres and it is possible to heat it up to a temperature of 1100 °C. The power is at 1.8 kW and the rated voltage supply is at 230 V. [64]
The main apparatus in this experiment was the reactor. A schematic drawing of the reactor can be seen in Figure 3.8. For temperature measurements, an Inconel sheathed K type thermocouple and thermometer was used. There are different types of thermocouples (type J, K, E, T) and they all have different kinds of temperature ranges in which they work. Depending on their temperature range and functionality, the price also varies. In this case, it would be advantageous to have a range of temperature between 0 °C and 600 °C. So it would either make sense to use the type J (temperature range of 0 °C to 750 °C), type K (temperature range of -200 °C to 1250 °C) and type E (temperature range -200 °C to 900 °C). But type K works better in applications in corrosive environments and also in applications where the cable can be oxidized. [71].

The reactor contains the following elements:

1. Zirconia crucible: Highly temperature resistant containers

2. Molten Salt: Liquid molten salt (see section 3.3.1)
KNO₃ + NaNO₃ + LiNO₃ (52/28/20)

3. Nut: Weight to keep the mesh in the liquid

4. Metallic mesh: To avoid the probes from floating on the surface

5. Probes of the wind turbine blade

The samples 1, 3, 4, 5 and 6 were used to conduct a pyrolysis. There were no glass fibers present in the dust material, which means it was not made out of GFRP. Therefore, it would not make sense to separate the glass fibers from the plastic matrix. From all these probes, smaller pieces of the blade materials were cut off and the samples were weighed, so their weight would range from one to two grams. Since a lot of molten salt was required to have the samples fully immersed in the liquid, the sample size of the wind blade material was kept small. Under the heat, a lot of bubbles were created, so if there was too much molten salt in the crucibles, it would spill.

In a first step, the crucibles were filled with the molten salt, which was in a solid state. The heater was turned on and was heated to the respective temperature. In the first trial, the maximum furnace temperature was set at 400 °C. When the temperature was reached, the containers were inserted in the furnace at a temperature of 396 °C. After one hour, when the molten salt was fully melted and reached a temperature of 300 °C, the containers were taken out of the oven and the samples were inserted into the molten salt and the containers were put back into the furnace. It is important to consider here that the temperature in the furnace and the molten salt will not be the same and therefore, the temperature in the molten salt needed to be measured with a thermocouple. If the temperature in the furnace was set at 400 °C, the maximum temperature that could be reached in the molten salt was only at 300 °C. After the containers with the samples were inserted into the furnace, the furnace was opened in time intervals of 15 minutes and all five samples were taken out for inspection to check if the pyrolysis reaction had occurred already. When the samples have turned white, the pyrolysis process has melted all the plastic and the furnace could be turned off. The original colour of the glass fiber is white, so if the matrix material has been completely separated, only the white glass fibers will be left. If after a maximum time of 60 minutes the reaction did not occur, the samples were taken out of the furnace and it was noted that the reaction at this temperature will not happen [11]. When the samples have cooled down, the molten salt will harden again, so the samples had to be immersed in a warm water bath for some time. When stirring in the container filled with water, it was possible to dissolve the salt. This was done until all the salt was dissolved and just the sample was left. The sample was left to dry for some time and weighed again. The process has been documented in a diagram, which can be seen in Figure 3.10.

This experiment was repeated for different temperatures of the furnace at 450 °C. This was done with the furnace KSL-1100X High Temperature Muffle Furnace. Another furnace was used in this case, because it was not possible to use the SNOL 8.2 heater anymore.

© Uppsala University

Kerstin Benz
This furnace was smaller, so it was faster to heat up the molten salt to around 400 °C. The required power is at 3500 W and the operating voltage at 220 V. It has a temperature range between 100 and 1100 °C. [31] It was not possible to fully conduct this part of the experiments since the thermocouple stopped working after 15 minutes. This led to a temperature decrease after the 15 minutes.

3.3.1 Molten Salt

There are different types of molten salt and depending on their composition, they have different characteristics which can be advantageous or disadvantageous depending on what
they are used for. Generally, they have a low melting point, high thermal conductivity, low viscosity, high boiling points and high specific heat, but they are also highly corrosive at higher temperatures [41]. As has already been mentioned in the research gap, the goal is to find a molten salt with a low melting point and a low price (see chapter 2.5).

It was quite challenging to determine the price accurately since some papers have included the price but some of them were older papers so the accuracy of this value can be questioned. Additionally, in cases where the price was not specified, an online search was conducted to find prices, but they varied a lot based on the origin of the salts and their level of purity. So it is important to look at the prices from a logical perspective. When looking at the Table 3.1, it is clear that Lithiumnitrate is more expensive than Potassium-, Calcium- or Sodiumnitrates. Due to the fact that Calciumnitrate was not available in the laboratory, the combinations with this salt had to be omitted. The lowest decomposition temperature found in the different samples with the TGA was at 150 °C, which means that the melting point of the molten salt would need to be lower (see chapter 4.1). As a result, the molten salts with a lower melting point than 150 °C will be the only ones considered. This leaves the following salts:

- **KNO$_3$ + NaNO$_3$ + LiNO$_3$ (57/13/30)**
- **KNO$_3$ + NaNO$_3$ + LiNO$_3$ (52/28/20)**
- **KNO$_3$ + NaNO$_3$ + NaNO$_2$ (53/7/40)**

It can be seen that the combination of potassium nitrate, sodium nitrate and lithium nitrate gives a low melting point. The mixture using 57% potassium nitrate, 13% sodium nitrate and 30% lithium nitrate has a low melting point of 123 °C [16]. Another combination which uses 20% lithium nitrate, 52% potassium nitrate and 28% sodium nitrate leads to a melting point of 130.15 °C [17]. The melting point from the second mixture is only an insignificant amount higher with a 7 °C difference. The component with the highest costs in both mixtures will be the lithium nitrate, which costs 45 US$/kg [59]. This means that the optimal mixture would be the one with 20% lithium nitrate, since the price is significantly cheaper but the melting point is not much higher. The combination of potassium nitrate, sodium nitrate and sodium nitrite could not be tested since sodium nitrite was not available.

The potassium nitrate that was used for the experiment had a 97% purity, the sodium nitrate had a 99.3% purity and the lithium nitrate had a 98% purity.
Table 3.1: Collection of the different values for different molten salts

