RECYCLING WIND TURBINE BLADES

A study into the possibilities of implementing pyrolysis as end of life solution for glass fibre reinforced composties from wind turbine blades in the Port of Rotterdam.

Graduation thesis

MSc Industiral Ecology

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A STUDY INTO THE POSSIBILITES OF IMPLEMENTING PYROLYSIS AS END OF LIFE SOLUTION FOR GLASS FIBRE REINFORCED COMPOSITES FROM WIND TURBINE BLADES IN THE PORT OF ROTTERDAM

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Abstract

Driven by the energy transition from fossil fuels to renewable energy sources aimed at mitigating global warming, the wind energy industry has increased significantly in the past decades. Until now, most research on renewable energy production is concentrated on increased efficiency and capacity and less attention is paid to possible secondary effects of the renewable energy production. The composite waste from wind turbine blades is becoming an increasingly important environmental issue for which innovative end-of-life (EoL) solutions are needed. This study aims to investigate to what extent the recycling of glass fibre reinforced composites from EoL wind turbine blades (WTB) by the means of a pyrolysis process can create environmental benefits within the context of the Port of Rotterdam (PoR) in the coming 5 to 10 years. An explorative study provided a better understanding of the concepts based on combination of academic knowledge (desk study) and practical experiences (field study) and was used to define three hypothetical EoL scenarios for WTB including landfill, cement-kiln and pyrolysis. A comparison analysis considering these scenarios showed that pyrolysis could deliver both environmental and economic benefits, providing that the majority of the pyrolysis products find high-value secondary applications and that the combustion of the pyrolysis oil as fuel oil is avoided. Although the extent of the environmental benefits that could be created by the implementation of pyrolysis remain uncertain, the presented results indicate that pyrolysis could form an early step in a larger, long-term transitional movement towards a carbon-neutral and circular economy. Based on these findings the PoR is recommended to adopt a participating or pioneering role in this transition, enabling technology optimization for pyrolysis and investing in cooperation with a network of (future) stakeholders.

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Glossary

CF	carbon fibre
CFRC	carbon fibre reinforced composites
CE	circular economy
CK	cement kiln scenario
DCP	Dutch composites polymers (organization)
EoL	end of life
EuCIA	European composites industry association
EUW framework	European Union Waste framework
EWEA	European wind energy association
FRC	fibre reinforced composites
GCV	gross calorific value
GF	glass fibre
GFRC	glass fibre reinforced composites
IE	industrial ecology
LCA	life cycle analysis
LCT	life cycle thinking
LF	landfill scenario
NF	natural fibre
NFRC	natural fibre reinforced composites
NRK	Nederlandse Rubber en Kunststoffenindustrie, Federation for Dutch Rubber and Plastics Industry
PMC	polymer matrix composites
PoR	Port of Rotterdam Authority, Havenbedrijf Rotterdam
PYR	pyrolysis scenario
R&D	research and development
SRF	solid recovered fuel
TRL	technology readiness level
WTB	wind turbine blade

Introduction

Energy transition and composite materials

Driven by the threat of excessive global warming and resource scarcity, our society is looking for alternative approaches to sustain our way of life on this planet. For that reason, various transitions are needed in our energy system and our use of materials and land. The current linear economic system will have to evolve towards a more circular system. In a linear economy, products and materials are produced, used and discharged, spoiling valuable resources and creating a lot of harmful emissions. In a circular economy, products are designed to be repeatedly used and to allow an easy recovery of used materials, in order to limit the emission of greenhouse gases and the waste of necessary resources.

One of the main transitions is taking place in the field of energy production. Renewable alternatives to fossil fuel-based energy production technologies are being developed, both to reduce greenhouse gas (GHG) emissions as well as to ensure future energy supply even without the use of fossil resources.

Wind energy has become one of the most popular and successful renewable energy alternatives. This energy sector grew vastly in the past decades. Both in reach as well as in scale of the wind turbines used to generate electricity. Although subsidies for renewable energy projects are abundant, to be able to compete with the established fossil fuel energy market, efficiency, production costs and quality play an important role in the development of the wind turbine as we know it today.

Composite materials have played an important role in the development of wind energy generation. The favourable characteristics of composite materials and the possibility to tailor complex composite materials for a specific application makes them very suitable for the production of wind turbine blades (WTB). Currently, WTB are generally made of a composite with glass fibre reinforcement combined with a polyester or epoxy resin. This creates a material that allows great form freedom (read: aerodynamics), stiffness to withstand both dynamic and static forces created by the wind and is lightweight and thus improves the efficiency of electricity production. The Dutch ministry of Economic Affairs and Climate therefore identified composite materials as “key technology” in the energy transition (DCP & Ministry of Economic Affairs and Climate, 2018).

Circular necessity

However, it is important to take notice of side effects of new technologies. New technologies are mostly designed and developed to solve one problem. But there is always a risk that they may create new and unforeseen secondary problems in the future. For example, in the 20st century many technologies where being developed to facilitate an efficient and profitable production and transportation of goods. For a long time, no one was thinking about the huge amount of fossil fuels that were needed by the use of these technologies, nor about the accompanying greenhouse gas (GHG) emissions.

Today, when it comes to the design and production of renewable energy technology, most attention is concentrated on delivering power. Less attention is paid to possible secondary effects of the technology.

Wind energy has proven to be a suitable alternative to fossil fuel-based energy. With the urge of reaching the GHG emission reduction goals as defined in the Paris agreement (2015), (inter)national governments put their stakes on the large-scale implementation of this kind of energy production. The many publications focus on technological improvements and economic benefits. But until now less attention is being paid to the question of what will happen to all the thousands of kilos of composite materials used in wind turbines, once they reach their end-of-life (EoL) stage. Will they end up as environmentally unfriendly waste or will there be huge costs to burn them? This question is also relevant, because our society wants to stimulate circular use of materials. Up till a few years ago, only minimal research was done into the field of recycling wind turbines including wind turbine blades made of almost non-recyclable composites. But, due to the fact that in relatively short time from now, the first large wind parks will reach their EoL after 15-20 years, releasing vast amounts of EoL WTB material, the first outlines of this problem have become clear. Lately this issue is drawing increased attention from researchers, technicians, businesses and possible investors, who are looking into the development of circular design and re-use potential of wind turbine blades. In this report it will be referred to as the *composite waste issue* in short.

Port of Rotterdam

Amongst others, the Port of Rotterdam Authority (PoR) has shown interest circular economy principles and has created a circular vision for their own business in order to become a carbon-neutral port area. Circular economy practices focus on a high-value EoL solution for “waste” streams. Output material from one process can serve as input for another process. Becoming a pioneer in circular solutions for composite material can deliver both commercial benefits and contribute to a more circular flow of materials in the port. The PoR aims to reach these goals preferably with opportunities that link with existing activities in the PoR, which put suggests a focus on EoL solutions related to the existing chemical cluster.

The PoR perceives the increasing EoL material flow of composites as an interesting issue to further investigate considering circular and business purposes. Therefore, they proposed the possibilities of composite recycling and the potential role of PoR as research topic for a master thesis. The thesis research project included a four-month internship at the business management department of ‘Process, Industry and Bulk Goods’. This internship helped to give insights in the strategies and business approaches of PoR, the focus of business opportunity analysis and provided knowledge about existing projects that could be related to the topic.

Report

This document reports the methodology, findings and conclusions of this thesis research project that aims to investigate to what extent the recycling of glass fibre reinforced composites from EoL wind turbine blades by the means of a pyrolysis process can create environmental benefits within the context of the Port of Rotterdam.

The first part of the report explains how the research question was defined, based on the approach that was taken on for this project and introduces the research questions that were defined. The research strategy and methods are introduced in the second part of the report. The research was divided into two phases. First, desk and field study led to a better understanding of the relevant concepts, these findings are presented in Part III of this report. Secondly, a comparison analysis considering three hypothetical EoL scenarios is reported in the fourth part of the report. The final part evaluates the findings. This includes a discussion of the results, recommendations for further research, a proposed advice for the PoR and a final conclusion.

PART I
APPROACH

Following a general introduction of the considered case, this part aims to explain the adopted approach to the case which led to the defined research question. The significance of both the context of the Port of Rotterdam and the scientific field of Industrial Ecology to the research are explained. Thereafter the research questions are introduced in the final chapter of this part.

1 Context of the Port of Rotterdam

This research is conducted for the Port of Rotterdam Authority (PoR) therefore their perspective is of importance to the approach that is adopted for this research. This chapter elaborates on the current business and future strategies of the PoR. Based on findings from the preliminary research recapped in this chapter, the meaning of this perspective to the research is indicated.

1.1 General

The port of Rotterdam is one of largest seaports of Europe with an annual transhipment of 467,4 million tonnes of goods (Port of Rotterdam, 2018b). Because of its strategic geographical location, the PoR is a hub for international flows of goods, hosting vessels from all over the world and engaging with other large international ports. The terminals in the port allow transhipment of containers, unit loads, dry bulk and wet bulk goods. The port of Rotterdam is also home to a large chemical industrial cluster and a variety of other processing industries. The revenue model of the PoR is based on the exploitation of plots and the facilitation of transhipment movements. This business includes core activities that range from the exploitation of the industrial area's and maintenance of the port utilities to port wide strategy development.

1.2 Future Strategies

To keep up with the changing world around them and to be ahead of developments that will affect their business, the PoR defined a future strategy, including a vision to the issue of climate change considered with CO_2 emissions. Because of the large chemical-industrial sector located in the port areas, the PoR is a major CO_2 emitter in the Netherlands as it accounts for 17% of the total Dutch emissions (Port of Rotterdam, 2018a). In 2018 the Port of Rotterdam created its vision "Port of Rotterdam, CO_2 neutral" (Port of Rotterdam, 2018a), presenting 4 scenario's and goals towards a CO_2 neutral port in 2050 (Figure 1-3). It describes the inevitable contribution to the goals defined in the International climate agreement of Paris (2015).

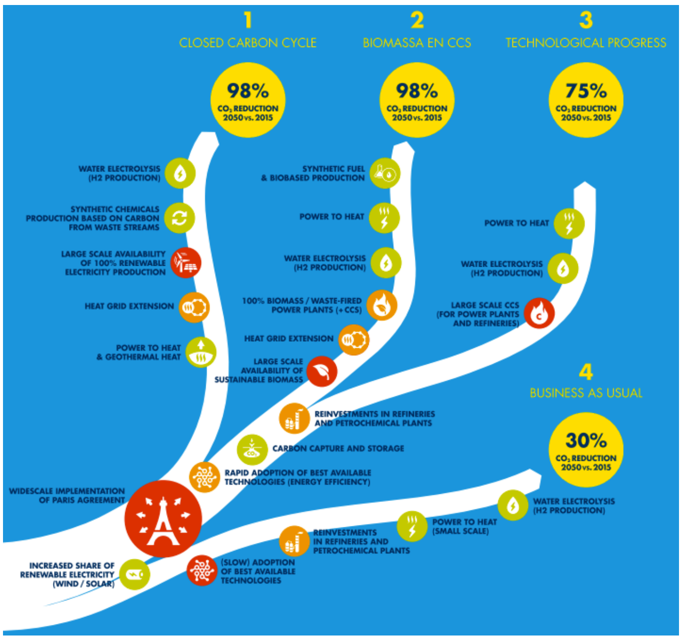

Figure 1-1: Four different scenario's with measures towards a CO2 neutral port (Retrieved from Port of Rotterdam (2018a).

Establishing circular economy principles is one of seven development directions from this vision. PoR aims to be a hub for the re-use of materials. According to the vision waste should become an input, materials and cycles should be closed as much as possible in such a way that only a minimal amount of virgin material has to be added to the cycle (Port of Rotterdam, 2018a). Also, utilized energy sources should be as renewable as possible. The incineration of waste to generate energy should only happen when the waste product has no higher value application (Port of Rotterdam, 2018a).

Another aspect of the PoRs' future vision is the aim to give room to newly emerging businesses that contribute to goals such as circularity between industries and CO_2 reduction. This is strengthened with the shift towards a more CO_2 neutral society and port, which implies that big fossil fuel-based companies located in the port, such as coal and oil transhipment, will scale down in the coming decades and more room becomes available for other industries. However, the presence of a large fossil-based industry is perceived as a source of valuable insights and acting power in this transition, which could be used to execute the transition in an effective and economic way (Port of Rotterdam, 2018b). Since the PoR is a large player in the Dutch economy on which many people and companies rely upon, a sudden change of strategy should be prevented. Therefore, PoR aims for a gradual transition that in the meantime respects existing agreements with current (fossil-based) clients (Port of Rotterdam, 2018b).

1.3 Business Opportunity Analysis

In line with their future vision, the PoR is constantly looking for business opportunities that could contribute to the goal of becoming a CO_2 neutral port. Criteria that help business managers to decide if and how to continue with the development of an opportunity, are summarized Box 1 and schematically depicted in Figure 1-3. A new business should fit in the chain of activities in the PoR and preferably contribute to it or initiate a new chain of activities. A positive assessment on this point will contribute to the revenue model as well.

To assure there is a solid business model for the new opportunity it is important to consider all of the three key elements of the chain; the feedstock market, the process itself and the sales market. Firstly, the feedstock market is subjected to the availability of the EoL material flows, the valuation of the EoL material and the presence of competition. Additionally, the accessibility of the composite material within the EoL flow fluctuates between the industries that the EoL materials flow from. Secondly, the process can be assessed on its technology readiness level (TRL), the quality of the output product and the progress of competitive technologies. Lastly, the whole effort of conducting the process is useless if there is no potential market for the output product. This market potential is based on the quality of the output product as well as on the presence of competition. It should be noted that competition in this case is a very broad; it stretches from competitors that produce the same output product to competitors that produce another product but aimed at the same purposes.

Due to the consecutive developments in the field of composite production and recycling it is important to make future predictions of the business model too. Criteria such as the ones mentioned before change over time due to the emergence of new competitors on the market.

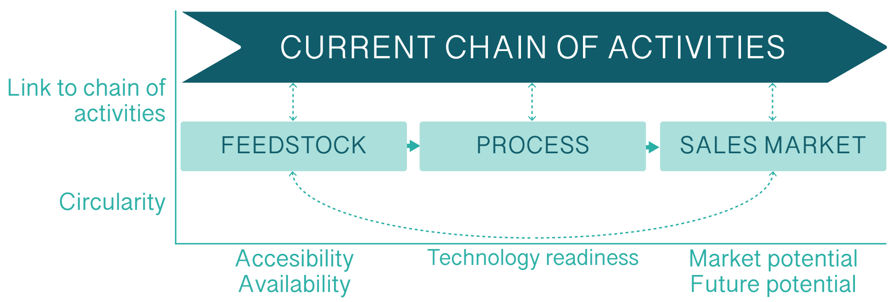

Figure 1-3: Schematic overview of business opportunity criteria (in orange) following the context of the PoR.

- Link to chain of activities
  The relevance of the opportunity is based on the potential contribution to current or new chain activities in the port areas. This includes fruitful cooperation with current located companies.
- Availability
  For a new business it is important to have reliable and accessible feedstock. The availability of the feedstock is dependent on the EoL material flows that are released by the industries. This availability can be further specified by the quantification of flows from specific industries and/or their geographical occurrence.
- Accessibility
  The accessibility of the feedstock flow is intertwined with the availability of the EoL material flows because the accessibility is also determined on the geographical occurrence of the flows. However, accessibility also in this case the accessibility of the composite material within its EoL volume flow is assessed. For example, in electronic goods the composite is often mixed with other materials and it takes a lot of effort to separate them.
- Technology Readiness Level
  Technology readiness is based on the maturity of the EoL technology development. This is based on the efficiency of the process, the quality of the output product and how the performance relates to comparable technologies.
- Market Potential
  Includes the presence of a sales market for the output product considering competitive co-producers and products.
- Future potential
  Assesses whether there is room for optimization of the technology (use) and how future feedstock and sales markets might evolve.
- Circularity
  Assessment of how the opportunity contributes to a circular economy (in the port). By for example minimizing waste outflow and virgin material input of one or more processes. The aim is always do devaluate as less as possible.
- CO_2 reduction (potential)
  Even though this is hard to grasp, it is important to touch upon; not easily assessed by any means, thus hard to use as a criterium.

Box 1: Selected list of criteria based on the context of PoR

1.4 Perspective translated to the research

The predicted release of large volumes of composite materials in the coming years is perceived as possible business opportunity to the PoR. Besides, tackling the recycling issue of composite material and finding a more circular solution fits within the circular economy development programme. Therefore, the PoR proposed an initial study into the possibilities of recycling composite and the potential role of PoR as a research topic for a master thesis.

The focus of the study was narrowed down to the recycling of end-of-life (EoL) Glass Fibre Reinforced Composite (GFRC) material from the wind energy industry by the means of pyrolysis based on the criteria following the company's perspective as introduced in Paragraph 1.3.

Most of the composite material from the wind energy industry is GFRC. This is currently the most frequently used type of composite used in WTB. The wind energy sector and especially the offshore wind energy sector is easily linked to activities in the port. Also, the growing wind energy industry will deliver an increasing and continuous flow of EoL composite material in the coming years. Pyrolysis was selected as the EoL solution to focus on because of the potential link to the current chain of activities of the chemical cluster. A second reason to focus on this technology was that pyrolysis cluster that aims to cooperate on the implementation and development of pyrolysis processes in the port of Rotterdam for all kinds of purposes, is already existent in the PoR.

2 Industrial Ecology perspective

This chapter elaborates on the Industrial Ecology perspective and how the approach adopted for this research relates to it. Additionally, the definition and assessment of environmental benefits based on this perspective are elaborated.

2.1 Industrial Ecology analogy

Industrial Ecology (IE) is a scientific field that takes an interdisciplinary approach to sustainability problems by combining engineering, environmental and social perspectives to enhance sustainable development. IE is often described by the analogy between natural and industrial process cycles. Where natural processes make use of closed cycles where waste from one process is input for another, there is a potential to also apply these circular principles to social-technological processes. By learning from these natural processes in the biosphere, our society can design and manage the socio-technological processes in a more sustainable manner. Compared to the current system where resources are exhausted and useless waste streams are produced, implementing IE theories may eventually facilitate an enhanced technological evolution towards a more efficient system in terms of material and resource usage. In practice, the aim of this perspective is translated into the pursue of a more circular economic system.

2.2 Definition of environmental benefits

Circular economy (CE) measures aim to lengthen the lifespan of a product by making it suitable for repair, repurpose and/or reuse and eventually, aim for a well-considered design to enable recycling of materials in the product. This will ultimately lead to a reduction of materials and resources usage and associated GHG emissions over the total lifespan of a product. This includes the energy and resources necessary for mining, processing and transportation steps required for the commissioning, decommissioning, reuse and EoL treatment of a product. Environmental benefits are often described along the lines of impact categories such as greenhouse gas (GHG) emissions, acidification and land use.

Pitfalls

When assessing the potential effects of changes in processes and products on the total economic and social system, it is important to check whether these changes will indeed bring improvements to the climate and other environmental aspects. Good intentions may have a contradictory impact or only shift or delay the problem that needs to be solved this is sometimes referred to as the rebound effect.

Another pitfall is a potential change that only shifts the environmental impact to another (part of the) product chain or delays the occurrence of it. For example; a recycling facility reduces the energy use of its process by adding a catalyst. It should be avoided that this catalyst causes an acidification of the waste water of the recycling process that has negative side effects such as; the water treatment plant is forced into additional energy use higher than the initial reduction or the soils absorb the polluted water and effects local environment over time.

2.3 Perspective translated to the research

The PoR is interested in treatment possibilities for the large volume flow of EoL material from (amongst others) the wind energy industry from a business perspective. At the same time, the circular aspirations of the PoR match with the aims of industrial ecology theories, which makes this a relevant IE case study. The reasoning and considerations that come across during the search for a solution to the case study of the PoR can serve as reference for similar challenges in other industrial systems or areas.

Overarching goal

Based on the IE perspective, the focus of the research lies on striving for circularity. The ultimate goal of a 100% circular product system for WTB would ask for optimizations in the design of WTB, such as design measures that enable the product to be repaired, and the materials to be repurposed and reused.

Present state

Unfortunately, current installed WTB's are not designed for reuse and repurpose. Therefore, the second-best aim is to ensure that they can be recycled properly and that the materials can be reused as much as possible. The environmental benefits that can be created by an IE approach with respect to EoL WTB are therefore related to the minimization of wasted material, the prevention of using WTB in landfilling and the retrieving of high-value reusable materials. The assessment of these environmental benefits should also include the total system accompanying the EoL solution. Thus, for instance, it should also look at the impact of the energy and resources which necessary for the processing and transportation of materials in the total chain.

3 Research objective and questions

This chapter introduces the research objective and scope and explains briefly how these were formed. This is followed by the introduction of the main research question and accompanying sub-questions.

3.1 Research objective and scope

This research aims to analyse to what extent recycling of GFRC materials from EoL WTB by the means of pyrolysis could contribute to the circular economy goals of the PoR and if it has potential to deliver environmental and/or economic benefits compared to the current situation. The research aims to give insights in existing knowledge about GFRC material and the use of it in WTB and in the current state of development of the pyrolysis technology. Additionally, the aim is to get a better understanding of the (dis)advantages of the pyrolysis technology relative to existing, more mature technologies and to find out how implementing pyrolysis could create both environmental and economic benefits compared to the current situation.

The time horizon of the research is defined at 5-10 years. Bearing in mind this timeframe, the research considers the pyrolysis technology at the current level of development and the composite material as existent in currently installed WTB. Predicted developments in both technology and material improvements will be considered at in quick glance. The geographical scope of the research is not specifically included in the research question. Even though the PoR is an international oriented company, the approach for this research is to avoid pointless transportation, suggesting a more local or regional geographical scoping area such as North West Europe.

3.2 Research questions

Based on the research objective the main research question is defined:

“To what extent can the recycling of GFRC from EoL WTB flows by the means of a pyrolysis process create environmental benefits within the context of the PoR in the coming 5 to 10 years?”

To be able to answer this question, a set of sub-questions is defined. Answering these helps answering the main research question. These sub-questions also serve as a guiding structure for the reporting of the results in Part III.

- How much GFRC material is flowing from EoL WTB in the region of the PoR?
    - What are the characteristics of composites in general?
    - What is the material content of EoL WTB?
    - What are the predicted volumes of blade waste from EoL WTB?

- What are possible solutions for the EoL treatment of GFRC?
    - What are available EoL solutions for composite material and GFRC in particular?
    - Which of these technologies allow for large scale implementation in PoR in the near future?

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- What are the details and possibilities of the pyrolysis technology?
    - What are the technological characteristics of the pyrolysis of GFRC? Including the working principle, requirements, output products and limitations of the technology.
    - How could output products be reused, preferably linked to the chain of activities in the PoR?
    - What is the predicted development of this technology in the near future?
    - Would the technology also be suitable for the treatment of carbon fibre reinforced composites and hybrid composites?

- What benefits can be created by the implementation of pyrolysis compared to the existing and/or more matured solutions?
    - What are the *environmental and economical* (dis)advantages of pyrolysis compared to these other EoL solutions?
    - Which impact categories should be considered while comparing different solutions?

PART II
METHODOLOGY

This part starts with the introduction of the strategy that was used conducting this research including an explanation of the individual steps and their coherence. The second chapter explains the two methods for data generation and how these were combined. Lastly, the method used for the evaluation of the data using two different scenarios is explained.

4 Research strategy

This chapter elaborates on the steps taken to reach the conclusion. The strategy that is applied for this research can be divided into two phases.

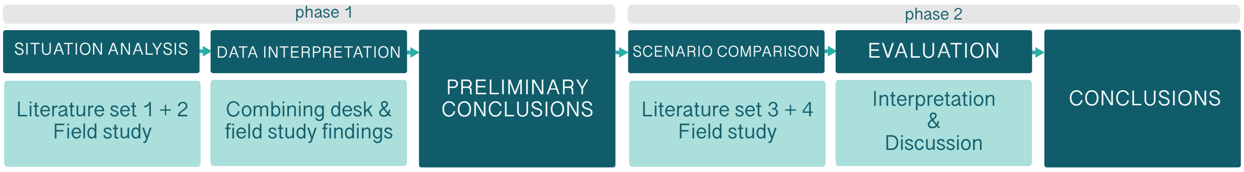


Figure 4-1: Schematic overview of the research strategy applied to this project.

4.1 Phase 1: Understanding the concepts

This phase aims to provide answers to the first three sets of sub-questions by evaluating research publications and interviewing experts in the field. This entails creating insights in existing knowledge about both the GFRC material characteristics and their appearance in the wind energy industry and summarizing the possible EoL solutions for GFRC. As well as explaining the pyrolysis process in detail and giving insights in the process requirements, output products and their potential applications (with a focus on the PoR). Data from both the field and desk study is used, this combination of academic knowledge and practical experiences provides a complete understanding of the context that helps to translate the findings to the case of PoR. The first phase concludes with a preliminary conclusion that can be used to formulate a scenario of the implementation of pyrolysis for GFRC in the PoR (*the pyrolysis scenario*).

4.2 Phase 2: Scenario comparison

The second phase focuses on finding answers to the last set of sub-questions. Three scenarios will be assessed on the set of criteria and compared to each other; the *business-as-usual* scenario, the *pyrolysis* scenario and a *reference* scenario considering landfill. The set-up of this comparison analysis is considered part of the study and is explained in Chapter 6. Ultimately a conclusion is drawn from the results of this phase that answers the main research question.

5 Data collection

The data for this research comes from two types of data resources. For both resources: a desk study and a field study. For both resources the data retrieval method is explained in this chapter.

5.1 Desk study

Desk study was used in both stage 1 and 2 of the research strategy. Four sets of literature where formed, based on the sets of sub-questions, see

Table 5-1. Each of these sets is used to provide answers to a set of sub-questions.

Each set is composed by a series of search attempts, combining different search terms and academic databases and search engines. An overview of the search terms that were used per literature set is given in Table 5-1, more detailed information about the datasets and search terms can be found in Appendix A. *Scopus* is the primary used academic search engine for this research, also the database of the *TU Delft Library* was used and to a lesser extent also *Google scholar*.

SET	GOAL	SUB-QUESTIONS	SEARCH TERMS	NR # PAPERS
		How much GFRC material is flowing from EoL WTB in the region of the PoR?		
1	Expand knowledge on technical characteristics of WTB	What are the characteristics of composites in general? What is the material content of EoL WTB? What are the predicted volumes of blade waste from EoL WTB?	"composite waste"; "glass fibre reinforced"; "wind turbine blade waste"; "structure"; "materials"; "characteristics" "wind energy"; "wind turbine blades"; "manufacturing" "glass fiber composite recycling"; "composite recycling" "end of life"; "decommissioning" "end of life"; "decommissioning" "wind energy industry"; "europe" "review"; "current status"; "outlook"; "developments"	8 to 10
		What are the details and possibilities of the pyrolysis technology?		
2	Expand knowledge on technical characteristics of pyrolysis	What are the technological characteristics of the pyrolysis of GFRC? Including the working principle, requirements, output products and limitations of the technology. How could output products be reused, preferably linked to the chain of activities in the PoR? What is the predicted development of this technology in the near future? Would the technology also be suitable for the treatment of CFRC and hybrid composites?	"recycling"; "recycling technologies"; "pyrolysis"; "end of life" "composite materials"; "fibre reinforced polymers"; "glass fibre"; "polymer matrix composite"; "thermoset"; "epoxy" "mechanical properties"; "products"; "gas"; "oil"; "energy" "circular economy" "review"; "current status"; "outlook"; "developments"	8 to 10
		What benefits can be created compared to the current situation?		
3	Selection of environmental and economic criteria	Which impact categories should be considered while comparing different solutions?	"life cycle assessment"; "LCA"; "impact categories"; "environmental impact"; "comparative study" "cement kiln"; "recycling" "GHG emissions"; "CO2 equivalent"; "energy (use)" "wind turbine blade"; "materials" "landfill"; "inceneration"; "pyrolysis"; "current state"; "developments"	3 to 5
4	Collecting data for each	What are the environmental and economical (dis)advantages of pyrolysis compared to these other EoL solutions?		2-5 per criterium

Table 5-1: Overview of the datasets for the literature study including the proposed size and content of each set.

Papers were found by searching for terms in the Title, abstract or keywords of a documents. Search terms are combined with the AND and OR commands to specify the search results. When a search still gave a list of more than 50 articles, a secondary search step was conducted to limit the resulting documents with the tools of the search engine. *Scopus* offers the option to search within the results with a secondary search term. For example:

Search 1: "recycling" AND "fibre reinforced composite materials" Results: 275 documents
Search 2: "pyrolysis" AND "glass fibre" Results: 34 documents

Scopus also allows to refine the search results in different categories such as year of publication, subject area, journal title and language with the option to "limit to" or "exclude" items from a predefined list. These predefined lists also show you how many papers are considered in that specific categories that you can limit or exclude from your search, already giving an indication of the impact of your action.
For example:

Search 1: "recycling" AND "fibre reinforced composite materials" Results: 275 documents
Limit to year: 2019,2018,2017,2016,2015,2014,2013,2012,2011
Limit to subject area: Materials science (220), Engineering (152), Environmental science (12)
Results: 108 documents

Another method for searching papers is redirecting via other papers, especially the ones identified relevant for the literature set. References of these papers also served as input for other additions to the literature set. This is also stimulated by *Scopus* by indicating related documents for each document.

In general, no papers older than 10 years were considered, however for some basic knowledge, for example about composite material in general, older papers were included. The fields of material science, environmental science, engineering and chemical engineering are mostly used as subject areas. Four journal titles that appear more than once in the list of references are: 'Waste management', 'Resources Conservation and Recycling', 'Reinforced Plastics' and 'Renewable and Sustainable Energy Reviews'.

When a list of less than 50 papers resulted from the search, the titles in the list were scanned. When a title was identified as relevant, the reading the abstract and scanning the content of the paper helped to decide whether the paper could be added to the literature set. When a couple (3-5 papers) were selected for the set, these papers were read carefully, and main findings were summarized in a literature matrix, which helps to structure and analyse the information given on specific subjects by different authors and to identify missing information or knowledge gaps. Thereafter the search was continued until the set was filled satisfactory.

5.2 Field study

Field study is mainly used in the first phase of the research. The data collected in the field study serve as a supplement to the data found in the desk study. Opinions and perspectives of people that are closer to the practicalities are considered to be interesting sources of information. It provides insight in the sentiment around the composites recycling issue in the field.

The field research existed of both the attendance of events as well as conducting informal interviews with people from various fields interesting for the topic. The information gathered from both the events as well as the interviews can be categorized in 5 topic categories: composite materials in general and the plastic industry, wind energy industry, manufacturing, design and material of WTB, EoL solutions for composite material and finally the pyrolysis process. Table 5-2 gives an overview of all the items of the field study and their corresponding topics, an elaborate overview of the events and interviews, including the main take-aways from each item, can be found in Appendix B.

Table 5-2: Overview of the field study elements and their topics.

	COMPANY / ORGANIZATION	composite (plastics) industry	wind energy industry	WTB design & material use	EoL alternatives
EVENTS					
Branche workshop	Sirris			X	X
DCP Consultatie	CompositesNL	X			
INFORMAL INTERVIEWS					
Wim Robbertsen	Business in Wind		X	X	X
Martin Dijkstra	Emergyia Wind Tech.		X	X	X
Frans van der Wel	FiberCore	X			
Albert ten Busschen	Windesheim				X
Julie Teuwen	TU Delft			X	X
Martin van Dord	NRK	X			X
Novita Saraswati	ECN by TNO		X		
Richard IJpma	Suwotec				X

5.2.1 Events

Two events that were attended also contributed to the data generated in the field research.

- Composites in Offshore Industries Workshop organised by the consortium of Agoira, Sirris, Go4Circle and OWI lab (Flanders innovation and entrepreneurship) in Ostend (Belgium) on 11th of September 2018. The goal of this event was to inventory end of life options for large composite structures in 2-3 years within the scope of decommissioning, logistics, pre-processing and valorisation based on developments of partners of the consortium.
- Dutch Composite Polymers (DCP) Consultation for the National Agenda organised by trade organisation CompositesNL and the Dutch ministry of economic affairs and climate in Bunnik on 17th of September 2018. There were two goals set for this event: first, the aim was to initiate a platform within the DCP industries to streamline research and development results. Secondly, in cooperation with the ministry, a national agenda should be defined, including the focus of the DCP industry for the coming years.

The preparation of the event included a quick scan of the event, organising companies/organizations, the programme and previous editions. During the event notes were taken and during the interactive workshop and respectively brainstorm session the team members were also questioned informally about their (companies) activities and their perspective on the recycling issue of composite material.

Right after the interview, notes were structured and elaborated in a summary. Additionally, the main take-aways from the day summarized. Appendix 0 includes the summaries for both events.

5.2.2 Interviews

The goal was to talk to at least 5-10 experts with various backgrounds and specialties. The interviews were arranged by contacting supposedly interesting parties. In total 8 interviews were conducted, they can be identified as informal interviews. The setting of the interviews varied between skype-calls, one-to-one talks and conference meet-ups.

The preparation for each interview included the set-up of a profile of the interviewee and a topic list (based on the expertise of the interviewee). The topic list served as guidance during the interview, making sure to cover all the topics of interest. Not all the topics were covered in each interview, because they were not relevant for each specific interviewee.

Right after the interview, a conversation summary was made based on the material from the meeting including notes and sometimes audio recordings and/or materials delivered by the interviewee (such as research reports etc.). This conversation summary was concluded with a shortlist of main take-aways from the conversation. Finally, the conversation summary including the main take-aways was send to the interviewee for verification. These conversation summaries can be found in Appendix B-III.

6 Scenario comparison

Phase two aims to answer the main research question and consists of a scenario comparison. This chapter describes the approach of this comparison, the set-up and the method for comparative analysis.

6.1 Approach

From the extensive analysis of phase 1 follows a potential development direction of the pyrolysis technology. However, to be able to answer the research question in terms of "To what extent environmental benefits can be created?", a comparison with the situation without interference is necessary. Therefore, a scenario comparison will be set up. Defining the comparison set-up, including the selection of comparison criteria and definition of the comparison case, is part of the process.

6.2 Defining the comparison set-up

The definition of the comparison set-up can be explained in three steps (Figure 6-1).

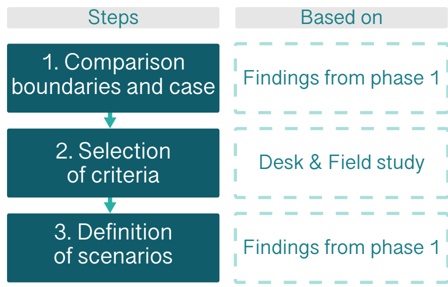


Figure 6-1: Schematic overview of the three steps that lead to the definition of the scenario set-up.

Step 1: System boundaries and case

The first step in the set-up is to define the system boundaries of the comparison and a comparison case. These elements determine the comprehensiveness of the comparison analysis. They will be based on the outcomes of the first phase.

Step 2: Selection of criteria

The second and most important step is to select the comparison criteria. To create a comprehensive comparison, the criteria will be sought for in three categories. Primarily, the emphasis lies on environmental criteria since the set of criteria should give insights into the potential environmental benefits of the pyrolysis of GFRC. Additionally, the criteria derived from the approach of the PoR will be taken into account. Lastly, also economic criteria will be considered because it is most likely interesting for a commercial company like the PoR.

For the selection of environmental criteria, the Life Cycle Analysis (LCA) impact criteria will be a source of inspiration. The LCA methodology enables to assess a scenario on a large range of criteria, called impact categories, including the whole lifespan of a product or material. Conducting a full LCA for both scenarios would provide a constructive answer to the research question. However, this is time consuming and requires detailed input data and does not fit within the time limitations of this research project. Besides, detailed information about the proposed new situation is not or very limited available since there are no comparable large scale implemented examples existent.

Findings from the first phase derived from desk study (see also Table 5-1) and field study will contribute to the identification of the set of criteria. It is expected that the final set of criteria is a mix of both qualitative and quantitative criteria. Important to notice is that the criteria should be defined in such way that the comparison is feasible in time and with assessable knowledge.

Step 3: Definition of scenarios

Based on the findings from phase 1, three scenarios will be defined; the *business as usual* scenario, considering the situation without emerging pyrolysis and the *pyrolysis* scenario, that presumes the implementation of the pyrolysis technology. Both scenarios have to be described in the same detail and thereafter will be assessed based on the same comparison case. Both scenarios differ in the type of EoL solution for GFRC that is applied. To put the results of the comparison between these two scenarios into perspective, a *reference* scenario is defined considering landfill.

6.3 Method for comparison analysis

The scenarios will be assessed on both quantitative and qualitative criteria. For the assessment of the quantitative criteria, some simplified calculations based on rough numbers from literature will be conducted. All assumptions regarding these calculations will be explained. It is expected that phase 1 will provide significantly more information about the pyrolysis scenario. Therefore, it is expected that some extra research into the EoL treatment solution of the *business as usual* scenario will be necessary. This will be the last part of the desk study (Table 5-1). For the qualitative criteria a scoring guide in the form of a rubric will be defined.

Ultimately, insights are given in the limitations of the comparison analysis and a conclusion is drawn. Because of the expected variety of criteria, the final conclusion will be draw based on evaluation and interpretation of the results. In the case of two very similar assessments for both the scenarios, criteria can be structured based on their importance by allocating weights to the different criteria.

PART III UNDERSTADING THE CONCEPTS

In this part of the report the findings of the first phase of the research are reported, creating a better understanding of the relevant concepts. Also the majority of the research questions are being answered and the preliminary conclusions following from this first phase are being presented.

7 Composites Wind Turbine Blades

This chapter aims to provide more insights into the content and size of the considered material flow in this research; glass fibre reinforced composite material from EoL wind turbine blades. Basic knowledge of composite materials and their general applications is explained. This chapter furthermore describes the structural design and material use of WTB and the development of the wind energy industry, with which the use of WTB is interconnected. Based on these elements, an estimation of the volumes of material considered with EoL WTB from the wind energy industry in Europe is given.

7.1 Composite material in general

Composite materials are built up from two or more basic materials with significantly different physical or chemical properties (Jones, 1999). Composite materials can be tailored to efficiently meet characteristics such as strength, stiffness, weight, corrosion resistance and cost, all in various directions (Jones, 1999). Jones (1999), distinguishes four categories of composite materials;

- Fibrous composite materials; that consist of fibres in a matrix
- Laminated composite materials; that consist of layers of various materials
- Particulate composite materials; that are composed of particles in a matrix
- Combinations of some or all of the first three types

The Glass Fibre Reinforced Composites (GFRC) that are used in WTB is a *fibrous composite material*. Where the fibres provide a unique set of properties such as good length to width ratio, environmental stability, uniformity, and flexibility, they are protected against abrasion and unfavourable environmental conditions by the second element, the so-called host matrix (also: resin) (Naqvi et al., 2018). Additionally, the matrix holds the fibres together and provides strength to the composite by transferring the applied load to the reinforced materials (Mittal, Rhee, Mišković-Stanković, & Hui, 2018). Below, the fibre and matrix component of composite material are further explored.

7.1.1 Fibre component

The most commonly used reinforcement fibres are glass fibres (GF) and carbon fibres (CF) (Fangueiro & Rana, 2016; Naqvi et al., 2018). There is a distinct difference between the application of glass fibre reinforced composites (GFRC) and carbon fibre reinforced composites (CFRC) as can be seen in Figure 7-1. CF is a very high quality fibre with a high strength (Naqvi et al., 2018). The mechanical properties such as yield strength and strength-to-weight-ratio of CF are higher than for GF (Cherrington et al., 2012; Mazumdar, Benevento, Pichler, Witten, & Hinrichsen, 2018). Therefore, also a smaller amount of matrix material is required for CFRCs (Cherrington et al., 2012). The production of CFs is an energy-intensive process, making CF and CFRC costly products mostly used for high-end applications such as custom (professional) sports equipment or high performance industrial products such as aerospace and aviation (Li, Bai, & McKechnie, 2016; Naqvi et al., 2018).

GF have lower mechanical properties than CF and are therefore also much cheaper. The production of GF requires less than half of the energy required for CF production (Cherrington et al., 2012). This makes GFRC a lower quality, but cheaper option compared to CFRC and it is therefore applied on a large scale in for example marine applications and WTB. With the right engineering of properties, GFRC can replace conventional construction material such as wood or steel, reducing the weight of the product significantly. This creates benefits in for example the transportation of the material (Cherrington et al., 2012). Currently GF is the most commonly used fibre for composite reinforcement for WTB (Job et al., 2016).

Noteworthy, the application of natural fibres is gaining more attention over the last decade (Fangueiro & Rana, 2016; Noryani, Sapuan, Mastura, Zuhri, & Zainudin, 2018). Natural Fibre Reinforced Composites (NFRC) use natural fibres (NF) such as flax, hemp and jute. They combine favourable mechanical characteristics such as great tensile strength and vibration absorbing properties, with low costs and a low ecological impact (Fangueiro & Rana, 2016). However, the application of NF is limited due to for example bad adhesion and degradation of the fibres above 200 °C. The potential for NF as reinforcement material lies mostly in the application in low-impact reinforcement, for example in applications in the automotive industry (Fangueiro & Rana, 2016). Although NF have gained popularity as a more sustainable, eco-friendly replacement for GF in the recent years (Fangueiro & Rana, 2016), they will not be further considered in this study because the limited current application does not present a direct urge of the recycling of this type of FRC.

Figure 7-1: Schematic overview of the application of fibre reinforced composites.

7.1.2 Matrix component

There is a wide range of materials that can be used as matrix materials, the focus of this in this research lies on the plastic polymer matrix composites (PMC). Polymers consists of long macromolecules that exists of a chain of repeated sub-units. Polymers are created by the polymerization of many small molecules, known as monomers. PMCs are especially distinguished by their low weights (Erden & Ho, 2017). This class consist of thermoplastics, thermosets and elastomers see Figure 7-1.

Thermoplastics are built up from loose molecules, that enable deformation such as melting or pulling. This allows them to be reshaped into new products and simplifies recycling (Erden & Ho, 2017). Thermoplastic composites are for example used in electrical applications and electronics or in product parts applied in aviation and automation industries.

Thermosets have crosslinked polymer chains, which create a more rigid material. The main advantage of thermosets is that they are suitable for application in more extreme conditions such as high temperature products as they do not lose structural rigidity when heated. However, because of this rigidity, thermosets are harder to recycle (Erden & Ho, 2017). Thermoset composite products appear in large product elements in for example the construction, aviation and automotive and wind energy industries. Both polyester and epoxy are common thermoset resins used for FRC. Epoxies are more complex polymer structures than polyesters, that allow for a greater degree of control in the cross-linking process of the polymer chains (Pilling, 2005).

The last group of PMC are the elastomers, these have crosslinked polymer chains and differ from thermosets and -plastics because of their highly elastic mechanical behaviour (Erden & Ho, 2017). Reinforced elastomers are for example applied in tires for high-end construction machinery and airplanes.

7.1.3 Application of fibre reinforced composites

Composite materials are very popular in a wide range of industries (see also Figure 7-1). Based on findings of Erden & Ho (2017) and Naqvi et al. (2018), five main industries for composite application were defined: transportation (automotive), aerospace, construction, electricals and electronics and wind energy. As explained in Part I, the scope of this research focuses on the wind energy industry. Appendix C briefly elaborates on the application of composites in the other industries. Ultimately, the EoL solution for composite waste from the wind energy might also be suitable for composite materials from other industries.