<table>
<thead>
<tr>
<th>Compound or Mixer</th>
<th>Melting point [°C]</th>
<th>Price [US$/kg]</th>
<th>Thermal stability [°C]</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>(KNO₃ + NaNO₃ + LiNO₃ + Ca(NO₃)₂) * 4H₂O (30/20/10/40)</td>
<td>61.3</td>
<td>48.56</td>
<td>600</td>
<td>[56]</td>
</tr>
<tr>
<td>(KNO₃ + NaNO₃ + LiNO₃ + Ca(NO₃)₂) * 4H₂O (40/10/10/40)</td>
<td>62.8</td>
<td>47.94</td>
<td>600</td>
<td>[56]</td>
</tr>
<tr>
<td>KNO₃ + Ca(NO₃)₂ + LiNO₃ (63.7/27.3/9)</td>
<td>76</td>
<td>1.14</td>
<td>450</td>
<td>[88]</td>
</tr>
<tr>
<td>(KNO₃ + NaNO₃ + LiNO₃ + Ca(NO₃)₂) * 4H₂O (50/10/10/20)</td>
<td>79</td>
<td>26.55</td>
<td></td>
<td>[56]</td>
</tr>
<tr>
<td>KNO₃ + NaNO₃ + Ca(NO₃)₂ (32/24/44)</td>
<td>80</td>
<td>0.58</td>
<td>600</td>
<td>[9]</td>
</tr>
<tr>
<td>(KNO₃ + NaNO₃ + LiNO₃ + Ca(NO₃)₂) * 4H₂O (60/10/10/20)</td>
<td>80.4</td>
<td>26.56</td>
<td>600</td>
<td>[56]</td>
</tr>
<tr>
<td>(KNO₃ + NaNO₃ + LiNO₃ + Ca(NO₃)₂) * 4H₂O (50/20/10/20)</td>
<td>82.2</td>
<td>31.05</td>
<td>604.9</td>
<td>[56]</td>
</tr>
<tr>
<td>(KNO₃ + NaNO₃ + LiNO₃ + Ca(NO₃)₂) * 4H₂O (50/20/10/20)</td>
<td>84.3</td>
<td>27.60</td>
<td>600</td>
<td>[56]</td>
</tr>
<tr>
<td>(KNO₃ + NaNO₃ + LiNO₃ + Ca(NO₃)₂) * 4H₂O (60/10/20/10)</td>
<td>85.4</td>
<td>20.36</td>
<td>612</td>
<td>[56]</td>
</tr>
<tr>
<td>(KNO₃ + NaNO₃ + Ca(NO₃)₂ * 4H₂O (33.6/15.1/42.3/9)</td>
<td>96.56</td>
<td>1.07</td>
<td>350</td>
<td>[74]</td>
</tr>
<tr>
<td>KNO₃ + NaNO₃ + Ca(NO₃)₂ + LiNO₃ (40:10:40:10)</td>
<td>97.7</td>
<td>1.108</td>
<td>439.04</td>
<td>[45]</td>
</tr>
<tr>
<td>KNO₃ + NaNO₃ + LiNO₃ (57/13/30)</td>
<td>123</td>
<td>16.18</td>
<td>595</td>
<td>[16]</td>
</tr>
<tr>
<td>LiNO₃ + KNO₃ + NaNO₃ (20/52/28)</td>
<td>130.15</td>
<td>13.12</td>
<td>600.05</td>
<td>[17]</td>
</tr>
<tr>
<td>Ca(NO₃)₂ + NaNO₃ + KNO₃ (48/7/45)</td>
<td>130.61</td>
<td>51.82</td>
<td>554.39</td>
<td>[17]</td>
</tr>
<tr>
<td>LiNO₃ + KNO₃ + Ca(NO₃)₂ (30/60/10)</td>
<td>132.15</td>
<td>26.95</td>
<td>567.18</td>
<td>[17]</td>
</tr>
<tr>
<td>(KNO₃ + NaNO₃ + LiNO₃ + Ca(NO₃)₂) * 4H₂O (70/10/10/10)</td>
<td>136.4</td>
<td>15.86</td>
<td>600</td>
<td>[56]</td>
</tr>
<tr>
<td>KNO₃ + NaNO₃ + NaNO₂ (53/7/40)</td>
<td>142</td>
<td>0.9</td>
<td>610.97</td>
<td>[14]</td>
</tr>
<tr>
<td>AICl₃</td>
<td>193</td>
<td>0.9</td>
<td>270</td>
<td>[14]</td>
</tr>
<tr>
<td>KCl + NaCl + ZnCl₂ (23.9/7.5/68.6)</td>
<td>204</td>
<td>1</td>
<td></td>
<td>[14]</td>
</tr>
<tr>
<td>Solar salt (60:40 NaK nitrate by weight)</td>
<td>225</td>
<td>0.65</td>
<td>588.51</td>
<td>[59]</td>
</tr>
<tr>
<td>LiNO₃</td>
<td>253</td>
<td>45</td>
<td>485</td>
<td>[59]</td>
</tr>
<tr>
<td>ZnCl₂</td>
<td>290</td>
<td>1</td>
<td>[14]</td>
<td></td>
</tr>
<tr>
<td>NaNO₃</td>
<td>306.5</td>
<td>6.19</td>
<td>650</td>
<td>[59]</td>
</tr>
<tr>
<td>FeCl₃</td>
<td>308</td>
<td>0.5</td>
<td>[14]</td>
<td></td>
</tr>
<tr>
<td>KNO₃</td>
<td>334</td>
<td>4.58</td>
<td>550</td>
<td>[59]</td>
</tr>
<tr>
<td>KCl + MgCl₂ + NaCl (17.8/68.2/14)</td>
<td>380</td>
<td>0.35</td>
<td>[14]</td>
<td></td>
</tr>
<tr>
<td>K₂CO₃ + Li₂CO₃ + Na₂CO₃ (32/35/33)</td>
<td>397</td>
<td>1.4</td>
<td>[14]</td>
<td></td>
</tr>
<tr>
<td>KF + LiF + NaF (59/29/12)</td>
<td>454</td>
<td>2</td>
<td>[14]</td>
<td></td>
</tr>
<tr>
<td>LiCl</td>
<td>610</td>
<td>3</td>
<td>[14]</td>
<td></td>
</tr>
<tr>
<td>MgCl₂</td>
<td>714</td>
<td>0.2</td>
<td>[14]</td>
<td></td>
</tr>
<tr>
<td>KCl</td>
<td>771</td>
<td>0.43</td>
<td>[14]</td>
<td></td>
</tr>
<tr>
<td>CaCl₂</td>
<td>775</td>
<td>0.3</td>
<td>[14]</td>
<td></td>
</tr>
<tr>
<td>NaCl</td>
<td>800.7</td>
<td>0.06</td>
<td>801</td>
<td>[59]</td>
</tr>
<tr>
<td>CrCl₂</td>
<td>824</td>
<td>3</td>
<td>[14]</td>
<td></td>
</tr>
<tr>
<td>Na₂CO₃</td>
<td>852</td>
<td>0.24</td>
<td>1600/1744</td>
<td>[79]</td>
</tr>
<tr>
<td>SrCl₂</td>
<td>874</td>
<td>1.15</td>
<td>[14]</td>
<td></td>
</tr>
<tr>
<td>K₂CO₃</td>
<td>898</td>
<td>1.02</td>
<td>[79]</td>
<td></td>
</tr>
<tr>
<td>BaCl₂</td>
<td>961</td>
<td></td>
<td>[14]</td>
<td></td>
</tr>
</tbody>
</table>

© Uppsala University             Kerstin Benz
3.4 Techno-economical analysis

A comparison between the different methods of recycling has already been done. The aspect that has been considered in this case is the price. In the case of comparing the process of mechanically grinding the blade material with pyrolysis, the costs for the mechanical treatment are cheaper than thermal treatments. This does not result in the fact that the recyclate produced by pyrolysis can be sold for a more expensive price, because when shredding or grinding the blades, the value of the recyclate is higher. The selling price of the mechanically treated recyclate is higher, because this product is more established in the market. As mentioned before, the mechanical recycling does not separate the GFRP back into its components. In order to have a more sustainable product, further methods than just the mechanical recycling should be considered.