7.2 Material use in WTB

This paragraph gives insight in the structural design and material use of WTB. This is relevant to give insight to the characteristics of the EoL composites from WTB.

Structural outline of WTB

Although WTB are designed to be used in different locations with specific wind speeds and produced by a variety of blade manufacturers, the general structure of a WTB is the same. Figure 7-2 shows a schematic view of the section of an average WTB. The basic structure of a WTB consists of two dissimilar aerodynamic shells that enclose a shear web structure and are joined with adhesive joints over the full length of the WTB. The load carrying structure consists of the inside shear web and the extra reinforced parts of the two aerodynamic shells (Figure 7-2, Figure 7-3) (Mishnaevsky et al., 2017). The shape of the aerodynamic shells and the shear web can vary from one manufacturer to another.

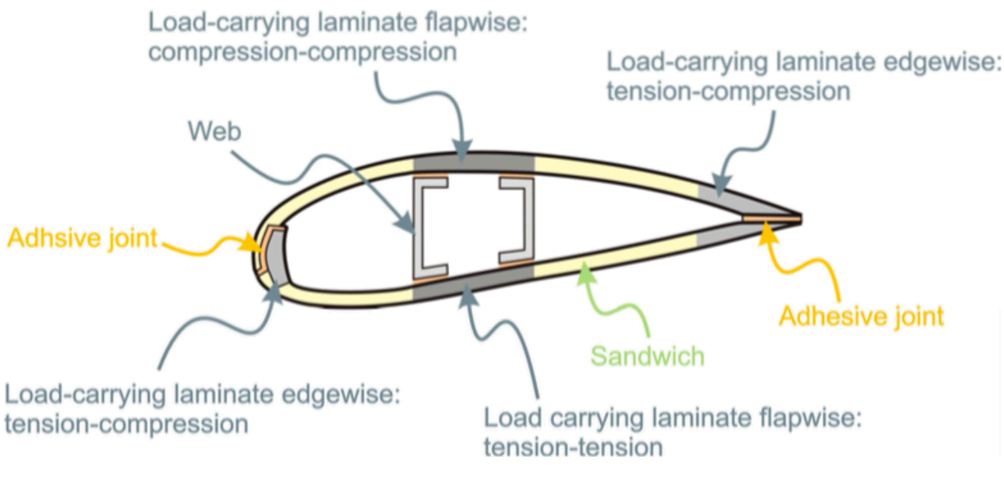


Figure 7-2: Schematic view of the section of a general WTB, including a description of the main elements (Mishnaevsky et al., 2017).

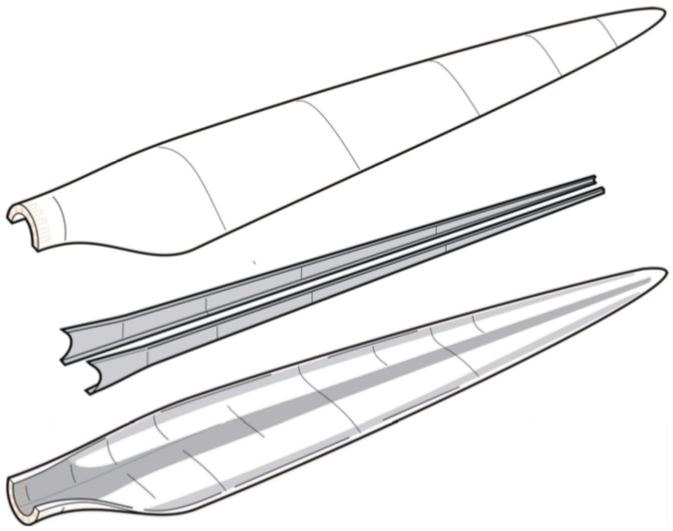


Figure 7-3: Schematics wind turbine rotor blade product parts that are assembled by bonding of two aerodynamic shells and two shear webs (grey colour indicates the primary load-carrying composites) (Mishnaevsky et al., 2017).

7.2.1 Material content of WTB

The major part of a WTB is the composite structure consisting of reinforcement fibres, resin and sandwich materials.

Glass Fibre (GF) is the primary used *reinforcement material* in WTB (Beauson & Brøndsted, 2016; Bech et al., 2014; P. Liu & Barlow, 2017; Mishnaevsky et al., 2017; Papadakis, Ramírez, & Reynolds, 2010). E-glass (borosilicate glass called “electric glass”) is the preferred type of GF for WTB applications, it provides the advantageous combination of high strength and stiffness with low costs (Bech et al., 2014; Mishnaevsky et al., 2017). To a lesser degree, carbon fibre (CF) is also used as a reinforcement material in WTB. Although CF has many advantages over GF (as described in 7.1.1), the high costs per volume of CF limit its deployment in the wind power industry (Skelton, 2017). Liu & Barlow (2017) also mention the applications of hybrid composites, consisting both GF and CF.

In terms of matrix material applied in WTB, currently most of the blades are produced with thermoset polymers like high-grade epoxy or polyester *resins* (Bech et al., 2014; P. Liu & Barlow, 2017; Mishnaevsky et al., 2017). Although epoxy is more expensive than polyester, Papadakis et al. (2010) state that the preferred resin material for WTB is epoxy because of its resistance to moisture and polluting elements as well as good mechanical properties. To enhance the recyclability, the use of thermoplastic resins for WTB is currently being investigated (Mishnaevsky et al., 2017).

Julie Teuwen, assistant professor aerospace structures and materials at TU Delft explains that for WTB, epoxy is often preferred over polyester because epoxy has better mechanical properties for WTB and polyester shrinks more during the curing process, which adds difficulty to the design (personal communication, 22 November 2018). Martin Dijkstra, from wind turbine blade manufacturing company Emergyia Wind Technologies (EWT) provided insights from practice. EWT manufactures 50-60m blades that are built up out of a pre-cut package of glass fibre mats and epoxy resin (personal communication, 13 November 2018).

In terms of material volumes, estimations of the ratio between reinforcement and resin vary amongst different studies (Table 7-1). The differences can be related to the type of reinforcement material and/or production technology (Skelton, 2017). Evidently, a WTB does not exist for 100% out of composite material but composites do account for a large share of the total weight of a WTB (Table 7-1).

The rest of the weight is built up from a so-called *sandwich material*, adhesive joint material, bolts & screws, polyurethane coating and metal (copper) lightning conductors (Larsen, 2009). The sandwich material is used to fill up the space between the layers of composite material and provides rigidity to the part without adding a lot of weight. According to Larsen (2009), PVC, PET and balsa wood are the most mainstream sandwich core materials. At EWT, blades are manufactured with incised sheets of PVC to allow for curvature in the mould (Dijkstra, personal communication, 13 November 2018).

Table 7-1: Ratio of resin/reinforcement of composites and weight percentages of composites as part of the whole WTB, by different sources.

AUTHOR	RATIO RESIN / REINFORCEMENT	% COMPOSITE
Skelton (2017)	60-70 wt% reinforcement 30-40 wt% resin	
Mishnaevsky (2017)	75 wt% reinforcement 25 wt% resin	
Bech et al (2014)	70 wt% reinforcement 30 wt% resin	2/3 = 67wt%
Liu and Barlow (2017)		90 wt%
Dijkstra, EWT	50 wt% reinforcement 50 wt% resin	80 wt%
AVERAGE	**70 wt% reinforcement** **30 wt% resin**	**79 wt%**

7.2.2 Developments in material use

There are many research and development (R&D) initiatives in a fast-growing industry like the wind energy industry. One of the R&D directions is the WTB design including structural design and material use, where the focus lies on increasing efficiency and the reducing WTB weight. These developments are not directly related to the RQ of this project but are however important to take into consideration when discussing if a new solution is "future proof" and able to cope with changes in the feedstock.

First of all, Liu & Barlow (2017) predict that developments in the manufacturing techniques and lower safety factors will also contribute to mass reductions eventually.

In terms of material use, Bech et al. (2014), Liu & Barlow (2017) and Mishnaevsky et al. (2017) all predict a trend towards the use of CFRC and hybrid composites to further reduce the weight of the ultralong blades. These hybrid reinforcements could (besides CF and GF) also include synthetic fibres such as aramid. According to Martin Dijkstra, hybrid reinforcements of CF and GF will mainly occur for larger blade classifications, and not for the class of the EWT blades that stretch between 50-60m (personal communication, 13 November 2018). It should be noted that the strength of a hybrid can be lower than the strength of the individual embedded reinforcement materials under some conditions, which requires for additional research into the application of hybrid composites for WTB (Mishnaevsky et al., 2017). As mentioned before, thermoplastics are identified as an interesting resin alternative because of their advantageous recyclability compared to thermosets.

Additionally, based on insights provided by TU Delft assistant professor Julie Teuwen, specialized in aerospace structures and materials, an increased awareness for the recyclability of WTB stimulates the R&D for recyclability. Given examples are; coatings for reinforcement fibres to either simplify the separation from the matrix or to protect the fibres against process heat, pre-designing shear-load parts for a second life and the use of thermoplastics for the aerodynamic blades, allowing them to be reshaped for a second application (personal communication, 22 November 2018). It is noteworthy that such treatment should not cause a more complex structure and therefore making the recycling process more complex on its turn

7.3 Development of the in the wind energy industry

Over the last two decades, wind energy has proven itself to be one of most promising renewable energy sources as alternative to fossil fuels, see Figure 7-4 (WindEurope, 2018). The cumulative installed capacity of the global wind energy industry is growing fast. Both in terms of the number of turbines installed (wind energy becoming more and more popular) as well as the size of the turbines (Larsen, 2009).

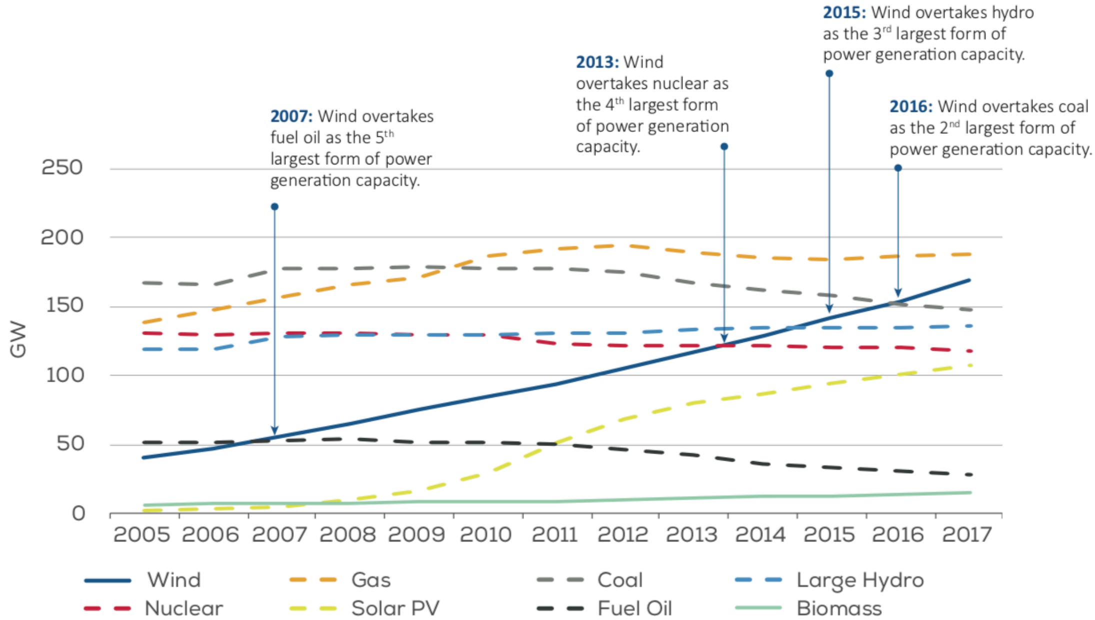


Figure 7-4: Total power generation capacity in the European Union 2005-2017 (WindEurope, 2018).

7.3.1 Rotor size of installed turbines

Over the past decades, the size of individual turbines has increased vastly. According to Bech et al. (2014), the rotor diameter of both on- and offshore wind turbines has constantly increased since 1997 (see also Figure 7-5).

Papadakis et al. (2010) stated that in 2010 the class of 1-3 MW turbines were mostly purposed for large scale power generation applications and smaller turbines of around 500kW were primarily used for small scale applications such as hard-to-access regions. This is confirmed by the information given about the mid-range sized blades from EWT that are mostly installed at 500-1000kW turbines in small-scale onshore projects or hard-to-access regions where the installation of a single turbine is sufficient for the energy requirements (Dijkstra, personal communication, 13 November 2018). Currently, both Vestas and Siemens are installing >8MW wind turbines with rotor diameters over 160m (Figure 7-5).

Although it is expected that WTB will continue to increase for now, according to Andersen et al. (2014) this development is hard to predict. One of the limitations to the growth of WTB according to Wim Robbertsen, former technical director at Lagerwey, is the transport of large size WTB, especially for onshore purposes (personal communication, 18 October 2018).

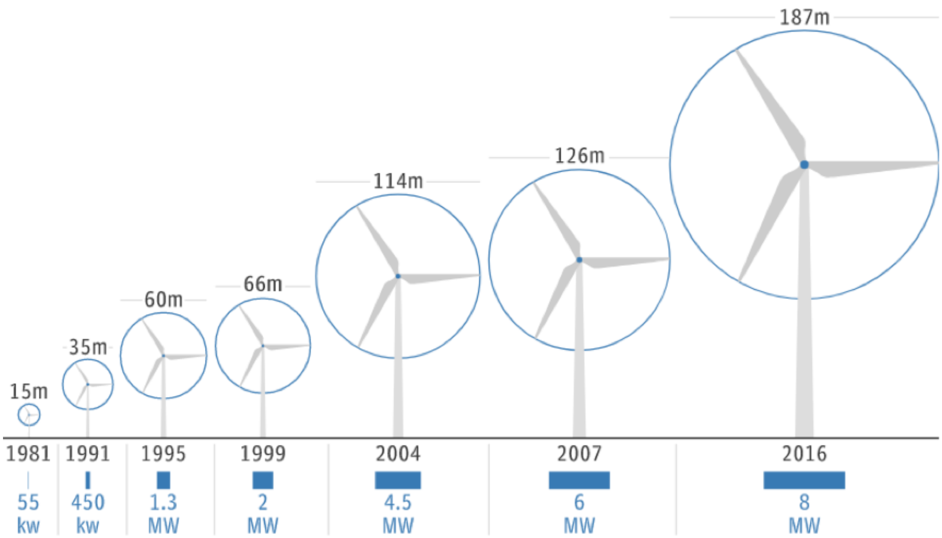


Figure 7-5: Progression of Wind Turbine rotor diameters (m) and their rated output power (MW) between 1980-2016 (NorthSeaRegion, 2018).

7.3.2 Increased popularity of wind energy

The production of energy from wind emerged already in the late seventies however, according to Liu & Barlow (2017), the installed capacity before 1998 is very small compared to the installed capacity since then. In an earlier publication (P. Liu & Barlow, 2015) the authors concluded that the global cumulative installed wind energy capacity increased from 6,1 GW to more almost 365 GW between 1998 and 2014. Andersen et al. (2014) reports an annual capacity increase 40GW over the period between 2009 to 2013.

As can be seen in Figure 7-4, wind energy is now one of the main forms of power generation in Europe. And not only in Europe this renewable energy production technology is gaining ground, also in China and the United States wind energy is gaining popularity. The continuous growth of wind energy is decidedly identified by the consulted literature. Andersen et al. (2014) references the "2 Degree Scenario" (scenario with an average global temperature rise of 2°C) drawn by the International Energy Association (IEA) that presumes the installation of 1400GW of wind power by 2030 and 2300GW by 2050. The GWEC even suggests global installed wind power of 2500GW in 2030 and 4800GW in 2050 (Andersen et al., 2014).

7.3.3 Regional differences

Although the increase in wind energy capacity is a global trend, specific growth rates may vary between geographical areas (Liu & Barlow, 2017). Figure 7-6 shows that the annually installed wind power capacity until 2014 also varied per region. It is clearly visible that Europe was an early adopter of wind energy, the first large offshore wind park was installed in 1991 near Ravnsborg in Denmark (Beauson & Brøndsted, 2016). Figure 7-6 also shows a strong industry growth in China since 2005.

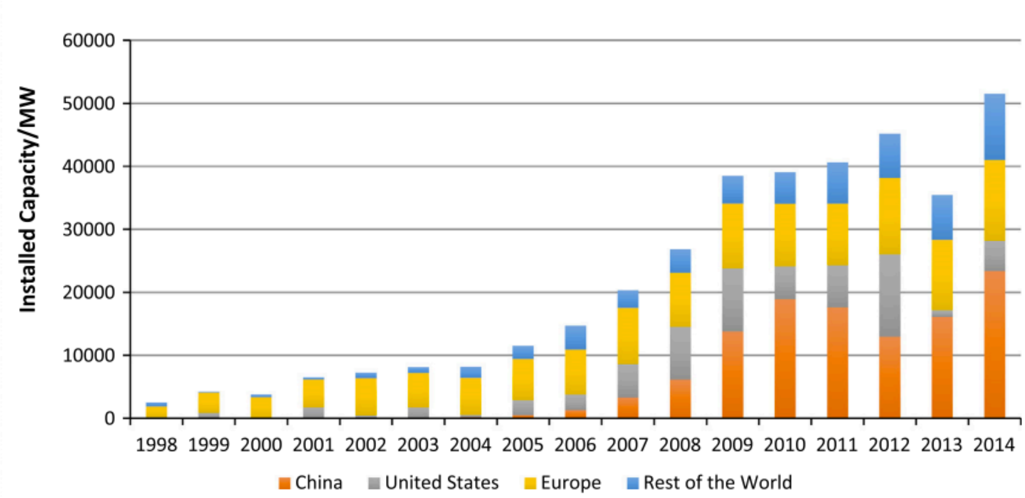


Figure 7-6: Annual installed capacity by region until 2014 (P. Liu & Barlow, 2017).

For Europe, the European Wind Energy Association (EWEA) has predicted that by 2020, there will be a capacity of 192 GW of wind energy (EWEA, 2014). Skelton (2017) reports that the total European wind power capacity had already reached almost 154 GW in 2016, covering 10,4% of the total European electricity consumption (in a normal wind year). WindEurope (2018) reports that in 2017 almost 169 GW of wind energy capacity was cumulatively installed in the European Union, including both on- and offshore wind parks. This means a 10% growth rate compared to 2016 (Figure 7-7). Interestingly, almost 60% of this capacity is installed in only three countries: Germany, Spain and the UK. The Netherlands is one of the seven EU-countries that has over 1 GW of installed capacity (WindEurope, 2018).

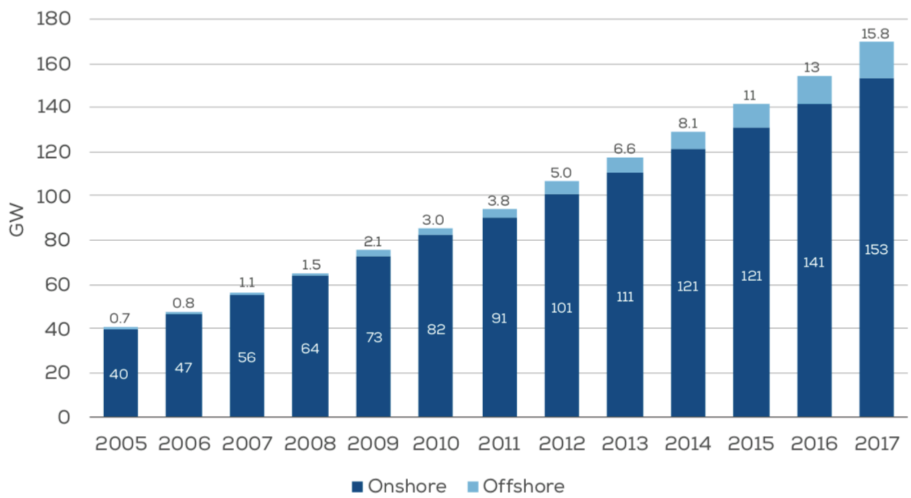


Figure 7-7: Cumulative installations onshore and offshore in the EU (WindEurope, 2018).

7.4 Waste Contributing factors

In this paragraph we explore the growing amount of end of life materials in the current global wind energy industry. In the perspective of the wind energy industry the composite material flowing from decommissioned wind turbines is indicated as “blade waste”, because it is of no use anymore. In the perspective of circularity/industrial ecology this terminology is controversial. The aim of this study is to find a solution that gives this “waste” a second purpose and therefore giving it value and not referring to it as waste anymore.

Liu & Barlow (2015) developed a logic flow model to make an estimation of the WTB waste volumes, see Figure 7-8. The input for the model considers aspects of WTB that were elaborated in the previous paragraphs such as the installed capacity of wind energy and material use. Additionally, the ratio of blade material used per unit of installed capacity is important, as well as other stages of waste since the material used in the final blades is only a part of the full blade waste inventory because waste is released over the whole life-cycle of the WTB (P. Liu & Barlow, 2017). Therefore, the model also includes an estimation of the share of different types of waste such as manufacturing waste and EoL waste.

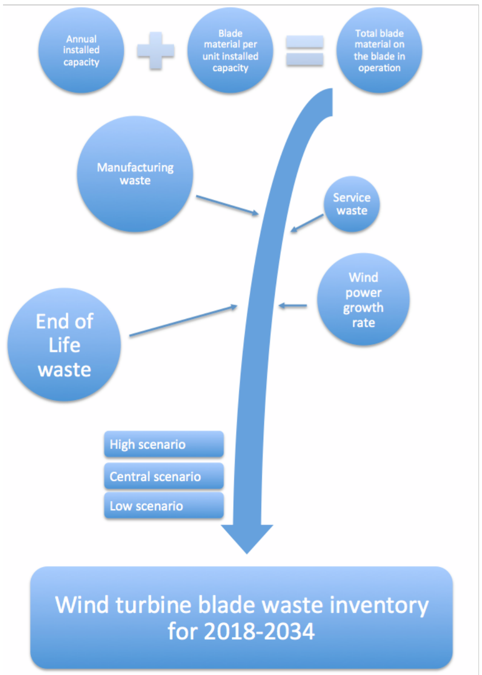


Figure 7-8: Logic flow of WTB waste inventory estimation (P. Liu & Barlow, 2015).

7.4.1 Weight per MW

For typical wind turbines there is a relation between the rotor diameter and the installed power. That means: longer blades give a higher the power output but go hand in hand with a higher blade mass. Based on this relation Albers (2009) made an estimation that each 1kW of installed capacity is related to about 10kg of rotor blade material. This estimation is incorporated by multiple other papers (Andersen et al., 2014; Larsen, 2009) and can be illustrated with the example of a 2MW wind turbine with three blades that together account for 19,5 tonnes of mass (Andersen, Bonou, Beauson, & Brønsted, 2014). Noticeably, this publication also includes the composite nose cone of the nacelle with an individual weight of 0,3 tonnes. These two components together account for 19,8t of mass of composite material for a 2MW wind turbine, this is in line with the estimation by Albers (2009).

Papadakis et al. (2010) studied the theory that blade weight should increase with rotor diameter with an exponent of 3 (cubic relation). His study found that this exponent in practice is only 2.3 or 2.35 (Papadakis et al., 2010). That the relation between the blade length and its weight is not linear is also noticed by Liu & Barlow (2017) and Skelton (2017) that both indicate slightly higher masses per MW for turbines with larger rotor diameters, respectively 13,4 t/MW and 12-15 t/MW. Figure 7-9 shows the differences in t/MW for various turbine sizes that result from the study by Liu & Barlow (2017). According to the author: “the results of this study have improved accuracy and also consider the effect of wind turbine upscaling”.

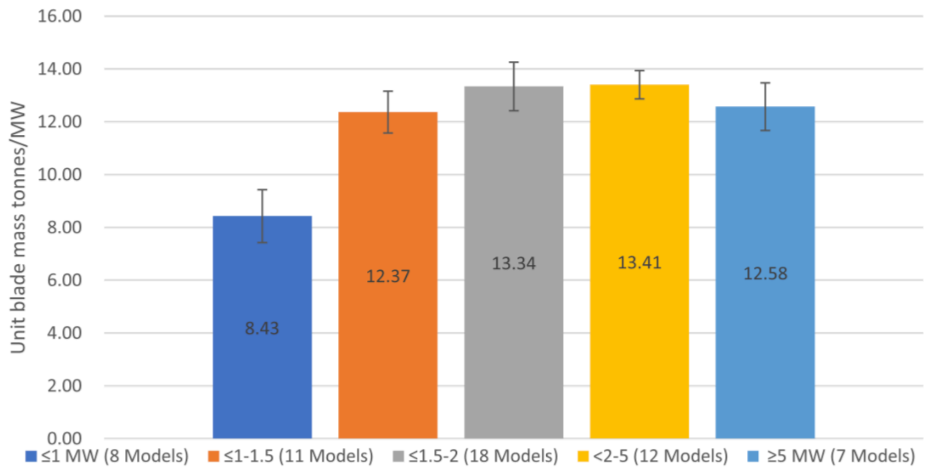


Figure 7-9: Blade mass per unit rated power for different turbine size classes (P. Liu & Barlow, 2017).

7.4.2 Stages of waste generation

The logic flow model by Liu & Barlow (2015) includes multiple stages in which waste is generated, including: manufacturing waste, waste from defective blades, test blades and in-service waste. The focus of this study lies upon the waste released at EoL of the WTB.

According to Liu & Barlow (2017) EoL waste forms the largest part of the total blades waste. When a WTB reaches EoL is dependent on the lifespan of the product. The commonly agreed lifespan for WTB is 20-25 years (Andersen et al., 2014; Beauson & Brøndsted, 2016; Larsen, 2009; Y. Liu, Farnsworth, & Tiwari, 2017; Skelton, 2017). More often economic EoL is reached earlier than technological EoL because of an increase in repowering opportunities and efficiency gains (Skelton, 2017). However, it should be noted that although WTB are designed for a technological life of 20-25 years, some of them are still running without problems after 30 years (Bech et al., 2014).

A complicating factor for the further treatment of the EoL WTB is the varying conditions of the blades at the time of decommissioning, depending on their design, reason for decommissioning and location of usage (Beauson & Brøndsted, 2016). To enhance this process, Bech et al. (2014) propose specific characterization procedures for the EoL WTB. This includes the analysis of surface properties, to determine the nature of the surface degradation, mechanical testing of the fibres and on a microscopic scale the analysis of fibre shape and surface structure.

Waste from the manufacturing stage is the second most significant provider of waste during the lifespan of a WTB (P. Liu & Barlow, 2017). Papadakis et al. (2010) introduces the rule of thumb that the manufacturing waste makes up about 10wt% of the total blade material. It is important to mention that the manufacturing waste from WTB is not necessarily all processed and thus also includes a lot of non-composites which do not lie within the scope of this study. Also, it is important to make a distinction between the total blade waste and the fraction of composite material.

Secondly, waste from defective blades and test blades can be considered as EoL blade waste since it considers full processed blades. The difference is that the material is released much earlier and in a different location than EoL blades that served on the actual turbine.

7.5 EoL material volume predictions

Considering the geographical position of the PoR, the European market and especially the North-West European market seem most interesting for the PoR. Following from its early adoption, this area will also be the first to meet the issue of WTB recycling on a large scale.

Based on the analysis with their logic flow model, Liu & Barlow (2017) have predicted the regional global wind turbine waste projection up to 2050 (Figure 7-10). According to the model, WTB will account for 2Mt of waste in 2050 globally (P. Liu & Barlow, 2017). Europe will be confronted with 25% of the total global WTB waste, which accounts for 50kt of EoL WTB annually in 2022 and almost 500kt annually in 2050. However, Europe was an early adopter of the wind energy industry and will therefore meet the EoL WTB problem earlier than other regions, see Figure 7-10 (P. Liu & Barlow, 2017). Andersen et al. (2014) predicts even higher values for the annual EoL material from WTB will; an increase to 400kt between 2029-2033 and to 800kt in 2050. Considering a time frame of 5-10 years (2024-2029), the annual released volume in Europe will increase from approximately 50kt to about 100kt over this timespan, increasing even further in the following years (based on Figure 7-10).

To put this number in perspective; each person in the Netherlands produces almost 500kg of waste per year (Milieu Centraal, n.d.). An annual waste production from EoL WTB of 75kt is in mass comparable to the annual waste production of 150.000 Dutch citizens, which is comparable to the size of a provincial city like Amersfoort or ‘s Hertogenbosch.

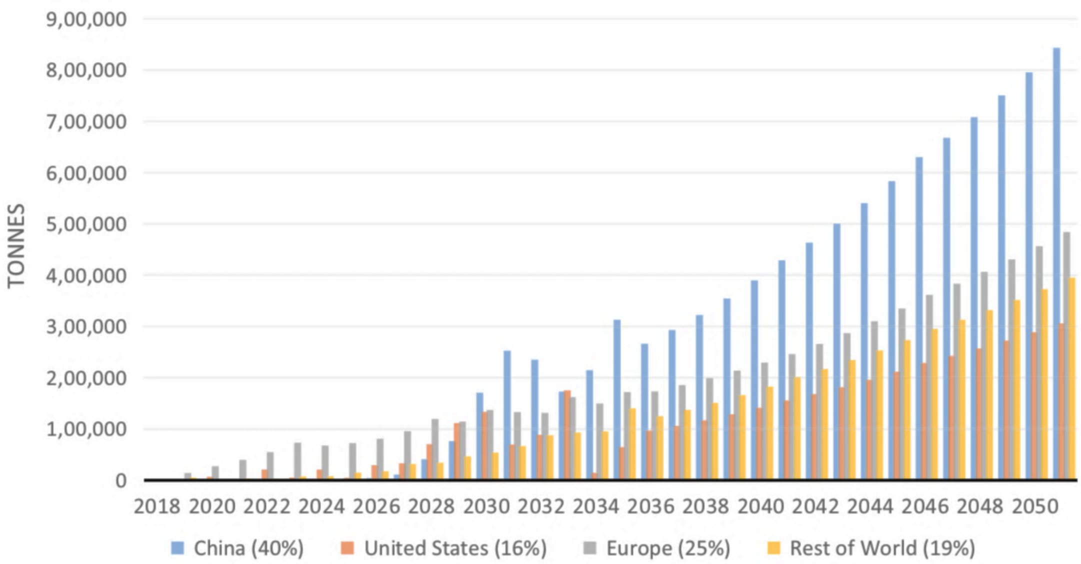


Figure 7-10: Regional wind turbine blade waste projection up to 2050 (P. Liu & Barlow, 2017).

7.6 On & Offshore Wind near PoR

The total capacity of the wind energy industry can be divided into onshore and offshore wind. In Europe, the majority of the wind energy is generated onshore (Figure 7-7). In the Netherlands, onshore wind is also dominating the wind energy industry. In 2015 approximately 3000 MW of wind energy capacity was installed onshore, compared to approximately 350 MW installed offshore, see Appendix D (CBS, 2015). A large share of the onshore wind turbines is located in the Flevopolder, the northern part of North Holland and on the coast of Friesland (red dots in Figure 7-11 and Appendix D).

However, there is an ongoing trend towards more offshore installed wind turbines. Currently is installing multiple offshore wind parks near the coast of their southern province Zeeland (Borssele 1 and 2) and there are more plans to expand the offshore wind capacity between 2020 and 2025 with another 10.500 MW of capacity (green patches in Figure 7-11, Appendix D) (Ministry of Economic Affairs and Climate Policy, 2016; RVO, 2018).

Decommissioning of offshore wind is logically more interesting for the PoR, because it is automatically related to transhipment of decommissioned part and thus to activities in the harbour. However, the majority of onshore wind in the Netherlands is located close to the shores and a variety of industrial harbours, which creates the possibility to transport decommissioned wind turbines by ship to the location of their EoL treatment. Considering the time horizon of this study, the decommissioning of the onshore wind turbines in the Netherlands is more interesting. They are expected to be decommissioned before the offshore wind turbines, based on the moment they were put into service and the expected lifespan of 20 years.

Figure 7-11: Wind energy near the Port of Rotterdam onshore (red) and offshore (green) (Geographixs, 2016; Windstats, 2017)

8 Composite End of Life Solutions

This chapter explains the existing EoL solutions for composite materials. Pyrolysis is assumed to be the most interesting EoL technology for the case of the PoR. This chapter gives insight in how pyrolysis relates to other solutions. Additionally, it explains the valuation of EoL solutions based on their potential environmental impact.

8.1 European Waste Framework

Different levels of EoL solutions can be distinguished and will be explained according to the European Union Waste Framework (from hereonwards EUW Framework) (Gharfalkar, Court, Campbell, Ali, & Hillier, 2015). Figure 8-1 shows the framework categories ranked by desirability from top to bottom. For each category, the processes that are identified as the most promising in that category are stated on the right (Suschem, 2018). The following sections shortly explain the stages of the framework.

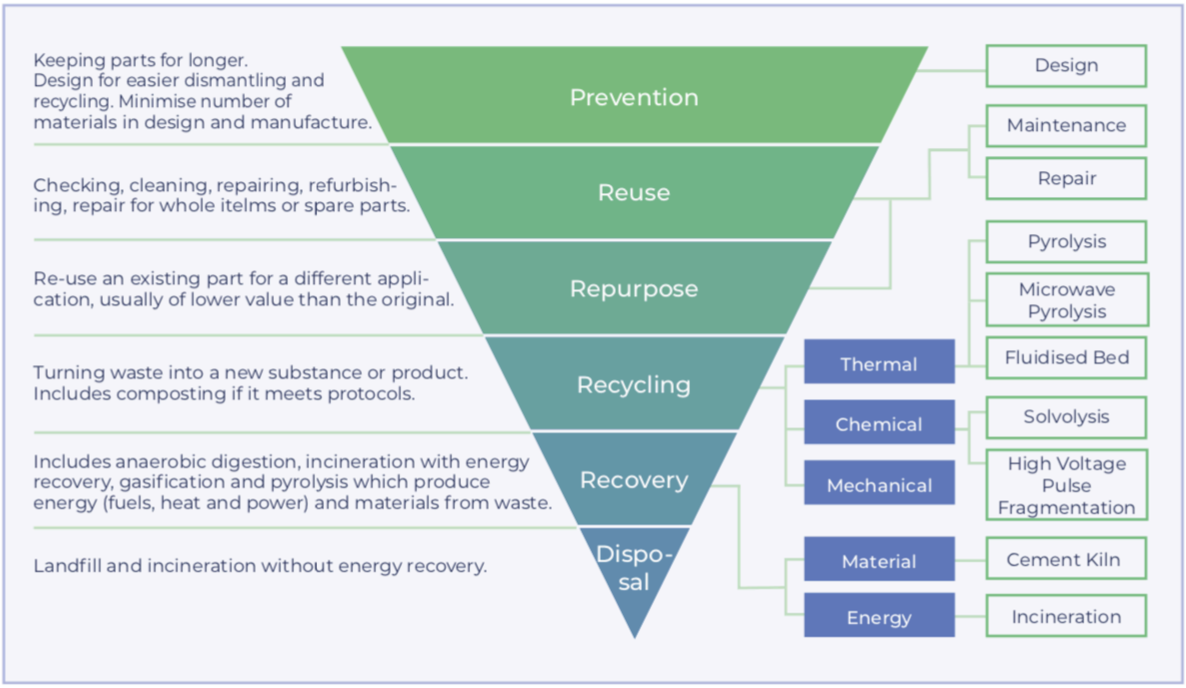


Figure 8-1: Explanation of the six stages of the European Waste Framework (Suschem, 2018).

8.1.1 Prevention

To prevent the emergence of waste is the most preferred EoL solution. The first question that arises here is: “What is waste?”, for which there is not one specific answer. In this study waste is considered as material that gets disposed, because it has no further function or value. Waste prevention means that either measures are taken that lead to the reduction of wasted materials or measures that lead to a reduction in the content of harmful substances in a product (Gharfalkar et al., 2015).

According to the publication by Suschem (2018), there are *two* key elements in the prevention of waste. First, design should serve a purposeful lifecycle of the product, matching the application requirements for as long as possible and or contain a pre-defined second-life application. Additionally, the EoL phase of the product should already be considered during the design phase, in which materials are chosen and combined. Secondly, maintenance, treatment and repair contribute significantly to postponing EoL as much as possible, ensuring that value of the product elements is retained along the useful life of the product.

The relation between PoR and waste prevention for WTB is very small. The design phase of wind turbines is not directly related to the activities and existing industries in the port. But there are certain design guidelines for WTB that foster the recyclability by means of pyrolysis, these are elaborated in Appendix 0.

8.1.2 Reuse / Repurpose

This second stage of the waste framework considers the *reuse* of (parts) of the product. This includes activities such as maintaining and repairing the product to extent its lifespan. If the product is not suitable for its first application anymore, it can be refurbished, or parts can be taken from the initial product and a secondary purpose for them can be found. Gharfalkar et al. (2015) include any operation that contributes to “wasted product parts” serving for a useful purpose. This can be enhanced by either incorporating spare or second-hand parts into the design of a product and allow the EoL and damaged part to be reused or repurposed in other applications (Suschem, 2018).

For WTB, the second-hand market is small. The main limitation is the initial cost for transportation and the foundation, which are similar for virgin and reused wind turbines (Robbertsen, personal communication, 18 October 2018). Also, there are currently examples of repurposed WTB used as parts of children playgrounds, city furniture or slow traffic bridges (Figure 8-2) (SuperUse studios, n.d., Speksnijder,2018). However, it should be acknowledged that these are limited markets, since there is no unlimited demand for city furniture, playgrounds and slow traffic bridges.

Figure 8-2: Projects of SuperUse studios; a) Wikado, children’s playground in Rotterdam; b) REwind, city furniture made out of repurposed wind turbine blades at Willemsplein Rotterdam (SuperUse studios, n.d.)

Another possibility is *repurposing* large composite parts on a material, this is studied by the Dutch university of applied sciences Windesheim. Dr. Ir. Albert ten Busschen is head of the research group that focuses on reuse applications of composite material, without decomposing the composite and thus preserving its special characteristics (personal communication, 21 November 2018). This principle is further explained in Appendix 0.

Figure 8-3: Section of the sheet piling walls with fragments and flakes of EoL composites as reinforcement, produced by Windesheim (Ten Busschen, 2018).

8.1.3 Recycling

Recycling is the fourth stage in the EUW Framework. Operations that reprocess "waste" into products, materials or useful substances are considered as recycling. No distinction is made between products that serve the original or a new purpose. Recycling includes the reprocessing of organic material but does not include energy recovery and the reprocessing into materials that are to be used as fuels or for backfilling operations (Gharfalkar et al., 2015). In literature, three different types of FRC recycling are distinguished; mechanical, thermal and chemical recycling, some literature combines the thermal-chemical technologies. It should be noted that there is not one optimal technology. This is dependent on multiple factors such as the content of the input material and the process characteristics.

Mechanical recycling involves breaking-down the FRC material by shredding, crushing, milling it. Typically, mechanically-recycled composites are used as a filler reinforcement in the construction industry, for example in asphalt, concrete or composites (Pimenta & Pinho, 2011). It should be noticed that mechanical recycling diminishes the potential high-end application of the composites and thus their value significantly.

Some consider both pyrolysis and solvolysis as forms of chemical recycling, literature often indicates pyrolysis as thermal recycling and solvolysis as chemical recycling. From here on the names of the processes will be used. These two technologies are very similar in the core. The difference lies in the method used to decompose the matrix the matrix, which can be done either with a high temperature treatment such as pyrolysis (Pimenta & Pinho, 2011; Verma et al., 2018) or with a chemical treatment such as solvolysis (Oliveux et al., 2015). Both the processes cause a degradation of the fibres' mechanical properties.

Pyrolysis is the most widespread technology as it is proved and frequently used in other chemical applications (Oliveux et al., 2015). From the industrial-scalable EoL technologies for FRC, pyrolysis allows the lowest value loss but it is still not a high-value recycling method and requires high investment and running costs (Suschem, 2018). However, improvements for pyrolysis are plenty such as the combination with processes with robotic precision cutting and hybrid solutions, combining pyrolysis with mechanical grinding (Suschem, 2018). Solvolysis requires a relatively low temperature, resulting in a lower degradation of fibres. Moreover, there are strong environmental concerns associated with the toxic chemicals necessary for the solvolysis process (Oliveux, Dandy, & Leeke, 2015; Suschem, 2018).

Both pyrolysis and solvolysis processes have been more developed to recycle CFRC than GFRC, whereas GF suffer significantly more than CF from the high temperatures and corrosive chemicals that decreases their mechanical properties by at least 50%. Making the process economically more interesting for CF (Oliveux et al., 2015).

8.1.4 Recovery

In the publication by Suschem (2018), a distinction is made between the recovery of energy and the recovery of material. Gharfalkar et al. (2015) describes recovery as: "any operation that recovers some sort of energy like fuel, heat or power".

A technology that allows for both the recovery of material and energy is the cement-kiln route. First, large composite parts are size-reduced and thereafter mixed with so-called solid recovered fuel (SRF). SRF consists of shredded and dehydrated solid waste, typically coming from the combustible components in municipal solid waste. Secondly, this mixture is fed into the kilns to produce the cement. Although this technology has a high cost effectiveness and efficiency; it is downgrading the composite material and should therefore only be used when there is no more value in the composites through any other EoL solution.

Cement-kiln however, is accepted as *recycling* technology by the industry. For GFRC, the European Composites Industry Association (EuCIA) even recommends that EoL materials are recycled through the cement-kiln route (Job et al., 2016). During a stakeholder meetup of the Belgian and Dutch composites trade-organisations, it was acknowledged as the only economical viable recycling route for composites. (Sirris workshop, personal communication, 11 September 2018). The German-based Neowa provides the cement-kiln route at an industrial scale. However, in this research it is not considered to be a recycling technology since in the cement-kiln route, the GFRC material does not flows into products, materials or substances, but is used as a filler in another product.

Energy recovery is mostly done by the incineration of material, used to recover energy in the form of power or heat (Suschem, 2018). The most common incineration of GFRC happens in combined heat and power plants (CHP), where the heat is used to generate electricity. However, this incineration is problematic because the inorganic materials from GFRC are non-combustible at the relatively low CHP temperatures, glass fibres will only decompose at temperatures far above 1000°C, which infeasible for a lot of regular waste-to-energy plants (in the Netherlands, Vakblad Afval (2018)). This means that at regular CHP incineration temperatures, about 60% of the inorganic composite material is left behind as some sort of sticky ash (Jensen & Skelton, 2018; Vakblad Afval, 2018; Yang et al., 2012). These inorganics can lead to the emission of hazardous flue gases that can furthermore cause damage to the incinerator and chimney (Yang et al., 2012). For this reason, incineration plants often decline the material, or ask for outrageous prices for the treatment (Jensen & Skelton, 2018). The ashes of the incineration have a potential use as fillers in building materials or have to be landfilled. However, this option is affected by commercial limitations like the low prices for virgin fillers for building material (Job et al., 2016) and local factors such as legislation considering landfilling (Jensen & Skelton, 2018).