The objective is to also estimate the costs of the molten salt pyrolysis in order to compare it with the other processes. The costs for the process will be calculated using the cost of the materials used in the laboratory and the power used by the furnace. These costs will be compared with the energy required per recycling method which was already calculated in a paper by Fonte et al. [20]. The results can be seen in the Table 3.2, where the costs of mechanical recycling are compared to the conventional pyrolysis process. These values were obtained from the study by Fonte et al. [20].

<table>
<thead>
<tr>
<th>Method</th>
<th>[kg/hr]</th>
<th>[MJ/kg]</th>
<th>kWh/kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mechanical</td>
<td>150</td>
<td>0.16</td>
<td>0.04</td>
</tr>
<tr>
<td>Pyrolysis</td>
<td>unspecified</td>
<td>2.8</td>
<td>0.78</td>
</tr>
</tbody>
</table>
4 Results

4.1 Part 1: Thermogravimetric Analysis

The probes were taken from different parts of the wind turbine blade and analyzed with a TGA Q500. The maximum weight that was analyzed was 20 mg of each sample. Some probes were small pieces and some were in powder form.

The first result of the probe 1 can be seen in Figure 4.1. The furnace was turned off before it reached 700 °C, because the decomposition happened very quickly and already at a temperature of 180 °C the whole sample was burned off. Comparing this result with the other Figures created from the other samples, a big difference occurred in this analysis. Between 150 °C and 180 °C, the weight seems to increase to almost 150% and an immediate drop in weight to almost 0% occurs. Throughout this drop, the temperature is reduced from circa 175 °C to 155 °C. The decomposition temperature is marked as the temperature where the highest decomposition rate occurs. The decomposition rate can be determined by taking a derivative of the weight percentage curve. In this sample, the decomposition temperature was determined to be at 154 °C and at the end around 3.74% of the total weight was left. The probe was taken from what looked like a layer that was not made out of GFRP. No glass fiber could be found in this layer and it was a transparent, smooth layer. The measured probe was measured in powdered form.

![Thermogravimetric analysis of Sample 1](image)

Figure 4.1: Result of the TG analysis from Sample 1 (Graph created by the author)

The sample 2 was part of the dust of the wind turbine blade. It was a brown, porous material and the sample was a small piece of the sample not in a powdery form. The first
Results

decomposition occurs between around 240 °C and 280 °C and the second one between 430 and 490 °C. The maximum decomposition rate occurs at a temperature of 259 °C. Looking at the sample, it could be seen that there was no glass fiber present in the sample.

![Thermogravimetric analysis of Sample 2](image)

Figure 4.2: Result of the TG analysis from Sample 2 (Graph created by the author)

In sample 3, the sample consisted of an outer layer that was grey and not transparent and it did not contain any glass fibers. It was attached to another layer which was made out of GFRP, so when filing off the surface, some glass fibers ended up infiltrating the probe. The process of heating up sample 3 seemed to have only one step where the full decomposition occurred. The maximal decomposition rate could be found at a temperature around 380 °C and around 10% of the material was left at the end of the experiment. This 10% was probably the glass fibers that were in the sample and did not burn off.
The material from sample 4 looked very similar to the one in sample 1. There was more glass fiber and the transparent layer was thinner than in sample 1. The sample was not in a powdery form, but a piece of the transparent material was taken and there were some glass fibers attached to the probe. The decomposition temperature at 381.5 °C is very similar to the one from sample 3 and less than 5% of the probe was left in the end. What is also similar to sample 3 is that the decomposition also occurs in one step and there are not several steps like in sample 2.

The sample 5 was labeled as the outside blade and there was a very thin, gray layer on top of the sample. The sample was taken by filing off the grey surface. Below the grey surface, there was a layer which was made out of GFRP. The decomposition temperature at around 373 °C is quite similar to the two prior samples but what seems to be very
Results

different from the other samples is the fact that there was almost 50% of the weight left at the end of the TG analysis.

![Thermogravimetric analysis of Sample 5](image)

Figure 4.5: Result of the TG analysis from Sample 5 (Graph created by the author)

In sample 6, the sample contained a lot of glass fiber and it was not possible to omit having some parts of glass fibers in the probe. The decomposition process is very similar to the previous ones since it is also a process that happens in one step and the temperature is also at 373 °C which is similar to the sample number 5. What was left after the process was mostly glass fibers, which is the 11% of residues that were left after heating up the sample.

![Thermogravimetric analysis of Sample 6](image)

Figure 4.6: Result of the TG analysis from Sample 6 (Graph created by the author)

The probe 7 was part of the dust from the wind turbine blade. It was a black piece of an unknown material and the probe to measure with the TGA was filed off and in a powdery form. It did not seem to contain any glass fiber. The decomposition temperature was around 385 °C and at the end of the process, almost 24% of the probe was left.
Table 4.1: Comparison of the different types of Recycling

<table>
<thead>
<tr>
<th>Sample Nr.</th>
<th>Part of Wind</th>
<th>Start Weight [mg]</th>
<th>Decomposition Temperature [°C]</th>
<th>Weight at the End [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Inside Blade</td>
<td>8.514</td>
<td>154.0</td>
<td>3.74</td>
</tr>
<tr>
<td>2</td>
<td>Dust</td>
<td>8.74</td>
<td>259.1</td>
<td>14.16</td>
</tr>
<tr>
<td>3</td>
<td>Longer side</td>
<td>16.442</td>
<td>380.2</td>
<td>10.98</td>
</tr>
<tr>
<td>4</td>
<td>Diverse</td>
<td>15.447</td>
<td>381.5</td>
<td>4.57</td>
</tr>
<tr>
<td>5</td>
<td>Outside Blade</td>
<td>13.31</td>
<td>373.53</td>
<td>43.93</td>
</tr>
<tr>
<td>6</td>
<td>Diverse</td>
<td>10.941</td>
<td>373.1</td>
<td>10.94</td>
</tr>
<tr>
<td>7</td>
<td>Dust</td>
<td>10.337</td>
<td>385.2</td>
<td>23.92</td>
</tr>
</tbody>
</table>

4.2 Part 2: Molten Salt Pyrolysis

The results of the pyrolysis were documented in the Tables 4.2 and 4.3. The weight before the experiment and after the experiment were noted. During the pyrolysis, the samples were taken out of the furnace every 15 minutes and the colour of the sample was noted plus the smoke coming out of the sample was observed. In the first experiment documented in Table 4.2, the initial plan was to take them out every 10 minutes, but the temperature decrease when opening the furnace every 10 minutes would have been too high, so it was decided to take them out every 15 minutes. When taking out the sample 5 after 55 minutes, the crucible fell. The liquid got out but the sample was still inside. The crucible was refilled with molten salt and melted again without the sample. At 70 minutes the molten salt was melted and the probe was inserted again and left in the furnace for 15 minutes longer than the other samples.
Table 4.2: Process of Pyrolysis at 400 °C