Nevertheless, both Yang et al. (2012) and Jensen & Skelton (2018) indicate that incineration is currently the most common route for EoL composite materials globally, but no exact numbers are given. Energy can also be recovered from the product gases of pyrolysis or solvolysis processes (Oliveux et al., 2015; Verma, Balasubramaniam, & Gupta, 2018). This energy recovery typically only applies to the matrix material of FRC, because the fibres are non-combustible (Cherrington et al., 2012).

8.1.5 Disposal

Coming back to the definition of "waste" in the beginning of this paragraph; when there is no second purpose for a material and where an operation does not have a secondary consequence in the form of reclamation of substances or energy is called disposal (Gharfalkar et al., 2015). According to Suschem (2018): "landfilling translates into an absolute loss of resources and is, therefore, preferably to be avoided".

Currently, in the Netherlands the minimum standard for the treatment of thermoset plastics waste is: "to turn into another useful application, including the use as fuel" to provide power and/or heat. This includes incineration but not landfilling (Ministerie van Infrastructuur en Waterstaat, 2017). Also in Germany landfill of FRC materials is already forbidden and Oliveux et al. (2015) predicts that other EU countries will follow this example. The Dutch government states that they are constantly looking for new recycling options and that "as soon as new technologies meet the requirements for raising the minimum standard, this will be considered" (Ministerie van Infrastructuur en Waterstaat, 2017). This means that if recycling technologies are more mature and industrially scalable, self-contained recovery will be prohibited as well.

8.2 Pyrolysis as focus of this study

From an environmental perspective, pyrolysis is not the most preferred EoL solution. This was also acknowledged by Martin van Dord, innovation manager at the NRK (The federation for Dutch Rubber and Plastics-producers) (personal communication, 28-11-2018).

Even though, pyrolysis is considered to be the technology of focus for this study (from the perspective of the PoR). First of all, the pyrolysis technology has a potential link to the current chain of activities of PoR, because the decomposed matrix material has a potential application in the chemical industry. Secondly, it is the most widespread technology as it is proved and frequently used in other chemical applications (Oliveux et al., 2015). The choice is enhanced by the fact that a pyrolysis cluster that aims to cooperate on the implementation and development of pyrolysis processes is already existent in the PoR.

8.3 Cascading products

Pyrolysis could provide a solution later on in the lifecycle of the material. As stated in the Suschem publication (2018); the EoL of a product, part or application does not necessarily also mean the EoL of a material. The EoL of a product is reached when it cannot serve for its initial purpose anymore. On the other hand the EoL of a material is only reached when no more value can be extracted from it (Suschem, 2018), which is not the case if there is still a potential to reuse or refurbish the part/product, and both material and products can have multiple lifetimes.

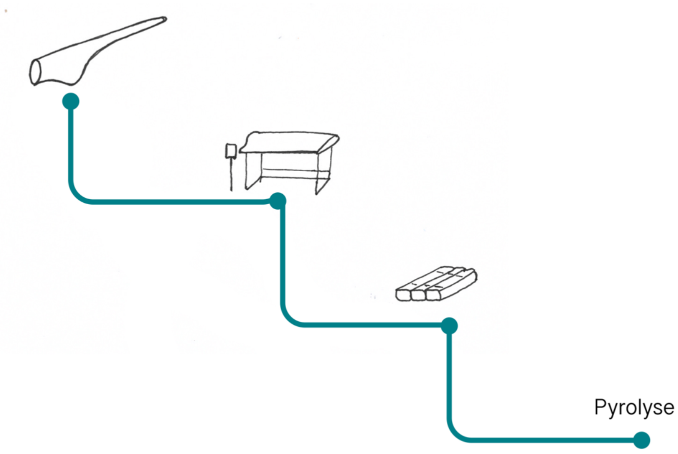


Figure 8-4: Cascading product flow.

In the case of present WTB, a 100% circular system is not possible, since these blades cannot be reused or repurposed for a new nacelle, because the blades should perfectly fit their nacelle in terms of weight, length and attachment. Also, recycling of the composite elements will downgrade the fibres, making them unsuitable for reuse in a new blade. Therefore, in the present situation looking for secondary or tertiary product or part application potentials of WTB is the best option.

Consecutive life cycles imply a cascading use of material. This means a product(part) or material is first re-used for more valuable purposes before it gets to the less valuable recycling stage (Figure 8-4). For example, an EoL WTB could get a secondary purpose by serving as structural outline of a bus shelter (Figure 8-5a). When the bus shelter also reaches its end of life, the composite material in the old WTB structure can go into its tertiary lifecycle by implementing the Windesheim technology (Appendix 0) and use the composite strokes and flakes to produce heavy-duty bog mats for the construction sector (Figure 8-5b).

Ultimately, the composite in these products cannot be reused for a meaningful purpose any more. However, Martin van Dord (NRK) pointed out there is an urge to further develop the technology for the pyrolysis of composites, because in the end it will be the most suitable, necessary solution over incineration for various kinds of plastics (personal communication, 28-11-2018).

Although these repurposing and reprocessing EoL solutions are not directly linked to the PoR at the present moment, the further developments in this field by other stakeholders might be of interest to the PoR, because it is related to the return of the material. Potentially, these secondary applications could be located in the PoR, for example in quay reinforcements.

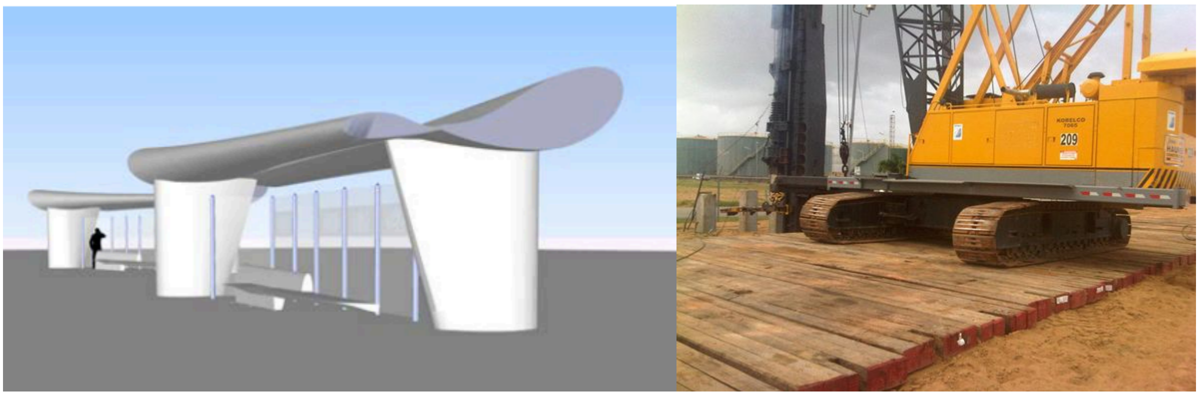


Figure 8-5: a) Bus shelter made from REwind Almere (Superuse studio) (left); b) Hardwood bog mats for heavy construction works (right)

9 Pyrolysis of composite material

In this chapter, more specifics about the pyrolysis for GFRC are given. First the working principle of the technology is explained. Thereafter the output products of the process and their possible applications are described. The limitations of this technology and the possible developments in this field are also included in this chapter.

9.1 Working principle

Pyrolysis uses heat to decompose the polymer matrix of a composite in an (almost) inert atmosphere, (Oliveux et al., 2015; Papadakis et al., 2010; Verma et al., 2018). The absence of oxygen prevents combustion, and thus reduces the air pollution effects of pyrolysis compared to the incineration (Giorgini et al., 2016). The glass fibres in the GFRC are non-combustible at temperatures below approximately 1000°C, whereas the resin is combustible. The decomposition of the resin produces gases and oily liquids during the process. The solid product, consisting of fibres and char, is left in the reactor.

9.1.1. Process steps and reactor types

Figure 9-1 gives a schematic explanation of the standard pyrolysis process, however it differs for different reactor types. There are various types of pyrolysis reactors, standard types include: heated boilers, autoclaves, rotary kilns or screw conveyors, the most significant difference between them is the way the material is heated (Kaminsky, 2010). The two most discussed alternatives are the microwave pyrolysis and a fluidised bed reactor (Figure 9-2).

In a microwave pyrolysis reactor the material is heated with microwaves into the core, this allows for better control of the heating process and minimizes the damage to the fibres (Suschem, 2018). The fluidised bed reactor makes use of a flow of an inert gas that is blown through a layer of fine-grained material like sand or carbon black, to create a swirl in the bed so that the bed of fine-grained material acts like a liquid. The interaction with the fluidised bed will decompose the matrix material layer by layer by attrition of the resin (Kaminsky, 2010; Oliveux et al., 2015). The big advantage of a fluidized bed reactor is the short residence time of only a few minutes compared to 20 minutes for standard reactors (Kaminsky, 2010).

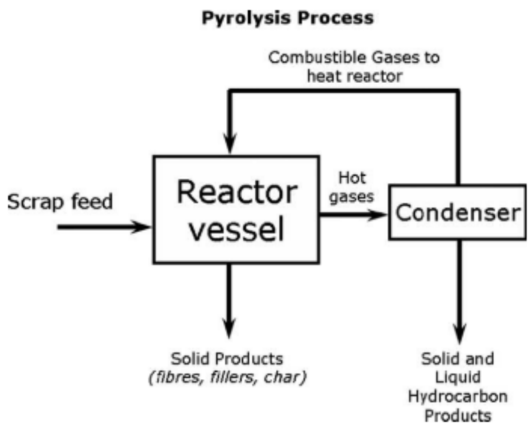


Figure 9-1: Schematic overview of the standard pyrolysis process steps as described by Pickering (2006).

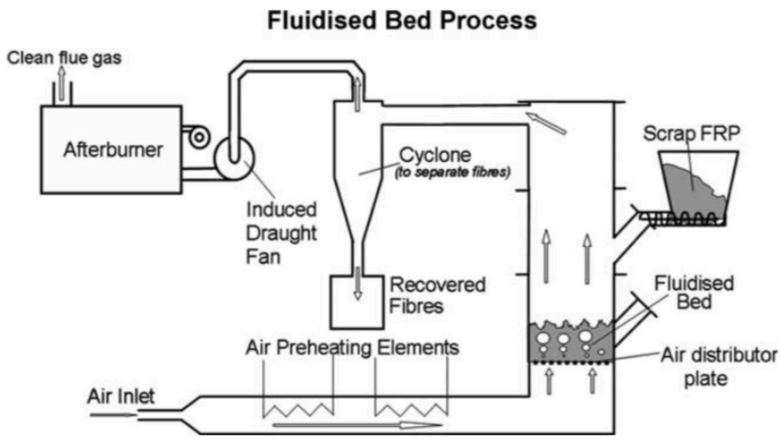


Figure 9-2: Schematic overview of process steps with fluidized bed reactor ((Pickering, 2006).

9.1.2 Input requirements

The GFRC material is inserted in the pyrolysis reactor in either large chunks or shredded scrap, this depends on the type of reactor. The large chunks provide some kind of fibre length conservation but limit the efficiency of heating the material and transport to the pyrolysis facility. Also, in current pyrolysis processes, the mechanical characteristics of the fibres are degraded to such an extent, that the input of the fibre length could be irrelevant. The mechanical treatment preceding the pyrolysis reactor is not considered part of the process since this generally happens closer to the source of the decommissioned material.

The main requirement for the process is heat, the temperatures mentioned in the various studies range between 300 and 800 °C. The temperature is dependent on the type of resin that was used for the composite, whereas polyester resins decompose at lower temperatures than epoxies. According to Oliveux et al. (2015) to decompose the resin, the pyrolysis reactor needs to be heated up to 450-700 °C. Pickering (2006) states that at 450 °C polyester resins have fully decomposed, other resins such as epoxy need a higher temperature of 500-550 °C and that processes under 400 °C are unsatisfactory because resins do not completely decompose.

9.2 Output products

Figure 9-3 shows the transformation of the GFRC material in a pyrolysis reactor. It is visible that the material has lost its rigidity during the process and the solid product that is left in the reactor is completely covered in char. The standard pyrolysis process for composites produces three different output products; a gaseous, liquid and a solid part (Larsen, 2009; Oliveux et al., 2015; Pickering, 2006; Torres et al., 2000; Yang et al., 2012). Analysing the output products of the pyrolysis process gives insights in their potential use as secondary resource or material. This aspect of the process is of high importance of the economic viability of the recycling process and affects the circularity. If the products of the recycling process are of no-use and need to be discarded, the recycling effort oversteps its goal. In Table 9-1 a generic description of the content and potential secondary purposes of all three product groups based on studies by Oliveux et al. (2015), Pickering (2006) and Torres et al. (2000) is given.

It is important to notice that the output of the process both in terms of content and the ratio between gas, liquid and solid, is dependent on the chemical nature of the polymeric resins of the pyrolyzed GFRC. Table 9-2 shows study results that demonstrate that the resin is mainly decomposes into liquids and gases. The discrepancy in the study by López et al. (2011), can be explained by the formation of char from resin residue. Additionally, the ratio between gas, liquid and solid products is also dependent on the process temperature. Table 9-1 shows the influence of temperature on the output product distribution based on by Oliveux et al. (2015). The following sections will elaborate on each of the output streams in more detail.

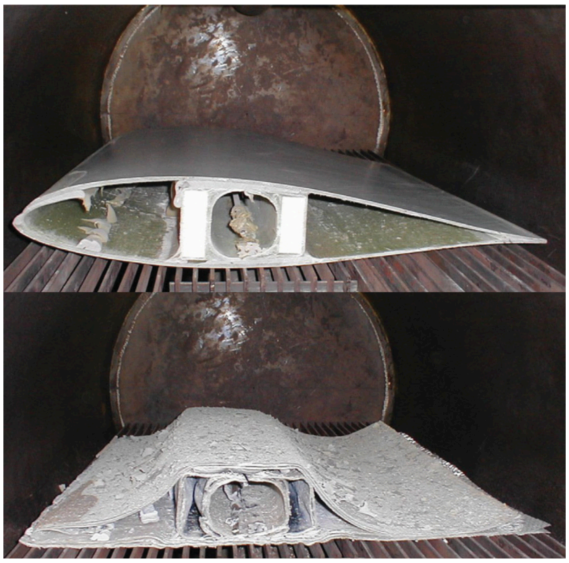


Figure 9-3: a) The before and b) after look of a part of a WTB treated in a pyrolysis reactor (picture courtesy of ReFiber; Larsen, 2009).

Table 9-1: Overview of output products and weight proportions for different temperatures (based on: Oliveux et al., 2015; Pickering, 2006; Torres et al., 2000).

Types of pyrolysis products	Content	Purpose	~ Weight proportions For different temperature				
			300	400	500	600	700
Solid yield	mixture of fibre glass or carbon fibre, filler materials and solid carbon	Re-use (separation necessary)	82,6	75,2	74,9	73,9	72,6
Liquid yield	Complex mixture C_5-C_{20} organic compounds, high calorific values (34-37MJ/kg)	Non-polluting liquid fuels; 40% used as petrol, 60% mixed with fuel oils	9,7	14,5	14,2	14,2	13,7
Gas yield	Very rich in CO and CO_2; low calorific value (13.9-16.4 MJ/kg)	Energy source to self-sustain the process	6,1	10,5	11,0	11,5	12,8

Table 9-2: Conversion from composite to product yield, results from studies Oliveux et al. (2015) and López et al. (2011)

	INPUT		OUTPUT	
Oliveux et al (2015)	GF reinforcement	75%	Solid	75%
	Resin	25%	Liquid	14%
			Gaseous	11%
López et al (2011)	GF Reinforcement	64,5%	Solid	68%
	Polyester resin	35,5%	Liquid	24%
			Gaseous	8%

9.2.1 Gaseous product yield

During the pyrolysis process, the macromolecules of the resin (either epoxy or polyester) are decomposed into smaller molecules that evaporate from the material and can be captured at the top of the reactor (Meyer, Schulte, & Grove-Nielsen, 2009; Pimenta & Pinho, 2011). The gaseous part accounts for the smallest part of the output products, roughly between 5-15% of the total weight.

The exact composition of these gases is dependent on multiple factors such as: chemical composition of the resin material, reactor type and process temperature and is therefore hard to predict. But examples from literature are given to create a better understanding of the composition of these gases. Giorgini et al. (2016), analysed the gases released by a pyrolysis process of chunk of composite made from polyester matrix reinforced with an isotropic glass fibre mat. They analysed the gases with a micro gas chromatograph, these results are given in Table 9-3. The main elements of this pyrolysis gas are: CO, CO_2 and different types of hydrocarbons including CH_4 (Meyer, Schulte, & Grove-Nielsen, 2009; Pimenta & Pinho, 2011).

Table 9-3: Chemical composition and gross calorific value (GCV) of the gas produced by pyrolysis of GFRPs scraps at different process temperature (Giorgini et al., 2016).

Pyrolysis gas components (vol%)	Process temperature (°C)		
	500	550	600
H_2	5.8	7.5	11.5
CH_4	10.6	15.4	20.7
CO	24.2	24.0	21.8
CO_2	32.6	26.0	20.4
C_2H_4	4.8	5.0	5.2
C_2H_6	2.8	3.3	3.7
C_3	1.4	1.4	1.3
C_4	2.6	2.7	2.5
Others	15.2	14.7	12.9
GCV (MJ/m^3)	31.1	33.1	34.1

The output gas can be used as energy source for the process. The amount of energy that can be derived from the gas is dependent on the gross calorific value (GCV) of the gas. The GCV value is dependent on the ratio of CO and hydrocarbons, which can be combusted to generate energy, and CO_2 which is non-combustible and does not contribute to energy generation (Giorgini et al., 2016). Table 9-4 shows the GCVs found by different studies. Again, this shows that the GCV depends on the chemical nature of the polymeric resins and the temperature of the process. Compared to polyester resins, gases yielded from epoxy resin would contain a higher H_2 content than for gases form pyrolysis of polyester, and thus a higher GCV (López et al., 2011). This data will be further analysed for the consideration in the hypothetical scenario comparison in part IV.

Table 9-4: GCV of the gaseous product found by different studies.

	MJ/kg	MJ/m3
Giorgini et al. (2016)		30-35
Oliveux et al. (2015)	14-16	
Yang et al., (2012)	15-20	
López et al. (2011)		26

9.2.2 Liquid product yield

The liquid output product is often referred to as ‘pyrolysis oil’ and is recovered in a condenser (Giorgini et al., 2016). This oily substance is a complex mixture of C_5-C_{21} organic compounds with a high calorific value. Often a small amount of water (H_2O) is also present in the oily substance (±0,5wt%) (Pickering, 2006; Torres et al., 2000; Yang et al., 2012). The liquid product accounts for roughly 15-25% of the total weight of output products.

The relative concentrations of the different organic compounds are primarily influenced by the temperature of the pyrolysis process and by the chemical nature of the resin (Giorgini et al., 2016). A large number of compounds is detected in the investigated pyrolysis oils by Giorgini et al. (2016). From these, benzene, toluene, ethylbenzene and styrene were indicated as the compounds of interest because of their relatively high market value as a source of light aromatics (Giorgini et al., 2016; López et al., 2011). All of these compound oils are composed mainly of carbon, hydrogen, nitrogen, and oxygen (Giorgini et al., 2016). Table 9-5 gives the compound quantifications for the by Giorgini investigated substance for these compounds of interest.

Table 9-5: Benzene, toluene, ethylbenzene and styrene content in oils obtained at different temperatures (Giorgini, 2016).

Pyrolysis oil components (g/l)	Process temperature (°C)		
	500	550	600
Benzene	3.4	9.5	6.8
Toluene	15.0	31.1	27.3
Ethylbenzene	16.7	30.0	21.5
Styrene	7.9	13.7	13.6
Total (g/l)	43	84,3	69,2

Pyrolysis oils have a potential purpose as fuel oil and feedstock for the plastics industry. In order to estimate their potential commercial value for the plastics industry, the compounds are analysed on the presence of contamination with for example sodium, sulphur or chlorine. Giorgini et al. (2016) concluded that the low contamination of the obtained pyrolysis oils makes them suitable for use as fuel without requiring any further purification process. López et al. (2011) also studied pyrolysis oils from the pyrolysis of polyester fibreglass and concluded that that specific pyrolysis oil contained about 27% styrene, making it potential suitable as feedstock for the manufacturing of new polyester resin.

The relatively high GCV of the pyrolysis oils of 30-40 MJ/kg is comparable to the GCV of fuel oil (Pickering, 2006; Torres et al., 2000; Yang et al., 2012). A study by Torres et al. (2000) shows that the GCV is not strongly dependent on the process temperature (Table 9-6). The lower GCV value of pyrolysis oils yielded at a process temperature of 300°C is explained by their higher oxygen content (Torres et al., 2000). Furthermore, López compared the pyrolysis oil to automotive diesel and gasoline oils and concluded that about 50% of the pyrolysis oil compound can be used as commercial gasoline and the other 50% could be used as heating oil when mixed with commercial fuel oils (López et al., 2011).

Oliveux et al. (2015) remark that not all the oily compounds are valuable and to justify the separation of the valuable compounds, they should be sufficiently present in the oily liquid product. It should also be noted that the remaining solution of non-valuable compound still requires disposal.

Table 9-6: Elemental composition (wt%), H/C atomic ratio and gross calorific values of pyrolysis oil for different process temperatures (Torres, 2000).

Temperature [°C]	300	400	500	600	700
GCV [MJ/kg]	33,9	36,7	37,1	37,0	37,2

9.2.3 Solid product yield

The solid fraction of the output products consists of the released fibres, which account for the biggest weight percentage of the products, approximately 75% (Table 9-1) (Oliveux et al., 2015; Pickering, 2006; Torres et al., 2000). The solid product yield of the pyrolysis generally consists of a pile of fibres, covered in a thin carbonaceous layer of resin residue often referred to as char, see also Figure 9-3 (Oliveux et al., 2015; Torres et al., 2000). Because of this large share of solid product, it is extra important that there is an economically viable secondary life existent for this product stream. However, until now producing a high-quality fibre product from fibres recovered from pyrolysis has proven to be a challenge, mainly due to three limiting factors.

First, the heat of the pyrolysis process degrade the fibre strength (Larsen, 2009; Pickering, 2006). Although the loss of fibre strength caused by heat has been intensively studied, the explanation remains undisclosed (Feih et al., 2011). According to Fraisse et al., (2016) it has been assumed that the effect is coupled to different aspects such as: the surface structural relaxation and water absorption into the glass molecular network, of which the latter leads to the formation of defects at the fibre surface. Several studies have shown that the effect of heat on the tensile strength of glass fibres is both dependent on temperature and heating time. The heating temperature and heating time are dependent on the matrix of the composite material. It was found that polyester resins have decomposed fully at a temperature of 450 °C, whereas the other resins generally need a higher temperature of 500–550 °C. (Pickering, 2006).

The effect of the temperature and heating time on the degradation of tensile strength is showed by the experimental test results shown in Figure 9-4 (Feih et al., 2011). The figure shows that the tensile strength drops rapidly with time between 250–550°C and reaches a minimum steady-state determined by the process temperature (Feih et al., 2011). At the recommended pyrolysis temperature of approximately 500°C, the tensile strength is reduced to less than 50% of the original strength (Feih et al., 2011; Oliveux et al., 2015; Pickering, 2006). Fraisse et al. (2016) explains this transformation with the densification of the glass molecular network and the removal of sizing during the heating process.

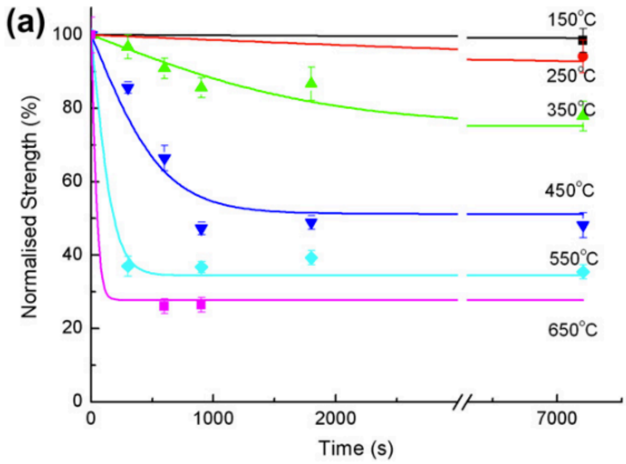


Figure 9-4: Effects of temperature and heating time on tensile strength of single glass fibres, with normalized tensile strengths to 2284 MPa, the average original strength at room temperature (Feih et al., 2011).

Secondly, carbonaceous deposition is generated by secondary repolymerisation reactions in the gaseous phase (Figure 9-5a) (Lopez, 2011). A study by Torres et al. (2000) showed that the organic matter of residues consists of mainly carbon (90wt%) and is therefore referred to as char or coke. The amount of resin residue deposited on the fibres is dependent on the temperature of the process, the higher the temperature, the cleaner the fibres (Meyer et al., 2009; Pickering, 2006; Yang et al., 2012). López et al. (2011) studied a solid residue that consisted of 97wt% glass fibre and 3wt% char for the pyrolysis of GFRC with a polyester resin.

The char decreases the adhesive properties with a new resin (Naqvi et al., 2018). In case of recycling the glass fibres in a new composite material, the solid yield requires a post-treatment such as an after-burner (Larsen, 2009), a vitrification process (Lopez, 2011) or an oxidation process to clean them completely (Figure 9-5b) (Giorgini et al., 2016; Oliveux et al., 2015). It is important to notice, that the heat necessary for this post-treatment will also affect the mechanical properties as described before, this means there is a trade-off existent between the preservation of mechanical properties and cleanness of the fibres.

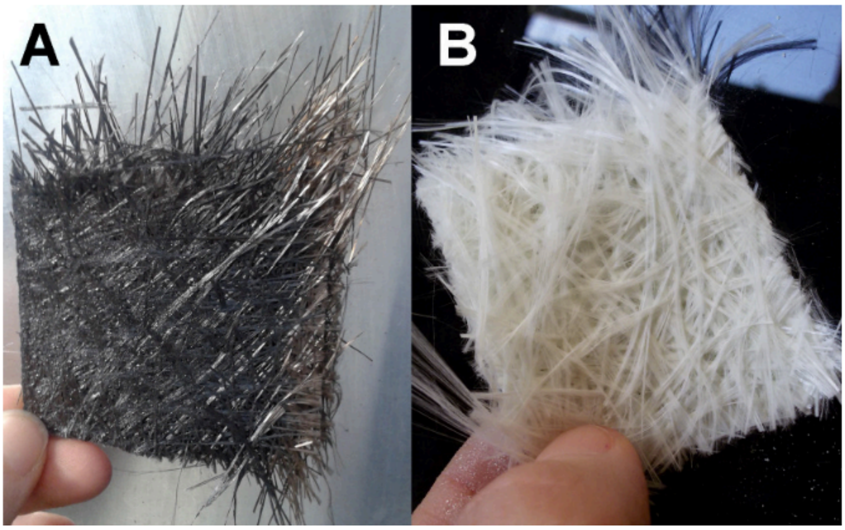


Figure 9-5: a) Solid product yield from GFRC pyrolysis at 500°C and b) clean recovered glass fibres after oxidation at 500°C (Giorgini, 2016).

Lastly, for some secondary applications, such as fibre mats, the arrangement of the fibres is important. Therefore, tangled fibres should be avoided. According to Lopez (2011) the output of the fibres is comparable to the input material. This means that shredded material will deliver a tangle of glass fibres and hand-size chunks will result in these same oriented hand size chunks (see Figure 9-5) (Giorgini et al., 2016).

Despite these three challenging factors for the quality of recovered glass fibres, there are several applications of this material described. One of the potential applications of the recovered fibres is the production of thermal resistance insulation materials like glass wool (Larsen, 2009; Yang et al., 2012).

Preferably, the recovered fibres are reused in a similar use like their original: reinforcement for high-end FRC. However, other than as a filler material, recovered fibres have not yet been used in virgin high-end composite (Pickering, 2006).

According to Oliveux et al. (2015), recycled fibres especially show potential for commercial application such as light duty parts like vehicle headlight housings or instrumentation panels. By means of pyrolysis recycled glass fibres from high-end composites have been successful implemented in these light-duty applications with concentrations up to 50% of the reinforcement, without affecting tensile, flexural or impact properties of the new material. However, beyond 50%, the properties significantly deteriorated (Oliveux et al., 2015).

Interesting to notice is the quick progress in this field whereas in 2006, Pickering reported that only 25% of virgin short glass fibres in polyester DMC could be substituted with recycled fibres without compromising on mechanical properties of the final composite. Does this offer perspective as well for the reuse in high-end composites?

9.3 Limitations

The limitations of the pyrolysis process stretch from the nature of the process to the yielded products of the process. On the one hand the limitations are concerned with the justification of pyrolysis as an environmental beneficial technology, on the other hand with the economic viability of the technology. They will be briefly discussed in this paragraph.

First of all, pyrolysis is ranked low in the EUW Framework. The definition of recycling as introduced in Paragraph 8.3 states that operations that reprocess EoL material flows into products, materials or substances are considered as recycling. No distinction is made on whether the new products serve the original or another purpose. It includes the reprocessing of organic material but does not include energy recovery and the reprocessing into materials that are to be used as fuels or for backfilling operation (Gharfalkar et al., 2015).

From the analysis of the potential application purposes of the process products, it becomes clear that in practice, the gaseous product of the pyrolysis of GFRC will be used for energy recovery (to power the process) and thus does not technically qualify as recycling. Also, the purpose of the pyrolysis oil is disputable if the oil is solely combusted as fuel oil. The current technology allows for reuse of the recovered fibres; however, these are lower-value purposes which means that the material is downgraded. Pyrolysis for GFRC from WTB could classify as higher-end recycling process providing that the pyrolysis oils can be used for the production of new polymer resin and the recovered fibres find a relatively higher application as composites reinforcement.

Besides the prospect of environmental benefits, the aim for improvement of output products is also driven by the economic viability of pyrolysis of GFRC. A higher quality output product increases the value and thus the economic viability of the process which on its turn increases the potential to commercialize the pyrolysis of GFRC. Generally spoken, the output of the process needs to achieve a higher quality than the current, especially for the solid part of the product yield.

The limitations concerned with each of the three basic output products of the pyrolysis process were discussed in Paragraph 9.2. Especially for the recovered fibres in the solid yield, quality improvements are necessary. According to Oliveux et al. (2015), for recycling by the means of pyrolysis to be economical viable, currently it is necessary to also recover the valuable products from the resins, such as the liquids and the gases. From an environmental perspective, this is always the case.

The optimization of the solid yield is concerned with a certain trade-off between the three limiting factors determining the quality of the recovered fibres (Paragraph 0). The mechanical properties of the fibres (such as strength) degrade significantly from the heat of the process, whereas the heat is necessary to remove the resin residue from the fibres. The higher the temperature, the stronger the mechanical degradation. Meyer et al. (2009) notices that it is possible to affect the fibre properties by minimizing the limiting factors in such way that the recovered fibres fit the demand of a predetermined application.

Additionally, it is important to notice that although the quality of the recovered fibres might be improved compared to the current situation, there will always be the comparison to virgin glass fibres. Currently degraded recycled fibres are not able to compete with virgin fibres in terms of costs and mechanical properties (Larsen, 2009). Therefore, until now the application industry is conservative in their choice of fibres. There is no incentive for them to choose for recovered fibres instead of virgin fibres. Reducing the costs of recovered fibres could achieve this.

The optimization of the product output of the pyrolysis process is strongly related to the execution of the pyrolysis process. As of now, there seems to be a gap in the understanding of the optimal process parameters to be able to commercialize the pyrolysis technology (Naqvi et al., 2018; Oliveux et al., 2015). This can also be identified as the reason for the lack of matured pyrolysis projects applied on an industrial scale. A lack of cooperation between stakeholders of the process may be stalling the further development of the technology. Combined power, knowledge and finances will contribute to the development process. Based on the information provided by Teuwen (personal communication, 22-11-2018), Saraswati (personal communication, 11-12-2018) and Suwotec (personal communication 17-01-

2019), more collaboration between potential stakeholders could accelerate the optimization of the pyrolysis for GFRC.

9.4 Developments in the field

Despite the limitations described in the previous paragraph, pyrolysis is currently the most promising recycling technology for composite waste as it is a proved and frequently used technology in other chemical applications (Oliveux et al., 2015) and it can potentially be applied at a larger scale. Further research and development will be needed to improve the recycling of GFRC by means of pyrolysis (some experiments in this direction are sketched below).

9.4.1 Economic feasibility

Currently, this type of pyrolysis is not executed on industrial scale. Previous projects have mainly failed because of economic reasons. One of the attempts for upscaled application of the pyrolysis of GFRC was conducted by the Danish company ReFiber. ReFiber is mentioned in several of the studies as the most matured GFRC recycling project. They had established a disposal and recycling route for GFRC from EoL WTB to glass wool insulation material, however the project ended in 2007 due to financial reasons whereas landfilling was the cheaper option for a large share of their clients (Larsen, 2009; Beauson & Brøndsted, 2016). However, policy is changing, and an increased number of countries is banning the landfilling of materials like GFRC (Ministerie van Infrastructuur en Waterstaat, 2017). This offers a chance/nudge for the industry to further develop a new, sustainable EoL solution.

The pyrolysis and solvolysis processes have been more developed to recycle CFRC than GFRC, whereas GF suffer from the high temperatures and corrosive chemicals more significantly than CFRC (Oliveux et al., 2015). For CFRC recycling by means of pyrolysis multiple industrial scale, commercially exploited examples are currently existent (Oliveux et al., 2015). This offers good prospect and leaves a clear gap in the market of GFRC recycling, which will become increasingly necessary in the coming decades because of the increased application of GFRC in the past decades (Paragraph 7.5).

9.4.2 Pre- and post-pyrolysis treatments

According to Pickering et al. (2000) the process economics can be optimized by improvements in the fibre yield or better preparation of the GFRC scrap feed. This can be achieved by the optimization of the pyrolysis process, as well as with the optimization of pre- or post-pyrolysis treatments. Pre-treatment developments of the fibres were already discussed in Paragraph 7.2. In terms of post-treatment options, Oliveux et al. (2015) mentions a patent by The University of Strathclyde that covers a cost effective, industrially applicable treatments to regenerate the strength of thermally recycled glass fibres. These treatments could increase the value of the recovered fibres and widen their potential applications. Nonetheless, these treatments will be accompanied with increased costs, which may not be competitive compared with virgin GF (Oliveux, 2015).

9.4.3. Thinking ahead

The Dutch research organization ECN (Energy research Centre Netherlands) that acts as part of TNO (Dutch organization for applied, nature scientific research) today, is conducting research into the recyclability of composite materials from WTB amongst other things. The urge of developing a proper EoL solution for WTB is confirmed by the wind energy department at ECN by TNO (Saraswati, personal communication, 11-12-2018). To be ready for the increased volumes of composite material flowing from the wind energy industry in 20-25 years, R&D is necessary now. Although other EoL solutions are taken into consideration, ECN focuses their research on the pyrolysis technology. They aim to start up a demonstration project resulting in a pilot plant, with help from a subsidy from the Dutch government. ECN is attracting partners to support their project, to create a network of potential stakeholders and investors. Current partners are Shell and the offshore wind consortium GROW. ECN is considering locations like Vlissingen, Eemshaven and Port of Rotterdam for a beforementioned pilot plant (Saraswati, personal communication, 11-12-2018)

9.4.4 Controlled Clean Pyrolysis

In the Netherlands, a small consortium of entrepreneurs and engineers called “sustainable world technologies” (Suwotec) has done multiple inventions that contribute to technology optimizations. Their “green solutions” aim for circular systems that are energy, mineral and resource neutral. They aim at improving waste conversion, energy storage and energy conversion. Their technologies could reduce the environmental impact of for example combustion engines or batteries.

One of their inventions is a non-corrosive electrode that can be used in sensors or in a guiding system within the process (Suwotec, personal communication, 17-01-2019). These non-corrosive electrodes are versatile and can be programmed for a specific application, such as the pyrolysis of EoL car tires, artificial grass mats or WTB. The use of the electrodes allows the optimization of one basic process set-up for various pyrolysis applications.

Implemented in a pyrolysis reactor, they allow an accurate decomposition process called “Controlled Clean Pyrolysis”. Although a specific technological description remains undisclosed by the company for patent protective reasons, Table 9-7 indicates the most significant differences of this improved type of pyrolysis compared to the standard pyrolysis as described in Paragraph 9.1. The main difference is the use of a fully enclosing material in the reactor, in this case sand, which emphasizes the heat transfer, reduces the energy use and improves the separation and removal of reaction products (Suwotec, personal communication, 17-01-2019).

The development of the ‘Controlled Clean Pyrolysis’ reactor by Suwotec is still in an early phase. The consortium has drafted a three staged plan. In the first phase includes further detailing of the technology, the development of a business plan and the inventory of required financing, subsidies, stakeholders and permits. The second stage involves the realisation of a test-lab to enable the validation of the technology and quantify and qualify the product yields. Both the first and second stage require significant investments which are searched for among stakeholders that could potentially benefit from the development of the technology as well. The final stage entails the actual testing and optimization of the process for different composite types. The projected profits of this stage will be refunded to the initial investors.

From this initiative and the research efforts undertaken by ECN, the potential for further optimization of the pyrolysis technology becomes clear. Although the technology by Suwotec is far from mature, it offers insights in potential optimization parameters of the technology. Also, the concept that one basic process and pilot plant can contribute to the optimization of pyrolysis for a wide variety of (composite) materials is promising. This however, requires stakeholder involvement and investments, which would be encouraged by a stronger network among stakeholders from a wider range of backgrounds.

Table 9-7: Differences between standard pyrolysis and Controlled Clean Pyrolysis by Suwotec (Suwotec, personal communication, 17-01-2019).

STANDARD PYROLYSIS	CONTROLLED CLEAN PYROLYSIS
Works with fluidization in the reactor.	Works with sand.
Several steps necessary to decompose different components.	One process in which different components of the composite are completely decomposed into reusable resources.
Heat transfer by means of radiation.	Heat transfer by means of direct contact between sand grains.
Party uncontrollable process	Completely controllable process because of inert gas. Improved measurements because of direct heat transfer.
No closed loop	Closed loop for full decomposition
High energy use	Low energy use
Limited heat transfer	Sand operates as insulator
Limited decomposition	Improved decomposition, increasing
Limited production of gas for reuse	the production of gas for reuse
Static	Dynamic

10 Preliminary conclusions

This chapter finalizes the presentation of the research results from the first phase of the study. The preliminary conclusions are based on the outcomes of this phase, the findings are recapped, structured and reflected on. These will also form the basis for the comparison scenarios that will be sketched in Part IV.

10.1 Recap of results

Chapter 7 provides insights in the WTB material compound and characteristics and the projects of EoL WTB blade in the coming decades. Starting at the basis; the primary material use in WTB is fibre reinforced composites. Fibre reinforced composites consist of two main elements; a reinforcement fibre and a matrix material. FRC are characterized by their high strength to weight ratio and thus their suitability for light weight applications like WTB. Other components in the composite structure of a WTB include a sandwich material which is often a PVC foam. Currently, glass fibres (GF) are the dominating reinforcement fibre for WTB, but to an increasing extent also carbon fibres (CF) and hybrids reinforcements are applied. GF are lower quality fibres than CF bust also have significant lower costs, making them more suitable for wide spread application, whereas CF are generally applied in high-end applications. The matrix material for WTB is a thermosetting polymer that is characterized by its cross-links that provide stiffness but also limit the recycling potential. Epoxy and polyester are the most abundant matrix materials.

A significant growth of the wind energy industry can be perceived in the last decades, following from both an increased popularity and more wind turbines being built as well as an increased rotor diameter per individual wind turbine. Global cumulative installed estimations for 2050 vary between 2300GW to 4800GW compared to current the approximation of 500 GW. The current cumulative installed capacity varies per region, but Europe was an early adopter of the wind energy (with ±160GW cumulative installed in 2017) and will therefore also meet the EoL WTB material issue first. This provides to opportunity to be a pioneer in the development of composite recycling technology. Considering an average lifespan of 20 years, the prediction for blade waste material in EU stretches form 50kt in 2024 to 100kt in 2029. About 80% of the total blade waste is assumed to be composite waste.

From chapter 7 it can be concluded that there is an existing urge to develop an industrial-scale recycling option to be able to treat the EoL GFRC waste that will flow from the wind energy industry in the coming decades. To further optimize the sustainable nature of the wind energy industry, this technology should be suitable to stimulate the use of GFRC with a minimal environmental impact. When it comes to the PoR, this is in line with their strategic future vision regarding sustainable development, but it should link to their current chain of activities as well.

Chapter 8 reviewed the existing EoL solutions for composite waste, their relation to the context of the PoR and their potential to be further developed in the future. These solutions are structured along the lines of the EUW Framework. The most preferred option appeared to be to prevent the generation of EoL composite waste by improving the design, but that option is not realized yet. A second option, especially seen from an environmental perspective, is the encouragement of reusing (parts) of the WTB. Currently, there are some friendly initiatives that apply parts of WTB in the construction of city furniture, bus shelters or children playground. However, it is assumed that there is no large market for this type of application which makes it less interesting for the case of PoR. A third option which seems promising is, repurposing the composite material, without decreasing its mechanical characteristics. Reprocessing flakes and strokes of the composite material, for instance as initiated at Windesheim, provides an interesting solution for secondary use of the composite material. However, at the end of its secondary life, it will still need a recycling treatment to dispose the composite material. With respect to the fourth option, recycling, several options are available, but pyrolysis was identified as the best scalable alternative amongst the chemical/thermal recycling options because it is not associated with any chemical/toxic chemicals.

Finally, also two disposal options are described. With respect to the first one, incineration of the composite material, it is concluded that GFRC are non-combustible at the temperatures of an average incineration plant. They also may damage the incineration installation, which makes it hard to find plants that accept the EoL composite material. Therefore, high prices are asked. The second option is using the material for landfilling. Until recently this was the cheapest option. But an increasing number of countries have banned this option and have put restrictions on the export of composite waste as well.

From chapter 8 therefore it can be concluded that from an environmental perspective, pyrolysis is not the first choice of EoL solution for WTB. But taking into consideration the suitability for industrial-scale implementation and relation to the context of the PoR, this treatment was identified as the most promising.

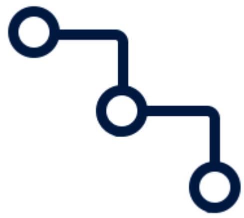
Chapter 9 elaborates on the working principle of the pyrolysis technology and the output products of this process. Different types of pyrolysis reactors are existent; varying from lab-scale to industrial-scale development stage. Basically, the only requirements for the process are energy to provide heat and an input material. Generally, three process output products are identified: gas, pyrolysis oil and recovered fibres. The exact content of the mix of these products is determined by the chemical composition of the composite materials used. The resin part decomposes in two products: (1) a gaseous product yield that can be used to provide the process itself with energy (low GCV); (2) a liquid product yield called 'pyrolysis oil' that is comparable to fuel oil and can used either directly or when mixed with conventional fuels. In some cases, the pyrolysis oils are suitable as a resource for the production of new polyester resin. The reinforcement fibres make up the biggest part of the product yield. Unfortunately, the solids, which consists of recovered fibres are mechanically degraded because of the heat in the process and come out covered in a thin layer of resin residue.