<table>
<thead>
<tr>
<th>Sample Nr.</th>
<th>Temperature [°C]</th>
<th>Time [min]:</th>
<th>Weight before [g]</th>
<th>Time [min]:</th>
<th>Temperature [°C]:</th>
<th>Weight after [g]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>400</td>
<td>0</td>
<td>1.485</td>
<td>10</td>
<td>375</td>
<td>1.297</td>
</tr>
<tr>
<td>3</td>
<td>400</td>
<td>0</td>
<td>1.325</td>
<td>10</td>
<td>375</td>
<td>1.008</td>
</tr>
<tr>
<td>4</td>
<td>400</td>
<td>0</td>
<td>1.458</td>
<td>10</td>
<td>375</td>
<td>1.262</td>
</tr>
<tr>
<td>5</td>
<td>400</td>
<td>0</td>
<td>1.732</td>
<td>10</td>
<td>375</td>
<td>1.387</td>
</tr>
<tr>
<td>6</td>
<td>400</td>
<td>0</td>
<td>1.015</td>
<td>10</td>
<td>375</td>
<td>0.966</td>
</tr>
</tbody>
</table>

After finishing the pyrolysis, the pictures from the cleaned samples can be seen in the following Figures 4.8 and 4.9. All of the samples have turned black and look burnt. Looking at the first sample (see Figure 4.8a), the pieces of the glass fibers still are connected together, but there is no more plastic layer on top of it, as seen in Figure 3.2a. This part has been melted off. The third sample can be seen in Figure 4.8b and the thin layer has not been melted off, but some cracks were the surface. Some white glass fibers can be observed, but most of them turned black. Also in this sample, the glass fibers are still intertwined and cannot be separated easily. After pyrolyzing sample number 4 (see Figure 4.8c), the glass fibers have turned black and light brown. They are stuck together and some smaller pieces have been separated, but also these smaller pieces are still made out of glass fibers that are connected. Similar to the third sample, the fifth sample (see Figure 3.3a) still has a layer on the surface which has cracks in it. On the surface of the sample, some white glass fibers can be observed, which means that some glass fibers have been separated from the thermoset material. The sample 6 has a brown-blackish colour (see Figure 4.9b) and the glass fibers are still connected with each other.
Results

Figure 4.8: Closer picture after conducting the pyrolysis at 400 °C (Photo taken by the author)

Figure 4.9: Closer picture after conducting the pyrolysis at 400 °C (Photo taken by the author)

The Table 4.2 and Table 4.3 show what happened in the pyrolysis process. In the case of setting the temperature to 450 °C, the process could not be finished.

<table>
<thead>
<tr>
<th>Temperature furnace</th>
<th>450</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>Smoke?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample Nr.</td>
<td>1</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>Weight before [g]</td>
<td>2.0487</td>
<td>1.2448</td>
<td>1.7303</td>
<td>0.6593</td>
<td>0.9530</td>
<td>yes</td>
</tr>
<tr>
<td>Time [min]: 0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Temperature [°C]: 277</td>
<td>much smoke</td>
<td>much smoke</td>
<td>much smoke</td>
<td>much smoke</td>
<td>much smoke</td>
<td></td>
</tr>
<tr>
<td>Time [min]: 15</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Temperature [°C]: 450</td>
<td>black surface</td>
<td>white fibers with black surface</td>
<td>black surface (burnt)</td>
<td>black pieces with black surface</td>
<td></td>
<td>yes</td>
</tr>
<tr>
<td>Weight after [g]</td>
<td>1.588</td>
<td>0.2681</td>
<td>1.2386</td>
<td>0.3851</td>
<td>0.8757</td>
<td></td>
</tr>
</tbody>
</table>
Looking at sample 1 (see Figure 4.10a), the layer which was on top of the GFRP has been dissolved and a thin layer of glass fibers has turned white and they are separated from the matrix and fully pyrolyzed. Below that layer, the GFRP has turned black and the matrix still connects the glass fibers. It is not clearly visible in Figure 4.10b, but the fibers from sample 3 have turned white after the experiment and they are not connected anymore. Also in the fourth sample, which is visible in Figure 4.10c, some glass fibers have turned white and are not connected in a matrix anymore. The biggest part of the sample is still connected though and turned black. Looking at the Figure 4.11a of the cleaned wind turbine blade material after the pyrolysis, the sample 5 consists of smaller pieces that turned black and the pieces were inseparable. In the sixth sample (see Figure 4.11b), the pieces are still connected together and on the surface they have a light brown colour. What can be said is that there were smoke emissions in both the trials, but there was significantly more at a furnace temperature of 450 °C.

Figure 4.10: Closer picture after conducting the pyrolysis at 450 °C (Photo taken by the author)

Figure 4.11: Closer picture after conducting the pyrolysis at 450 °C (Photo taken by the author)
4.3 Techno-economical analysis

The costs were calculated for recycling one whole blade. The weight is around 12474 kg for a blade with a length of 47 meters [40]. The appropriate amount of molten salt was weighed in the beginning. Around 300 g of the mixture was produced. This would be enough for conducting the pyrolysis for around 15 samples. Consequently, around 20 mg of dried molten salt is necessary for 1 mg of sample weight.

According to Fernandez et al., the price for 1 kg of the molten salt that was used is 13.12 US$/kg [17]. In Euros, this corresponds to 11.94 Euros/kg (with an exchange rate of 0.91 Euros/US$ from the 9th of August 2023). The molten salt needed for pyrolyzing one whole wind blade with a length of 47 meters would be around 250’000 kg. The molten salt for this process would cost approximately 3 million Euros.

When using the heater from SNOL, the power is at 1.8 kW. The heater was running for around 60 minutes to heat to the selected temperature and melt the molten salt and another 60 minutes for the experiment. So, the heater needs to be running for around two hours and there is space for around 10 samples per round [64]. If the samples would be processed at the same rate as in the laboratory, it would take around 2.5 million hours to pyrolyze the whole wind blade. In case of using the furnace from SNOL, this would use around 4.5 million kWh of electricity. The average electricity price in Sweden was at 0.118 Euros/kWh in the year 2022 [81]. Since the electricity prices are very volatile, a yearly average from 2022 has been chosen to calculate the electricity costs. Only considering the electricity for the process, it would cost already more than 500’000 Euros.

When adding the price for the molten salt and the costs for the electricity, the cost would already exceed 3.5 million Euros. This does not include the salary yet for the working hours or the price for the machinery used. In this value, the costs for shredding the pieces of the wind turbine blade beforehand the pyrolysis process are also not considered.

To obtain the value at which the pyrolyzed product needs to be sold, the recovery rate of the pyrolysis needs to be used in order to find out, how many glass fibers could be retrieved when the process is finished. From the experiment, the weight percentage of the finished pyrolysis will be taken from sample 3 (see Table 4.4) at a temperature of 450 °C.

When taking the weight percentage of 21.54% from the start value of 12474 kg, 2687 kg of recovered glass fibers can be obtained after this process.

The costs for the molten salt pyrolysis can now be compared with the conventional

---

Table 4.4: Weight percentage left after the pyrolysis

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Sample</th>
<th>Weight %</th>
</tr>
</thead>
<tbody>
<tr>
<td>400°C</td>
<td>1</td>
<td>87.34</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>76.08</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>86.56</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>80.08</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>95.17</td>
</tr>
<tr>
<td>450°C</td>
<td>1</td>
<td>77.51</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>21.54</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>71.58</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>58.41</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>91.89</td>
</tr>
</tbody>
</table>
pyrolysis and also with the shredding, which is currently the most used recycling method. Looking at the conventional pyrolysis, 0.78 kWh is required for processing 1 kg of blade material. The total cost for treating one full wind turbine blade would add up to 1150 Euros. To be able to compare the conventional pyrolysis with the molten salt pyrolysis, the same weight percentage will be used. The selling price of the blade is currently at 240.5 US$/t [35]. Selling all of the recovered parts for this price, the whole blade would be worth 588 Euros.

When comparing this value with the shredding process, 137 Euros are necessary for powering the recycling process of one turbine blade (see Table 3.2). From the Table 2.1, the selling price for shredded pieces can be obtained with a value of 410 US$/kg. Adjusting this value to the whole blade with using 100% of the initial weight of the blade, the material can be sold for 4661 Euros. The results of this calculations are summarized in Table 5.3.

The goal of this thesis was not to apply the molten salt pyrolysis on a larger scale or increase the efficiency, but to find the temperature and residence time necessary for the process. This means that the method of the molten salt pyrolysis was only conducted on a laboratory scale and in being so, it is still a very inefficient process. This also explains why extremely high prices were obtained when calculating the costs.
5 Discussion

After completing the experimental part, the results were interpreted. After the TGA was completed, it was possible to plot the results. These graphs could be compared to previously conducted TG analyses that were conducted with commonly used materials for wind turbine blades. From this analysis, it is also possible to find the temperature where the maximum decomposition occurs. This can be used for the second part of the experiments, which is the molten salt pyrolysis.

Regarding the composition of the material, the decomposition temperature of different materials were examined and compared with the temperature obtained from the experiment. This gives more information on the material of the samples and also where in the wind turbine blade it occurs. The decomposition temperature of the different materials has been found in several studies that were previously conducted (see Figure 5.1, 5.1a, 5.1b, 5.2, 5.3, 5.4, 5.5). It is important to note that the conditions where the experiments have been conducted in the different studies can differ from the experiments that were conducted in the laboratory.

5.1 Part 1: Thermogravimetric Analysis

5.1.1 Probe 1

The start weight of the sample is 8.514 mg at room temperature. At the end of the experiment, when the reaction has finished, only 3.74% of the original weight is left, which means at the end, the weight is at 0.3184 mg. The reaction occurs in a very short time and temperature range between 154 °C and 180 °C (see Figure 4.1). High fluctuations can be observed in the weight in this period and also a slight decrease in the temperature. This fluctuation can occur from the fact that the weight of this sample was very low. When the weight is too low, there is a possibility that the sample can be affected by the nitrogen gas flow and fast changes in the weight can occur. In order to be able to reproduce and affirm the result, another TG analysis should have been conducted with another probe from sample 1.

It seemed like the material layer over the GFRP could be some sort of glue (see picture 3.2a). There was a study conducted by Lux et al. where an epoxy based resin was used. From the recommendations of the manufacturer, it was specified that the degradation occurs at a temperature of 160 °C. According to the paper, the epoxy based resin was used as an adhesive, which is used in a wind turbine blade to bond different materials together. The upper and lower part of the turbine blade are manufactured...
separately with the resin infusion technology and combined with each other with adhesives. According to the description from Vattenfall, the sample comes from the inside part of the blade, which is where the adhesives are applied. In conclusion, it can be said with certainty, that the material tested in the TGA is an adhesive. Since this adhesive has a low decomposition temperature, most of the sample will be burned off in the process and this also explains why there is a low percentage of residue left with 3.74%. [38]

5.1.2 Probe 2

For testing the sample 2, 8.74 mg of the sample was tested with the TG analysis. After the process, 14.16% of the sample was left which equates to 1.24 mg. When looking at the sample, it can be observed that there are no glass fibers present in the sample (see Figure 3.4a). In a study by Shi et al., a TGA of heat resistant cross-linked polyvinylchlorid (PVC) foams was conducted. In the wind turbine blade production, PVC foams are used as core material for sandwich structures, since the material is very stiff compared to its weight and it is also quite cheap. Four different types of PVC foam were tested in this study, which differ in the chemical composition. The four samples are "universal cross-linked PVC structural foam", "heat resistant cross-linked PVC foam 1", "heat resistant cross-linked PVC foam 2", "heat resistant cross-linked PVC foam 3". It is said that peroxide crosslinking increases the heat resistance of a material. Compared to the first sample, the other three samples are heat-resistant. Also, peroxide and crosslinking agents were introduced in the samples "heat resistant cross-linked PVC foam 1" and "heat resistant cross-linked PVC foam 2". The sample "heat resistant cross-linked PVC foam 3" contains Vinyl monomer and unsaturated anhydride. The results can be seen in Table 5.1. Compared to the sample of the wind turbine blade that was tested, the decomposition temperature of 259 °C seems to be in the same area as the PVC foam samples. The weight at the end that is left of the sample of the dust is in the same range with 14.16% compared to the "universal cross-linked PVC structural foam" with a residual weight of 18.08%. [62]

<table>
<thead>
<tr>
<th>Foam type</th>
<th>Rapid decomposition Temperature [°C]</th>
<th>Residual weight [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Universal cross-linked PVC structural foam</td>
<td>257</td>
<td>18.08</td>
</tr>
<tr>
<td>Heat resistant cross-linked PVC foam 1</td>
<td>259</td>
<td>21.41</td>
</tr>
<tr>
<td>Heat resistant cross-linked PVC foam 2</td>
<td>259</td>
<td>22.38</td>
</tr>
<tr>
<td>Heat resistant cross-linked PVC foam 3</td>
<td>265</td>
<td>23.38</td>
</tr>
</tbody>
</table>

5.1.3 Probe 3

The start weight of the sample 3 was at 16.442 mg and at the end of the process, 10.98% of the sample was left which corresponds to around 1.8 mg. Only a small amount of
the sample actually contained GFRP and the rest seemed like a coating material (see Figure 3.2b). In the article by Kjærside, four different types of coating material are used in the wind turbine blade industry. These different coating materials protect the blades from different factors which can cause degradation of the blade. These factors can be very cold or warm temperatures, rain, UV radiation from the sun, hailstorms or ice. The four different coating materials that are currently used in the industry are unsaturated polyester, acrylate, epoxy or polyurethane. [2]

In a study conducted by Kandare et al., unsaturated polyester resins with different chemical compositions were looked into with a thermogravimetric analysis. Six different compositions have been tested, where various amounts of flame retardant (APP), smoke suppressant (ZS, ZB and ZHS) and organically modified nanoclay (Cloisite 25A) were used (see Table 5.2). The pyrolysis was conducted at a temperature of 700 °C for 40 seconds. The resulting curves can be found in Figures 5.1. The structure of the curve seems to be quite similar for the different compositions and the main mass loss occurs in a temperature range between 300 and 380 °C. Two different moments of mass decrease occur, which is the one between 300 and 380 °C and also a smaller drop in mass between 400 and 600 °C. In all cases, the amount of mass% left after the experiment is below 20%. [29]

Table 5.2: Mass percentages of various components in the formulations [29]