Optimizing this system is associated with a trade-off between the optimization parameters of this product group. The quality of the fibres that come out of the pyrolysis reactor determines the economic viability of the process. Pyrolysis of GFRC materials is a relatively young technology that is still in full development. Lately innovation mostly aims at the optimization of the product output to enhance the economic viability of the process. It is also assumed that the further development of the pyrolysis technology can benefit from intensified cooperation and networking among actual and potential stakeholders.

10.2 Structuring the results

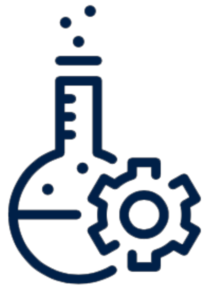
The results from phase 1 can be clustered in three cluster ideas.

Cascading composites



Although pyrolysis is not the most preferred technology, seen from an environmental perspective, reuse and repurposing the WTB material will also never reach a 100% circular material use and therefore have to be considered as in-between steps that postpone not fully reduce the amount of waste. It is assumed that at some point in the lifecycle, either after a single life cycle or after 3 lifecycles, the composite material cannot be reused or repurposed anymore and will require a technology such as pyrolysis. This current state of affairs this does not eliminate the urge for further improving composite pyrolysis technology.

Optimization of the pyrolysis technology



From the analysis of the pyrolysis technology in Chapter 8, several limitations can be identified. The pyrolysis technology for GFRC is currently not implemented at large industrial scale, many of the literature on pyrolysis describe lab-scale initiatives. This indicates that there is room for improvement of the technology. Following from the identification of these limitations, this optimization should be aimed at quality of the output products, especially for the recovered fibres, because the fibre quality determines the valuation of the product yield for a large share. Paragraph 9.4 reports about existing development initiatives that have adopted the same aims.

Increase cooperation between stakeholders

It was indicated by the existing pyrolysis developments initiatives that were consulted for this study, that the further development of this technology would benefit from more cooperation between actual and potential stakeholders. On the one hand to exchange information and acquire funding, on the other hand to learn and encourage from each other. Preferably these 'ecosystems' of stakeholders should consist of partners from various related disciplines and businesses. The meeting of these different perspectives may stimulate the creation of new knowledge, technologies and business opportunities.

First, the pyrolysis process is not solely suitable for GFRC recycling but also offers a potential recycling opportunity for other product groups such as artificial grass and car tires. Stakeholders from these fields can be interested to work together towards an optimized pyrolysis technology for the different input materials. Secondly, potential end-users of the output products can be involved. This group can provide specific information about the desired product-yield characteristics and might be incentivized to incorporate the pyrolysis product yield in their products. Lastly, overarching organisations that will be faced with the waste from EoL WTB issue such as WTB producers or wind park operators are interesting to include in cooperation.

PART IV SCENARIO COMPARISON

This part of this report describes the scenario comparison which was based on a three step-wise approach. Additionally, the comparison analysis and following results are presented.

This research is conducted for the Port of Rotterdam Authority

11 Comparison conditions

This chapter elaborates on the basic elements of the comparison: the system boundaries, the criteria and the context assumptions. Furthermore, the criteria that will be used to compare the scenarios with each other are introduced.

11.1 System boundaries

The boundary of the comparison sets the scope of the scenario analysis.

In this scenario comparison, the focus is on the closing part of the product system, because up to the decommissioning, the scenarios follow the same route (Figure 11-1). Product production, transport, product use and decommissioning are not expected to change due to a changing EoL solution.

Between the decommissioning of a WTB and its final EoL solution, transportation movements and a mechanical treatment are required. It is assumed that the EoL WTB can be reduced in size close to the decommissioning location. The transportation towards the EoL treatment plant are included in the system boundaries of the comparison. This means that the GFRC material enters system in chunks or hand-sized pieces that can be transported as bulk material in containers.

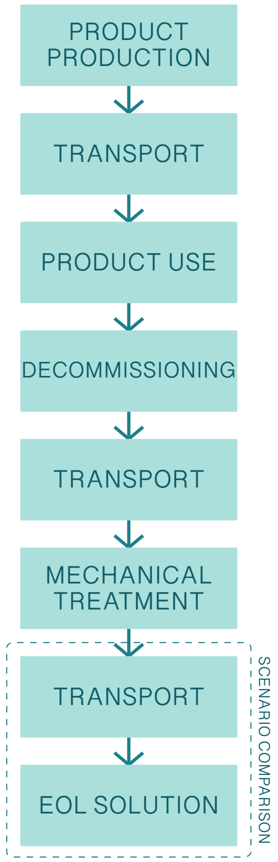


Figure 11-1: Schematic overview of system steps and the system boundaries for the scenario comparison.

11.2 Comparison Case

The scenarios will be compared based on the same conditions:

Time horizon: 5-10 years

It is assumed that it takes at least 10 years for a new technology, such as pyrolysis of GFRC, to mature and an industrial-scaled implemented technology. Therefore, the comparison case will assess the criteria at the end of this time horizon.

Amount of blade waste: 100kt in 2030

This amount is based on the findings from Paragraph 7.3, in 2030 is the end of the 5-10 year time horizon, 80% of this blade waste is composite waste (Table 7-1).

Recycled material: glass fibre reinforced composite

The material is considered to consist of 70% glass fibres as reinforcement material and 30% of epoxy resin (Paragraph 7.2) and has a GCV of 12 MJ/kg (Job, 2013). Other components such as the sandwich material and bolts and screws are assumed to be insignificant for the comparison case. The scenarios will be evaluated on their performance of treating 1 tonne of GFRC material.

Location of decommissioning: Flevoland

Paragraph 7.6 how the Flevopolder is one of the current hotspots for wind energy in the Netherlands. It is assumed that the wind turbines in this area are decommissioned in the considered time horizon.

Mode of transport: Over water

This comparison case assumes transportation over water EoL material. Appendix G elaborates on the potential transportation modes and the differences between them.

11.3 Comparison criteria selection

The criteria for the comparison were found in three categories; environmental criteria, economic criteria and criteria following the context of the PoR.

11.3.1 Environmental criteria and LCA impact categories

LCA criteria are used as guideline for the environmental comparison criteria. Figure 11-2 gives an overview of the mid- and end-point LCA impact categories (Bonou, Laurent, & Olsen, 2016). Not all of these criteria are significantly interesting for the defined comparison case.

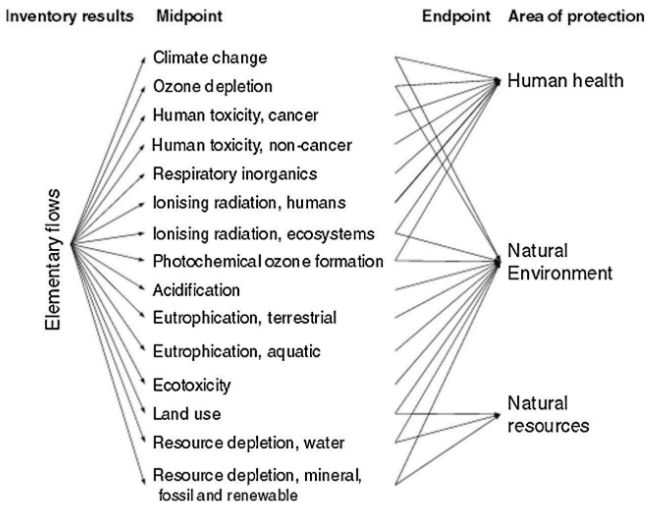


Figure 11-2: Mid- and end-point environmental impact categories of the LCA method (Bonou et al., 2016).

The midpoint impact categories are summarized in three endpoint impact categories also referred to as areas of protection (Figure 11-2). The aim for this study was to select criteria that could be linked to one or more of the areas of protection. The selected environmental criteria are:

- GHG-emissions
- energy use
- problem shifting; considering waste reduction and minimizing material use

The criteria of *GHG-emissions* and *energy use* are considered to contribute to climate change and therefore affect the Human Health and Natural Environment. The criterion of *problem shifting* is following from the overarching Life Cycle Thinking (LCT) that emphasizes the avoidance of shifting the problem from one part of the life cycle to another part or amongst different end-point impact categories (Chomkhamsri, Wolf, & Pant, 2011). *Waste reduction* and *minimizing virgin material use* are related to problem shifting and interlinked with the protection areas Natural resources and Natural environment.

11.3.2 Economic criteria and the Context of PoR

Also included in the research question is the boundary condition indicated with “the context of the PoR” in which the pyrolysis technology would thrive. Important criteria for this context were presented in Chapter 1 (Box 1).

One of the most important criteria from the PoR perspective is the *link to the chain of activities*. Together with the *market potential* and *future potential,* these three criteria are expected to provide interesting insights and will be assessed in the comparison. The market potential will be expressed in within the quantitative criterion of *product yield*, since the value is determined by the quality and market request.

Furthermore, the essential economic criterion *cost* is added to the set of criteria. Low costs allow quicker implementation and lesser financing and is assumed to be beneficial for both the environment, as well as for a commercial company like the PoR.

11.4 Comparison criteria explanation

The criteria selection resulted in a set of 7 criteria.

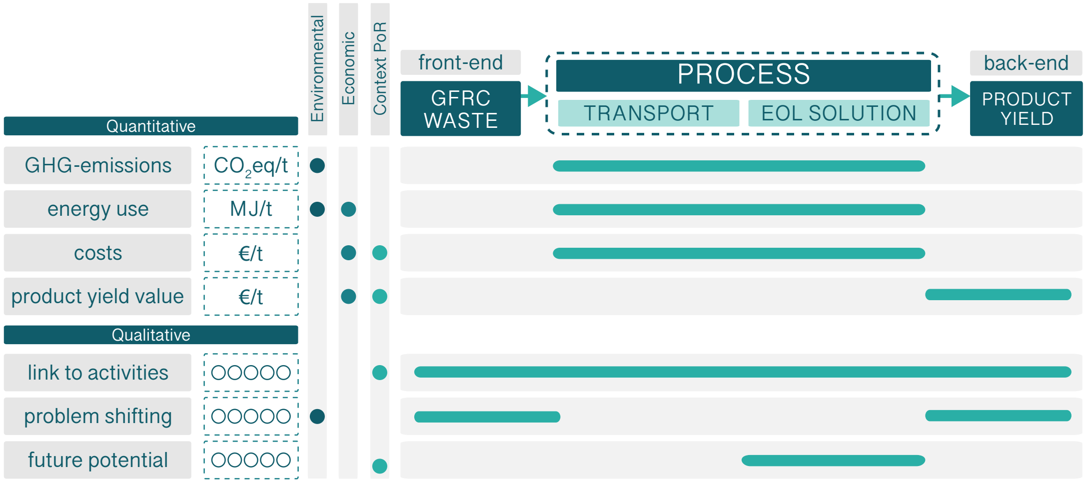


Figure 11-3 gives an overview of the criteria, their unit of assessment and their allocation to one or more of the categories. Additionally, it is indicated which of the system elements are considered in their assessment. In the following sections, each of the criteria and their (intended) method of assessment is explained.

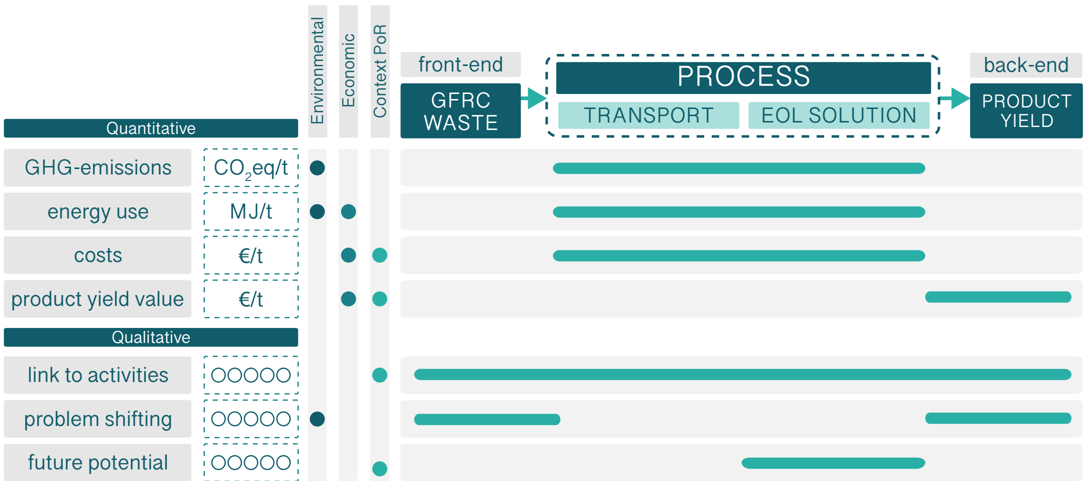


Figure 11-3: Comparison criteria with the unit of assessment, categorization and an indication in which of the system elements the criteria are considered.

11.4.1 Quantitative criteria

GHG-emissions [CO_2eq/t]

This criterion encompasses the transport to the EoL treatment facility and the GHG emissions of the treatment process itself. The GHG-emissions of the transport phase are determined by the distance between the decommissioning site and the EoL treatment facility. The unit of the GHG-emissions is CO_2 equivalent per tonne of treated GFRC material.

Energy use [MJ/t]

This criterion encompasses the transport to the EoL treatment facility and the GHG emissions of the treatment process itself. The energy use is expressed in Mega Joule (MJ) necessary to treat one tonne of EoL GFRC material.

Costs [€/t]

The criterion assesses the money that is necessary for the treatment one tonne of EoL GFRC, including the transportation and to execute the treatment process. This could include material costs, processing costs and initial investments. Note in this comparison potential additional costs like GHG-emission allowances are not taken into account.

Product yield value [€/t]

The value of the products is dependent on quality and necessity of the product. This criterion will assess the sum of the value of products yielded from 1 tonne of EoL GFRC.

11.4.2 Qualitative criteria

All qualitative criteria are assessed on a scale from 1 to 5. The rubric that was set-up for the assessment of these criteria is provided in Appendix I.

Link to chain of activities

This criterion is derived from the approach following from the context of the PoR (refer to Chapter 1). The link to the chain of activities is assessed from front-end to back-end of the system. For example, there is a relation between the input material (GFRC) and the port because of the wind energy industry. Furthermore, at the back end of the comparison scope there may be a strong link between one of the product yields of the process and the current activities in the PoR. No link to the chain of activities is indicated with 1, and a strong link with 5.

Problem shifting

The environmental approach of products and materials with LCT involves the consideration of 'problem shifting'. This criterion is related to the actual *waste reduction* and *minimizing virgin material use*. It should be avoided that the EoL treatment shifts the composite waste issue to or causes a new problem in another lifecycle stage or a different end-point impact category. In the considered scenarios, problem shifting could for example occur when the output products are applied in non-recyclables or if harmful additions are necessary to conduct the process. It is related to the front- and back-end of the system, because it concerns what comes in and what comes out of the process. Little problem shifting is indicated with 1 and major problem shifting it is awarded with score 5.

Future potential

Similar to a link to chain of activities, the *future potential* of an EoL treatment also contributes to attractiveness for the PoR. This criterion assesses whether the EoL technology offers perspective of further development, based on potential future changes such as different material use for WTB and laws and regulations. If a technology offers room for improvement and/or is adaptable to these future changes this is assessed as a positive future potential. This criterion is mostly related to the EoL solution of which technology can be optimized, including process optimizations considering a higher quality output product. An assessment of a low future potential is indicated with 1, and a high potential with 5.

12 Definition of the scenarios

In this chapter, a detailed description of the business-as-usual, the pyrolysis and the reference scenarios is given. To facilitate the comparison, the scenarios are simplified based on assumptions.

12.1 Business as Usual

The business-as-usual scenario describes the situation assuming that current recycling technology is continued and expanded, and pyrolysis is not further developed to become the primary recycling option for GFRC. It is assumed, that the business-as-usual scenario will be based on the most matured and least devaluating current EoL technology with a future application potential, assuming that this technology will be expanded and accepted. To simplify the scenario definition, note that it is assumed that one EoL solution dominates the field and other technologies are disregarded.

Identification of the business-as-usual EoL technology
Currently, four main routes are identified for the treatment of EoL WTB; landfill, incineration and recovery & recycling (Jensen & Skelton, 2018). Interestingly, a small share of the EoL WTB is stored to await a better recycling technology in the (near) future (Suwotec, personal communication, 17-02-2019).

From these four, the cement-kiln (CK) route is considered as the EoL solution for the business as usual scenario because it is a matured technology with a future application potential. The CK route is mentioned as one of the most popular current EoL routes by both Yang (2012) and Jensen & Skelton (2018). It is applied on industrial scale in Germany and the UK. Compared to incineration and landfill is ranked higher in the EUW framework. However, in Paragraph 8.1 it is discussed whether it is considered a recycling or recovering technology. The EuCIA recommends that EoL GFRC are *recycled* through the CK route (Job et al., 2016).

Working principle of Cement-Kiln route
According to EuCIA, (2011; Job, 2010), GFRC grind is an ideal raw material for cement manufacturing. The mineral composition of the glass fibres is coherent for the four basic oxides that are used in the production of cement and the organic fraction from the resin can supply fuel for the reaction heat.

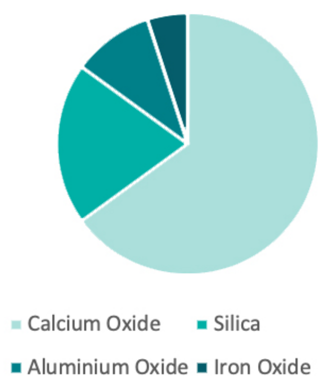


Figure 12-1: Ratio of basic oxides use in conventional cement (EuCIA, 2011).

The conventional cement clinker production process combines several raw material fractions with an energy source that is heated up to 1450 °C. The clinker is produced from a mixture of raw material that consists of four basic oxides in a specific proportion (Figure 12-1). These basic oxides also appear in the alumino-borosilicate glass (E-glass) that is typically used in GFRC. Borosilicate glass is produced by combing boric oxide, silica sand, soda ash and alumina (Job et al., 2016). It should be noticed that it was not investigated what the exact function of the glass fibre component is in the CK route. Additionally, the raw material inserted in the cement production process contains gypsum, an inert material like limestone and sometimes cementitious compounds such as coal fly. Together, this mixture of raw material is calcinated in the cement-kiln oven (Figure 12-2).

Both the calcination process, as well as the use of fossil fuels to heat to process are related to a significant amount of CO_2 emissions (EuCIA, 2011). To minimize their carbon footprint, the cement industry is developing alternatives that contribute to the reduction of the CO_2 emissions. For example, by replacing fossil fuels with alternative fuels (EuCIA, 2011). This provides an additional advantage of the addition of GFRC material to the process; the organic fraction supplies fuel for the reaction heat, *right at the spot where it is needed most* (EuCIA, 2011; Job, 2010; Job et al., 2016).

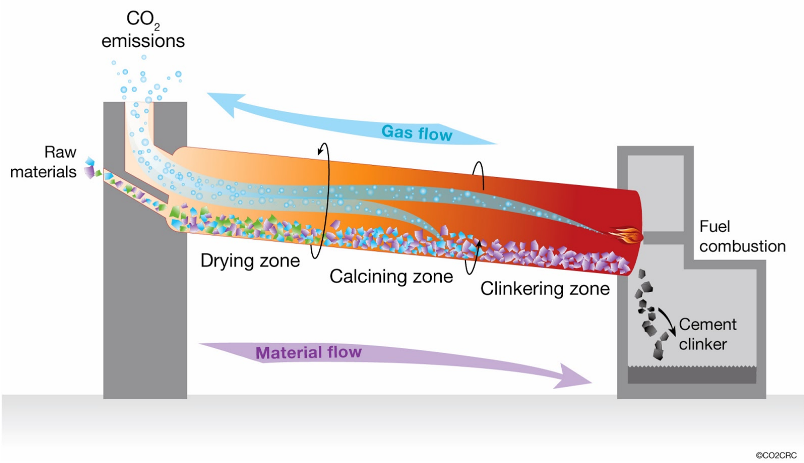


Figure 12-2: Schematic illustration of the production of conventional cement clinker (courtesy to CO2CRC).

One of the limitations for the cement-kiln route for GFRC is that the GFRC can only replace part of the input. According to Oliveux et al. (2015); Job et al. (2016), no more than 10% of the fuel input can be substituted with EoL GFRC material. This is due to the fact that the boron in the borosilicate glass fibres affects the performance of the cement at higher substitution levels. Noteworthy are the regional differences here, whereas E-glass from European manufacturers currently contain much less boron due to emissions regulations at manufacturing plants, compared to E-glass produced in China (Job et al.,2016). This means that GFRC with glass fibres from China should be carefully treated.

Figure 12-3 shows the included system steps for the cement kiln route. Compared to the pyrolysis scenario, besides the obvious difference in EoL technology, there may be differences in the energy requirements and the CO_2 emissions of the necessary mechanical treatment and the transportation distances. Appendix H contains the specifications for the cement-kiln route. Currently this EoL solution is provided at a cement production facility of Neocomp in Bremen. It is assumed that in 10 years this production facility will still be there and/or another installation will be available at similar distance. The conventional cement-kiln process is fuelled with coal.

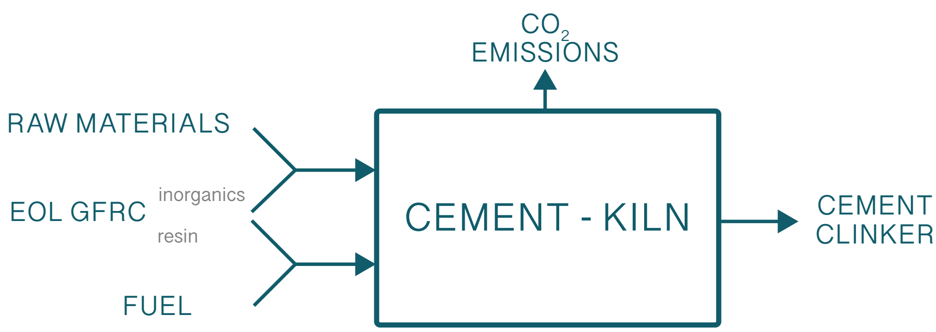


Figure 12-3: Schematic overview of the cement-kiln route for EoL GFRC treatment as considered in the CK scenario.