<table>
<thead>
<tr>
<th>Sample</th>
<th>Mass[%]</th>
<th>Cloisite 25A</th>
<th>APP</th>
<th>Smoke suppressant</th>
</tr>
</thead>
<tbody>
<tr>
<td>R</td>
<td>100</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>RA</td>
<td>83</td>
<td>-</td>
<td>17</td>
<td>-</td>
</tr>
<tr>
<td>RAZS</td>
<td>83</td>
<td>-</td>
<td>8.5</td>
<td>-</td>
</tr>
<tr>
<td>RAZB</td>
<td>83</td>
<td>-</td>
<td>8.5</td>
<td>8.5</td>
</tr>
<tr>
<td>RAZBC</td>
<td>79</td>
<td>4</td>
<td>8.5</td>
<td>8.5</td>
</tr>
</tbody>
</table>

(a) Result of the pyrolysis analysis of the first four samples from the Table 5.2 conducted by Kandare et al. [29]  
(b) Result of the pyrolysis analysis of the last two samples from the Table 5.2 conducted by Kandare et al. [29]

Figure 5.1: Mass loss of different polyester compositions [29]

In the paper from Stolov et al., different types of coating materials made with acrylate
were tested with a TG analysis. Most of the samples were dual coatings which means that different polymers were applied in different layers. The sample that was tested (see Figure 5.2) with the label "DA-1" was an acrylate mixed with urethane. It is a sample with dual coatings and in this case, both of the different polymers used contain urethane. In the case of "DA-3", it was also a dual coating polymer, but in this case one of the shares contains urethane and the other share does not. The sample "SiHTA-1" is also a dual coat and consists on one hand of Silicone acrylate, which does not contain urethane and on the other hand of a urethane containing coating material. The "Hyb" sample is a single coat containing silicone but no urethane. For the samples "DA-3" and "DA-1", the main mass loss occurs in a temperature range of 300 - 450 °C and all of the sample is burned off in the end. The biggest mass loss occurs at a later point between 380 and 500 °C for "Hyb" and for the sample "SiHTA-1", the mass loss occurs more slowly between a temperature range of 300 °C and 600 °C. In comparison to the other samples, "SiHTA-1" seems to have only one process of mass loss and not two as the other ones. "SiHTA-1" has around 20% of residue at the end of the process and "Hyb" around 10%. [66]

![Figure 5.2: Result of the TG analysis of the different acrylate samples conducted by Stolov et al. [66]](image)

In a study conducted by Bao et al., the thermal degradation of epoxy resin was conducted. This experiment was conducted at different heating rates and the result can be seen in Figure 5.3. The thermogravimetric analysis was conducted under the heating rates 5 °C/min, 10 °C/min, 20 °C/min and 40 °C/min until 600 °C. When considering the heating rate of 5 °C/min, the maximum decomposition rate occurs at 365.4 °C, at 10 °C, the temperature with the maximum decomposition rate is at 382.6 °C, with 20 °C respectively at 400.1 °C and with 40 °C/min respectively at 423.5 °C. In all the different conditions, the decomposition occurs in one single step and around 10% of the sample is left in the end of the experiment. [3]
Discussion

A study about the thermogravimetric decomposition process of polyurethane was conducted by Filip et al.. The thermogravimetric analysis was conducted in a nitrogen flow with a heating rate of 10 °C/min up to a maximum temperature of 700 °C. As it can be seen in Figure 5.4, the reaction happens in a temperature range between 250 °C and 500 °C with a residue at 700 °C of around 10%. According to the paper, the main weight loss occurs at a temperature of 346 °C. [19]

The result in Figure 4.3 shows only one single decrease in the weight and not two, which means that it is not possible for it to be unsaturated polyester or acrylate, since these polymers have two steps of weight loss (see Figure 5.1a, 5.1b, 5.2). When comparing the curves of epoxy at a heating rate of 10 °C/min (see Figure 5.3) and the curve of the polyurethane (see Figure 5.4), the curves seem very similar to the one of sample 3. Also, the residue of around 10% occurs with both coating materials. But the maximal
decomposition temperature of epoxy at 382.6 °C is closer to the decomposition temperature of 380.2 °C of the third sample.

5.1.4 Probe 4

This analysis was conducted with 15.447 mg of sample material of which 4.57% of the sample was left in the end, which is around 0.7 mg. The material from this sample did not look very similar to the one from sample 3 (see Figure 3.2c). Nevertheless, the maximal degradation temperature and the curve in general seem to be very similar to the one from sample 3 (see Figure 4.4). This means that the coating material present in the sample could be epoxy as well.

5.1.5 Probe 5

For sample 5, the experiment started with around 13.31 mg of sample and 43.93% of the sample was left in the end, which corresponds to 7.3 mg. In the experiment presented in the paper from Saidova et al., a TGA was conducted with a heating rate of 10 °C/min in a nitrogen atmosphere up to a temperature of 600 °C. The materials that were tested in the analysis are epoxy resins, glass fiber combined with ordinary epoxy resin (Resin S) and glass fiber with heat-resistant epoxy resin (Resin ST). Plus, carbon fiber has also been tested with heat-resistant epoxy resin (see Figure 5.5). Comparing the curve from sample 5 with the tested material, it is very probable that the sample was made out of glass fiber combined with fire-resistant epoxy resin (see Figure 4.5). The sample contained a lot of glass fibers and also the epoxy resin has an increased heat-resistance, which explains why there is a lot of residue after the experiment (see Figure 3.3a). Figure 5.5 shows that the curve for the heat resistant epoxy resin shifts to the right when comparing it to epoxy resin. Compared to sample 4, the fifth sample also makes a shift to the left. [58]
5.1.6 Probe 6

10.941 mg of sample 6 were used for the analysis and 10.94% were left after the experiment and 1.2 mg of the initial sample was left in the end. The curve from the TG analysis seems to have most resemblance to the one from sample 4, which means it is possible that the sample is made out of epoxy resin containing glass fibers (see Figure 4.6). The 10.94% that were left at the end of the experiment are the glass fibers that will not get pyrolyzed in the process. The maximum decomposition temperature of sample 6 is 373 °C a bit lower than the temperature in the experiment from Bao et al. [3]. Compared to sample 4, where the weight loss occurs on a bigger scale with a maximal derivative weight loss of over 1.5 \%/°C, while this value for sample 6 is below 1 \%/°C. This underlines the fact that the decomposition happens at a slower rate in sample 6. The decomposition occurs at a similar temperature than for sample 5. This could indicate that the material could also be made out of heat resistant epoxy resin (see Figure 5.5).

5.1.7 Probe 7

The sample 7 weighed 10.337 mg and around 23.92% were left at the end of the experiment which corresponded to 2.5 mg. The maximum decomposition happens around the same temperature as the sample 4, which means it probably is made out of epoxy resin as well (see Figure 4.7) [30]. No glass fibers were present in the sample, but almost 24% of residues were left at the maximum temperature of 700 °C (see Figure 3.4b). This means that probably another material is present in the sample which has a higher decomposition temperature than 700 °C. It is not quite clear what that material could be made out of.
From the conducted analysis, it can be estimated from where in the blade the samples could come from (see Figure 5.6). When it is known what kind of material occurs in the samples, the temperature of the pyrolysis can be adapted. The first sample contains an adhesive paste, which is used to glue the two parts of the turbine blade material together. The second sample is most probably made out of PVC foam, so it is used to stabilize the connection and prevent deformation. The sample seems to occur on the surface of the blade, since it contains protective coating materials. In the fourth sample, the glass fibers only follow one direction, so it is used between the tri-axial laminate as a filler material. The fifth sample has different layers, where the glass fibers are structured in different directions, which means it is part of the tri-axial laminate and comes from outside the blade. The fibers in sample 6 point in two different directions, which means they come from the connection point between the two blades, where the material is bi-axial laminate. It was not possible to pinpoint the origin of the seventh sample, since it did not contain any glass fibers but it was most probably made out of epoxies.

![Figure 5.6: Cross-section of the blade and indication where the tested sample could come from (Image adapted from [80], modified by the author)](image)

5.2 Part 2: Molten Salt Pyrolysis

The results from both Tables (see Table 4.2 and 4.3) show that a lot of smoke was produced throughout the process and almost all the samples turned black instead of turning white. The temperature of the furnace was probably too low, since the temperature of the molten salt only reached around 300 °C. This means that the reaction could not happen in this environment.

The furnace that was used for the second part of the experiment was smaller, so heating up the molten salt was faster and when the furnace temperature was at 450 °C, the temperature of the molten salt was at around 400 °C. This environment created a successful pyrolysis for Sample 3 after 15 minutes. It can also be seen in Table 4.4, that
most of the samples did not lose a lot of weight and only two samples reached a weight percentage that was lower than 70%. What can be observed is that the weight percentage for all the samples is lower at the temperature of 450 °C than at 400 °C, which means the reaction is more probable to happen at 450 °C. It would have been favorable to heat the samples longer in the furnace at a temperature of 450 °C to see if the full reaction would occur with the other samples. To sum it up, the temperature of the molten salt for the pyrolysis needs to be higher than 300 °C, but a temperature of around 400 °C seems to be sufficient. Looking at the time frame, most of the samples did seem to have some white fibers present after 15 minutes, so it would probably be sufficient to run the process for about 30 minutes.

5.3 Techno-economical analysis

The Table in this section shows the summary of the obtained results from the calculation in section 4.3. Since glass fibers from the molten salt pyrolysis have not been brought to the market yet, an estimation of the selling price does not exist yet.

Table 5.3: Calculated costs and selling price for the different processes not considering the machinery and the working hours (calculated for 1 blade with a weight of 12'474 kg)

<table>
<thead>
<tr>
<th>Process</th>
<th>Costs [Euro]</th>
<th>Selling price [Euro]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional Pyrolysis</td>
<td>1150</td>
<td>588</td>
</tr>
<tr>
<td>Shredding</td>
<td>59</td>
<td>4661</td>
</tr>
<tr>
<td>Molten Salt Pyrolysis</td>
<td>3'500'000</td>
<td>-</td>
</tr>
</tbody>
</table>

In order to not make any losses, the price of the electricity and the molten salt needs to be the same as the selling price. In this case, the whole material obtained from the blade should be sold at a price of 3.5 million Euros. When considering that 2687 kg of recycled glass fibers can be obtained when recycling one wind turbine blade, the selling price per kg would be 1306 Euros.

When looking at the Table 5.3, it is also evident that the costs for the conventional pyrolysis are already higher than the profit that can be made by selling the product. In order to level out the costs of the process, the fibers should be sold at 0.4 Euros/kg. Currently they are sold at a price of 0.2 Euros/kg [35].

It does not seem to be economically viable to conduct a molten salt pyrolysis compared to a conventional pyrolysis or a mechanical recycling process. What needs to be considered though, is that this calculation was only made for the costs of the material necessary for the process and the electricity used. The costs of the required machinery or the hours required to conduct the recycling are not included. Compared to the conventional pyrolysis, the molten salt pyrolysis just requires a furnace which does not need to work in an inert environment. What has also not been included in this study is the fact that the blade needs to be cut into smaller pieces when conducting any type of pyrolysis. This will
lead to an increase in the costs for both of the pyrolysis processes. However, the costs for the molten salt pyrolysis are extremely high, because it has only been tested in the laboratory and not on a larger scale. In practice, less molten salt will be necessary and also, less electricity will be required for treating the whole wind turbine blade.

Additionally, when comparing the time necessary for the recycling methods, the Table 3.2 shows that around 150 kg of material can be processed per hour. From the experiments conducted in the lab, a rate of around 0.005 kg/hr could be achieved. What is important to note is that the mechanical recycling of wind turbine blades is already a commercially applied method, which means it has been adjusted to a bigger scale and is obviously way more efficient. This makes it hard for companies offering the thermal methods to compete in the market.

A crucial point is to look for a necessity of the recycled glass fibers in the market. As mentioned already, buying new glass fibers is not very expensive, so there is no big incentive to sell recycled fibers. Additionally, when recycling, the quality of the fiber decreases, which makes it harder to reuse it for the same applications. There is a market for selling mechanically recycled fibers to the cement production industry. For this application, the pyrolysis process is too expensive and the quality of the recycled fibers is unnecessarily high. However, in the future, the industry will focus more on a sustainable way of reusing the parts of the blades separately and not on mechanically grinding the blades and downcycling them to a filler material. Following that, the price for the recylcate from the pyrolysis process will increase. Simultaneously, it is also necessary that the costs of conducting a molten salt pyrolysis will decrease. This can be achieved by trying to apply the process on a bigger scale and also, trying to find a molten salt that would be cheaper. Looking at the Table 3.1, a cheaper molten salt with a low melting point would be $\text{KNO}_3 + \text{NaNO}_3 + \text{Ca(NO}_3)_2$ (32/24/44), which has a melting point of 80 °C and does not contain and Lithiumnitrate, so it is a lot cheaper than the molten salt used in this experiment [9]. Other molten salts with different compositions could also be tested in further studies, for example $\text{KNO}_3 + \text{NaNO}_3 + \text{Ca(NO}_3)_2$ (45/7/48) or also $\text{KNO}_3 + \text{NaNO}_3 + \text{NaNO}_2$ (53/7/40).

In 2022, the market for recycled glass fiber was at 28 billion US$ and it is expected to grow to around 40 billion US$ by 2030. This growth will be based on the fact that the concept of circular economy will gain more importance in the next years. The adaptation of the sustainability concept in the construction and also automotive industry will contribute to this increase over the next few years. Additionally, governments will introduce regulations in order to improve the competitiveness of the recycled glass fibers in the market. Recycled glass fibers find their main uses in the market across construction or municipal sectors. Construction stands out as the key sector, employing these fibers to reinforce cement and other building components. Within the municipal realm, recycled glass fibers play a crucial role in the creation of drainage structures and piping systems. It is recommended to conduct a more thorough research on how the properties change for the different recycling processes and how the effect of the deterioration can be mitigated. [52]
6 Conclusion

Electricity produced by wind turbines is considered to be a sustainable energy source due to wind turbines operating without depleting finite resources or emitting greenhouse gases, unlike power generation from fossil fuels. There has been an upward trend of new installations since the 90's. A wind turbine has a lifetime of around 25 years and after, the degradation of the turbine is too high and it needs to be refurbished, repowered, repaired, or decommissioned. This means that in recent years, a lot of turbines have reached their end-of-life and more will follow.

The biggest part of a turbine is made out of metals and the blades are mostly made out of glass fibers reinforced plastic. Quite a big part of the metals are already being recycled, but this is not the case for the blade material, since it has a more complicated composition. The most common strategy to dispose of wind turbine blades has been the deposition in landfills. With new regulations from governments and companies investing more in sustainable concepts, different technologies to recycle the blades have been developed. The three categories of recycling are mechanical, thermal and chemical. The mechanical process, which is currently the most profitable one, consists of cutting the blade into smaller pieces. This method decreases the strength of the glass fibers which is why it is also important to look into the thermal or chemical processes and find a way to make them affordable and applicable for the big scale.

That is why a new process to recycle wind turbine blades has been explored. It is a type of pyrolysis, which is defined as the heating of a material in the absence of oxygen. Usually, this is done in a nitrogen environment, but in this case, it is done with molten salt. The advantage of this process is that the molten salt has a high heat storage capacity, which means less energy is required for the process. This could not be verified with the experiment, since the electricity requirement for the conventional pyrolysis was compared to the molten salt pyrolysis conducted in the laboratory. Obviously, the energy requirement for the conventional pyrolysis was lower for the same material input, since this value was calculated for a commercial scale. Additionally, a liquid reaction environment has a higher probability of a complete reaction. The molten salt was chosen to minimize the price and minimize the reaction temperature. Having a low reaction temperature was expected to create a smaller gaseous output. This hypothesis could not be tested, because the experiments could only be conducted at two different temperatures and smoke occurred at both temperatures.

In the first step, a thermogravimetric analysis of the blade samples was conducted. The target of this experiment was to determine the degradation temperature of the wind
turbine blade material. This is the temperature necessary for the thermoset to separate from the glass fibers. Depending on where the sample of the blade came from, the decomposition temperature would vary. The samples containing the glass fibers reinforced with plastic all have a similar maximal decomposition temperature at around 380 °C.

When the second part of the experiments was conducted, the intention was to find out if a molten salt pyrolysis could be conducted. If the material turns white after heating it in the molten salt, the pyrolysis process would have been successful and the separation of the glass fiber and the plastic matrix is completed. Several setups had to be tested before an actual experiment could be conducted. The first trial was done with a heating wire connected to a power supply, but the necessary temperature was too high and the heating wire broke. The pyrolysis was tested with three different furnaces and it was not possible to conduct more than one pyrolysis with all of them. This led to only one experiment being conducted successfully at a furnace temperature of 400 °C and one partial experiment at 450 °C. Nevertheless, one sample could be successfully pyrolyzed.

The reaction occurred after 15 minutes at a furnace temperature of 450 °C and the actual temperature of the molten salt was at 400 °C. It would be necessary to conduct further experiments to find the optimal temperature, where the reaction occurs the fastest and with the least amount of smoke being emitted in this process. Due to the difficulties with the furnace, it was not possible to conduct further experiments. The difference in the smoke emissions between the two temperatures had to be estimated with a visual examination. This would have been more accurate by measuring the gaseous emissions of the process with a gas analysis.

When looking at the financial aspect of this process, a general overview has been created of the costs of the process. This calculation does not include the costs of the machinery or the costs of the hours necessary for the process. As expected, the costs for the shredding process are the lowest and the value of the recyclate is currently the highest. The recyclate of the molten salt pyrolysis is not established on the market yet, so a selling price could not be found. However, the costs for the process are around 1600 times higher than the conventional pyrolysis and around 31'000 times higher than shredding the material. This calculation was done based on the trials in the laboratory. Comparing the costs of the commercial processes for the mechanical recycling and the conventional pyrolysis with the costs of the molten salt pyrolysis conducted in the laboratory does not yield very accurate results. In the future, the molten salt pyrolysis should become cheaper when applied to a larger scale and the recyclate of this process could be sold at a higher price when a market for the recycled glass fibers has been established. The process could be made more affordable when using cheaper molten salts. Different molten salts that do not contain lithium nitrate should be tested in order to lower the costs.

In further research, it would be necessary to look into how the strength of the fibers would change in this process. Plus, it would be beneficial to know what the gaseous output of this process would be. When the deterioration of the fibers is small and the
gaseous output can be minimized, a possible market study for recycled fibers could be established. At this moment, the biggest market for fibers is in the cement production industry, but they do not need good quality fibers, so they mostly buy mechanically treated fibers. A possible market could be the insulation industry or even the wastewater treatment industry to build structural materials [67]. What can be said is that the market for recycled glass fibers will increase in the next few years and there will be a need for good-quality recycled glass fibers. The production industry of wind turbine blades should also be re-focusing on using biodegradable materials instead of glass fiber reinforced plastic in order to simplify the recycling process. This would solve the problem in the future but not the recycling problem that occurs with the current materials used for wind turbine blades.
Bibliography


[7] Brendan LaChance [2019], ‘Wind turbine blades will generate about $675,000 at Casper landfill ’. 


URL:  www.elsevier.com/locate/jaap


**URL:** https://www.youtube.com/watch?v=CCME0FjHCo, Access : 22/05/2023


[18] *FiberEUse* [n.d.].
**URL:** http://fibereuse.eu/, Access: 10/03/2023


[27] IRENA [n.d.], ‘Wind energy’.
URL: https://www.irena.org/Energy-Transition/Technology/Wind-energy, Access:22/05/2023


URL: www.mtixtl.com, Access:10/07/2023


[37] Lucena, J. D. A. Y. and Lucena, K. A. [2019], ‘Wind energy in Brazil: An overview and perspectives under the triple bottom line’.


[53] Qiao, Y., Das, O., Zhao, S. N., Sun, T. S., Xu, Q. and Jiang, L. [2020], ‘Pyrolysis kinetic study and reaction mechanism of epoxy glass fiber reinforced plastic by thermogravimetric analyzer (Tg) and tg–ftir (fourier-transform infrared) techniques’, Polymers 12(11), 1–16.

[54] Rani, M., Choudhary, P., Krishnan, V. and Zafar, S. [2021], ‘A review on recycling and reuse methods for carbon fiber/glass fiber composites waste from wind turbine blades’.


[63] Siemens Gamesa [n.d.], ‘Behind the scenes of the onshore RecyclableBlade project’.

[64] *SNOL 8,2/1100 LSM01 | SNOL [n.d.]*.


[67] Strongwell [n.d.], ‘Fiberglass Products for Water and Wastewater Treatment’.


© Uppsala University Kerstin Benz

[71] Types of thermocouples | Learn about and compare Thermocouple Types [n.d.].


[73] Vattenfall commits to landfill ban and to recycle all wind turbine blades by 2030 - Vattenfall [n.d.].


URL: https://simple.wikipedia.org/wiki/Tensile_strength, Access: 20/03/2023


[77] Wind industry calls for Europe-wide ban on landfilling turbine blades | WindEurope [n.d.].
URL: https://windeurope.org/newsroom/press-releases/wind-industry-calls-for-europe-wide-ban-on-landfilling-turbine-blades/, Last accessed

[78] Wind turbines are getting old. What happens to the ageing fleet? - Down to Earth [n.d.].


[81] Xinhua [2023], ‘Sweden to face soaring electricity prices for another winter: expert’. 
URL: https://english.news.cn/20230704/d8f14a0911744b5783189668a864ed24/c.html, Access:28/08/2023


[86] Youtube [n.d.].
URL: https://www.youtube.com/watch?v=lNS7TwWmlrg, Access:13/06/2023