12.2 Pyrolysis scenario

The definition of the pyrolysis scenario (PYR) is based on the analysis in the first part of this research, leading to the preliminary conclusions as described in Chapter 10. It is important to notice that this scenario is includes the implementation of a technology that is not yet successfully implemented on large industrial scale. That means, that there is no accurate data available for criteria such as the CO_2 emissions and/or energy use of the process applied on large industrial scale. These criteria will be assessed based on assumptions and the result of studies of lab-scale implementation. Moreover, it should be noted that this comparison does not include or account for unexpected limitations that may only occur when the technology is practically implemented on an industrial level.

12.2.1 Considered implementation of pyrolysis

The product system steps of the PYR scenario are considered the same as for the CK scenario except for the EoL solution. Notice that the cascading of the material as was introduces in Paragraph 10.2, is not adopted in this scenario. This can be motivated by the assumption that this 'extra loop' would only be beneficial to the total environmental impact of a single unit of material. Nor has the implementation of this extra loop direct impact on the outcomes of the EoL treatment, because it only postpones the issue. Note that this is bound to the constraint that additional (pre)processing and transportation for a secondary application remain within reasonable limits. However, a full consideration of this aspect of the system loop does not lie within the reach of this scenario comparison.

In terms of the optimization of the pyrolysis process in 5-10 years, it is assumed that a large share of the product yield can be used for a secondary purpose. The gaseous part will serve as energy input for the pyrolysis process, the pyrolysis oils can be sold as fuel oils and the solid yield is divided into three parts; 40% of the recovered fibres is assumed to have relatively high quality and allows for application in high-end composites, 50% of the recovered fibres have degraded to low quality and allow for reuse in low-end composites and 10% of the recovered fibres is not suitable for reuse and will be wasted.

Although it is not expected that the pyrolysis of GFRC has reached wide spread implementation within the time horizon of 5-10 years, for the simplicity of this study the 100% pyrolysis scenario is considered.

12.2.2 Working principle of pyrolysis

The pyrolysis technology is extensively described in Paragraph 9.1. In this section the specifications of the assumed pyrolysis process characteristics for the comparison are explained. It is assumed that in the coming 10 years, the pyrolysis technology will be further optimized which translates in higher-quality yields. The energy input of the system is assumed to be generated by renewable energy sources with minimal GHG emissions. The specifications for the pyrolysis technology as considered in the pyrolysis scenario are given in Appendix H. Figure 12-4 shows a schematic overview of the pyrolysis process input and outputs.

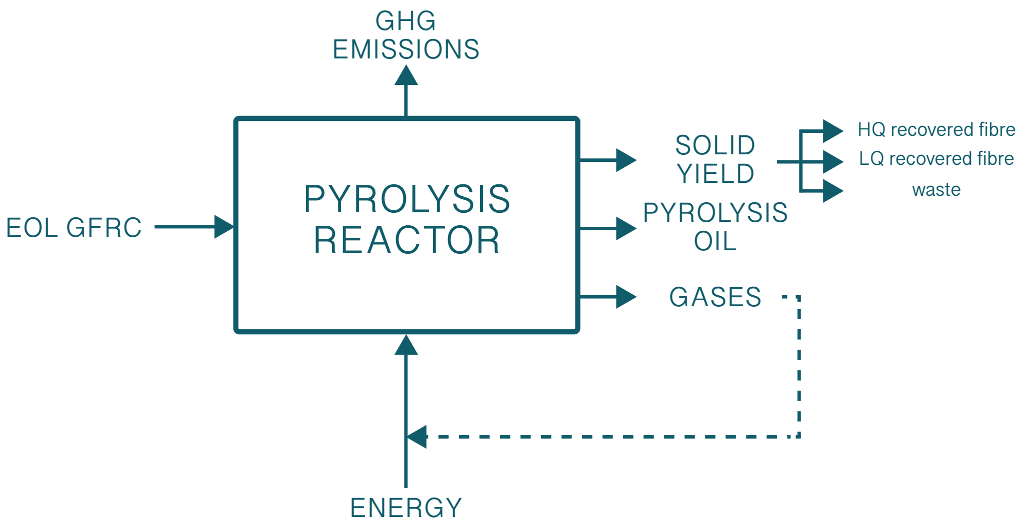


Figure 12-4: Schematic overview of the pyrolysis treatment of EoL GFRC as considered in the PYR scenario.

12.3 Reference scenario: Landfill

Although landfill of composite materials is becoming prohibited in an increasing number of countries (Paragraph 8.1), considering the landfill scenario (LF) puts the other scenarios into perspective. Landfill can be seen as an “easy” solution. Compared to other EoL solutions, there is generally little energy use and GHG-emissions related to landfill because it does not involve a treatment process besides the mechanical treatment. However, landfilling the waste does not truly solve the problem but leaves it for later generations.

For this comparison analysis, the system steps of the LF scenario are similar to the steps of *the business-as-usua*l and *pyrolysis* scenarios. It is assumed that:

- The EoL GFRC is mechanically treated on the decommissioning site and transported to the PoR.
- From there it is further transported over a radius of maximum 200 km by train to be landfilled in the country. The GHG-emissions and energy use for this step will be added to the transportation step.
- No more mechanical treatment is necessary than for the other technologies.
- It is assumed that the basis of a landfilling site is already in place.

13 Comparison Results

This chapter presents the findings of the comparison analysis for the quantitative and qualitative criteria. Additionally, a set of limitations related to the analysis is presented.

13.1 Quantitative criteria

This paragraph presents the available results for the assessment of the quantitative criteria and the related limitations are pointed out.

GHG-emissions and Energy Use

The results of the basic calculations for GHG-emissions and Energy use are presented in Table 13-1. The first column represents the CK scenario, the second column contains the results for the Pyrolysis scenario, based upon the assumption that only 60% of the GFRC is treated with pyrolysis, the other 40% with cement-kiln. For reference, an additional scenario in which 100% of the EoI GFRC is treated with pyrolysis is added in the third column. The calculations and assumptions that these results are based on are described in Appendix H.

Table 13-1: Numerical results from basic calculations for two of the quantitative criteria; GHG-emissions and Energy use (see Appendix H).

		CK	PYR	LF
GHG-emissions	[kgCO2eq/t]	9.454,2	±280-300	10,0
Transportation to facility		4,2	2,0	10
Process emissions		9.450,0	*±280-300*	0
Energy Use	[MJ/t]	32.450,4	12.024,0	184,0
Transportation to facility		50,4	24,0	184
Process energy use		36.000,0	13.500,0	*minimal*
Energy Yield		-3.600,0	-1.500,0	0

What can be concluded form these results:

- The CK process produces a significant amount of GHG-emissions.
- Compared the GHG-emissions of the CK process, the GHG-emissions related to transportation are negligible.
- The GHG-emissions in the pyrolysis process occur during the combustion of the gaseous product part but the quantity is dependent on the resin chemical composition, an estimation is given in Table 13-1 (for calculation see Appendix H). Compared to the GHG-emissions of the CK process as calculated in this analysis this amount is significantly lower than for the CK process.
- Based on these results, the 100% Pyrolysis process requires about one third the amount of energy necessary for the CK process.
- Compared to the energy use of the processes, the energy use for transportation is negligible.
- Both the CK process and the pyrolysis process yield energy by combusting (part of) the resin content of the GFRC material.
- Based on this assessment, the LF scenario is related to the lowest *GHG-emissions* and *Energy use*.

Costs & Value of the output products

For these financial criteria, no satisfactory data were found. This is mainly due to the uncertainties that are related to a technology under development (such as pyrolysis). There are many unknows that hamper the estimation of process costs and investment costs. Also, the quality of the output product also determines the value of the output products. Additionally, there is a wide variety between the accuracy and the embedded costs (profit margins etc.) of the different sources. Appendix H includes an exploration of these values, but it did not deliver a result.

13.2 Qualitative Criteria

The qualitative criteria are assessed on a scale from 1 to 5. This scale is explained in more detail for each of the criteria in the rubric provided in Appendix H. Figure 13-1 gives an overview of the assessments of the qualitative criteria.

Link to chain of activities

Considering the CK scenario as described in Paragraph 12.1, the link with the chain of activities with the PoR is assessed as weak. There is only a potential link with the back-end of the system; the processing of cement-clinker in the port of Rotterdam.

Qualitative criteria	CK	PYR	LF
link to activities	●●○○○	●●●●●	●○○○○
problem shifting	●●●○○	●●○○○	●●●●●
future potential	●●●○○	●●●●○	●○○○○

Figure 13-1: Assessment of the qualitative criteria for both the scenarios, based on the assessment rubric.

For the PYR scenario, the link to the current chain of activities of the PoR is assessed as strong. A potential link between all of the three product stages was identified. First of all, there lies an opportunity of the transportation of the bulk EoL GFRC material over the waterways or via coastal areas towards the port, this link would be even stronger when offshore wind turbines are considered. Secondly, there is a 'pyrolysis cluster' formed within the PoR, connecting stakeholders that are working with the pyrolysis technology for some process, provides an interesting basis for the development of the pyrolysis technology for EoL GFRC (Paragraph 1.4). Lastly, for two out of three output products of the process is a direct application in the port areas (Paragraph 9.2). Moreover, there is experience with the use of pyrolysis oils in secondary process available in the PoR.

For the LF scenario, transportation through the PoR is assumed, this gives this scenario a weak link with the existing chain of activities in the Port of Rotterdam, because there is a link with the front end (transportation) of the system.

Problem shifting

The CK scenario is associated with a moderate problem shift. The cement-clinker is used for the production of new concrete. Besides the GFRC it requires a lot of other (virgin) input materials and uses significant amounts of energy. However, ultimately the cement industry produces significant amounts of waste since the recycling technologies for concrete are still very limited. Currently, concrete is crushed and used as sub-base gravel in for example road constructions. However, it is expected though that there have been developments in the field of concrete recycling in 2030 (Schneider, 2011).

There is a moderate problem shift associated with the PYR scenario. All three output products of the process; gases, pyrolysis oils and the recovered fibres can used in new products. Also, no chemicals or other (Virgin) input materials are necessary for the process. Although the process has a significant energy requirement, part of the energy is provided by the gaseous yield of the process, which indicates a circular relationship. However, there still is a moderate problem shift because the recovered fibres will be used in a lower-grade application, eventually ending as waste.

For the LF scenario, this is a crucial criterion. From the assessment of the quantitative criteria for the LF scenario, the ban on landfill in an increasing number of countries cannot be reasoned. However, landfill is related to a major problem shift. Although this EoL solution does not need any other (virgin) input materials and does not use significant amounts of energy, LF does not solve the waste issue. The waste is hidden to deal with later (in a next generation), this can be identified as 100% problem shift.

Future Potential

The future potential of the CK scenario is limited. On the one hand the technology is expected to be further developed, for example to allow higher rates of GFRC material to be inserted in the process without affecting the quality of the cement clinker. From this analysis it did not become clear if CFRC and hybrids could also be treated with the CK process. However, if the reinforcement material is mainly used as a substitute of sand, it is assumed that the CF is too valuable to end up as a filler of cement-clinker. This would make the technology unsuitable for future materials.

The PYR scenario is assessed with a significant future potential, this is the average of two elements; future development and suitability for feature materials. In terms of development, pyrolysis is assessed moderately. Although currently there is room for improvement of the technology, as explained in Paragraph 9.4., it is taken into consideration that in 2030 the pyrolysis technology has improved strongly from its current status and the window for optimization is smaller than it istoday. In terms of suitability for the treatment of future materials pyrolysis is assessed with a high potential. Although for hybrid FRC some constraints are identified (Paragraph 9.3), it is argued that pyrolysis is even more interesting for CFRC than for GFRC (Oliveux et al., 2015). This is explained with the better resistance to heat of CF and the higher initial value of CF compared to GF, which results in less degraded, higher value recovered product yield.

The future potential of the LF scenario is assessed as non-existent. The ban on landfill for composite materials is installed in an increasing number of countries restricting the application and development of this technology.

13.3 Limitations of the results

During the assessment of the criteria, a number of limitations of this comparison analysis were encountered, these limitations re-appeared for different criteria. This paragraph clusters these limitations in 5 groups. Table 13-2 gives an overview for which criteria the limitations were encountered.

Table 13-2: Overview of the limitations of the comparison analysis that were encountered for the various criteria.

	Quantitative criteria				Qualitative criteria		
	GHG-emissions	Energy Use	Costs	Value output products	Link to chain of activities	Problem shift	Future potential
Allocation of the burden	X	X					
System boundaries	X	X				X	X
Uncertainties	X		X	X			X
Lack of understanding							X
Restriction of the comparison case	X				X		X

Allocation of the burden

- Both the *GHG-emissions* and the *Energy use* of the CK process are significant (9454 $kgCO_2eq/t_{GFRC}$; 36000 MJ/ t_{GFRC}), but these are not only related to the processing of the GFRC material but also to the production of cement, a product that most likely would also be produced without the processing of GFRC material.

System boundaries

- Considering the *GHG-emissions* and the *Energy use* of both systems, the system boundary can give a distorted view. This is explained by the following:
  - In the CK process the total resin component (300 kg) is combusted with a GCV of 12 MJ/kg. The energy yield of 3600 MJ per tonne GFRC and part of the total GHG-emissions associated with the combustion of the resin can directly be allocated to this process.
  - For the pyrolysis process, part of the energy yield and the GHG-emissions are only indirectly related to the process, because they appear in secondary use. In this process, the resin is split in a gaseous and a liquid part, the gaseous part (100kg, GCV 15 MJ/kg) is combusted from which 1500 MJ energy is retrieved and an approximate amount of GHG-emissions of 40-60$kgCO_2eq$ is emitted, directly allocated to this process. The liquid part is preferably not combusted but used as a resource for new resin material and therefore not releasing energy. However, if the liquid part is used as fuel oil, the energy yield would appear outside the system boundaries of this comparison and not be accounted for. The same is true for the GHG-emissions related to that combustion.
- The system boundaries also affect the outcomes of *problem shift* criterion assessment significantly. In this assessment, the rubric for this criterion included identification of the secondary use of process products. But the problem might be shifted to a more distant stage of the lifecycle. To really address this criterion a full LCA would be necessary.
- In terms of *future potential,* the system boundaries also restrict the span of the assessment. Potential developments outside of the comparison boundary are not taken into account. For example, companies that see a product (recovered fibres) and adjust their product to it or find a new application of it.

Uncertainty

- In general, due to the state of development of the pyrolysis, many process characteristics are still uncertain, this makes it hard to find reliable data for the pyrolysis process but also restrains the search for opposite data for the CK process.
- The uncertainty about the composition of the gaseous product of the pyrolysis process limits the calculation of the *GHG emissions* of this process. It requires more insight into the chemical composition of different resin types and to what gases and liquids they are composed.
- The data about the *financial criteria* that was found in this study was not reliable enough to draw conclusions from. This requires more certainty about the necessary development and the related costs, as well as a more in-depth search for data on product valuation (which for pyrolysis is again dependent on the development of technology).

Lack of understanding

- The assessment of the *future potential* of the CK process is hampered by incomprehension of the role of the composite substitute in the process. It is assumed that the silica from the glass substitutes part of the sand. Is the silica a requirement of can it also be substituted with carbon filler material?

Restriction of the comparison case

- Most likely, a large share of the *GHG-emissions* related to the CK process are induced by the combustion of coal to generate heat. For the pyrolysis process it is assumed that renewable energy resources are used for heat production. Although it is not expected use of renewable energy source will eliminate the *GHG-emissions* for the CK process, it will most likely significantly reduce them.
- Another assumption in the comparison case is that the pyrolysis oil produced by the pyrolysis process is used as source for new resin material. However, when the pyrolysis oil is used as fuel oil, and thus is combusted; the resin component of the GFRC is used in a similar way as in the CK process, releasing the same energy and *GHG-emissions*. One could wonder, if in this case pyrolysis isn't a very cumbersome solution.
- The assessment of the criterion *link to chain of activities* is affected by the definition of the comparison case. For example, would there be a different outcome if it was assumed that a CK facility/plant would be located in the port of Rotterdam?
- The PYR scenario is based on the assumption that within the time horizon of this study (10 years) pyrolysis will be the EoL solution for all the GFRC material. However, this quick implementation and a 100% monopoly for one technology is quite unlikely and therefore the *future potential* for the PYR scenario is distorted. Appendix H includes the assessment of the quantitative criteria for a scenario in which 40% of the GFRC is treated with CK and 60% with the pyrolysis treatment.

13.4 Conclusion of the Comparison Analysis

Based on this comparison analysis, no definite answer can be given to the main research question. The environmental benefits the PYR scenario compared to the CK scenario could not be quantified. However, the comparison analysis shows that, compared to landfill and cement-kiln, pyrolysis can deliver both environmental and economic benefits, providing that the recovered fibres and pyrolysis oil both find high-value secondary applications and that the combustion of the pyrolysis oil as fuel oil is avoided.

The impact categories considered in this analysis have been carefully selected but propose some limitations. These limitations form the basis for a set of recommendations for further research that are given in Paragraph 15.1.

PART V EVALUATION

This part aims to reflect on the research. The methodology and results are discussed and put into perspective. Recommendations for further research are defined and a final conclusion to the research question is given.

14 Discussion

The aim of this chapter is to reflect on the results. To zoom in on the results of the study; the research methodology is reflected on and the results are discussed. Thereafter we zoom out to see how the study relates to its broader context and has generated interesting insights on how pyrolysis could contribute to the overarching transition towards a circular economy.

14.1 Reflection on the Research Methodology

The method of the research is based on combination of academic knowledge (desk study) and practical experiences (field study). The expectation that this would provide a better understanding of the context was sufficiently met. However, by refining the methods for data generation in future studies, the results can be optimized.

Desk Study

Desk study provided a satisfying basic understanding of the different technical concepts that were part of this study. However, there were discrepancies between different studies that required to nuance the data before using them in comparison analysis. During the desk study it became clear that knowledge about the pyrolysis technology for GFRC is mostly limited to lab-scale experiments (Kaminsky, 2010; López et al., 2011; Oliveux et al., 2015; Pickering, 2006; Torres et al., 2000). In a next study, enlarging the number of reviewed papers is expected to provide a better overview of the achieved results in existing literature.

Field Study

The goal of the field study was to complement the theory provided by the desk study with knowledge from practical experience. The aim was to conduct (semi-structured) informal interviews with experts from different fields related to the research question. This structure gave the experts a level of freedom to explain their vision and knowledge. The field study provided interesting insights that were valuable for the course of the study. However, for a more in-depth technical research on the total life cycle of WTBs, it is recommended to select a bigger number of interviewees on one subject and to use a code scheme, to retrieve more objective information.

Comparison Analysis

The information retrieved from the desk- and field studies was combined in the set-up of a comparison analysis that aimed to answer the main research question. Although the comparison of the scenarios did not deliver an answer to the main research question as expected due to a variety of limiting factors, these limitations provide a basis for recommendations for further research (Paragraph 15.1). It can also be discussed if the set-up of the scenario comparison hampered the effectiveness of the analysis. Because the set-up of was part of the study, including the definition of the system boundaries and the selection the comparison criteria, it may be argued that the set up unintentionally generated biased results (e.g. confirmation bias, attentional bias and pro-innovation bias). In a next study, more attention could be paid to the selection of an existing, verified framework for such an analysis.

Existing Frameworks

Except for the LCA methodology, that was used for the selection of the comparison criteria, no other existing frameworks or methods are applied in this study. This can be explained by the explorative nature of the research, which demanded continuous adjustment to the interesting findings that came up during its execution. In a next study, more research into the applicability of existing frameworks or methodologies could be beneficial, to investigate which of these methodologies are preferable in this field of research or whether another methodology has to be developed.

14.2 Discussion of the results

This study has delivered results from the two phases of the research as described in Chapter 10 and Paragraph 13.4. This paragraph presents some critical comments and remarks on the results that could provide a starting point for future research.

Cascading

The first of the preliminary conclusions is that it is recommended to encourage cascading of the composite material in secondary and tertiary lifecycles before it is treated with the pyrolysis technology. This way, the material utilization is optimized. Besides, it will release time pressure on the composite waste issue, which creates more time to optimize the pyrolysis technology. A critical note to the cascading is that the material is most-likely scattered over a number of applications, with different release times and locations. It can be argued whether this scattering of material hampers the 'return' to the pyrolysis facility. However, it is believed that when the EoL solution is already taken into account in the design phase the scattering can be minimized and the potential to cascade composite materials or parts can be stimulated.

Technology Optimization

The need for optimization of the technology came forward from both the first and second phase of the research and forms one of the most important conclusions of this study. It is expected that the pyrolysis technology can deliver both environmental and economic benefits compared to landfilling or treatment with the CK process, providing that the recovered fibres and pyrolysis oil both find high-value secondary applications and that the combustion of the pyrolysis oil as fuel oil is avoided.

To be able to find use in high-value secondary applications, the quality of the products requires optimization. Therefore, unknowns about the working principle of the technology need to be disclosed such as, how the heat of the process degrades the glass fibres and the different compositions of pyrolysis oil.

Also, from an economical perspective the optimization of the technology is important. Phase 1 showed that previous attempts of pyrolysis for GFRC have failed because of (mainly) economic reasons, which could be overcome when more valuable output products could be produced by using pyrolysis. This study showed a strong interdependency between the economic benefits and the optimization of the process, as the economic benefits of the pyrolysis technology can be enlarged when products achieve higher qualities (Figure 14-1). This requires R&D projects for which the funding is not initially available and thus requires an investment.

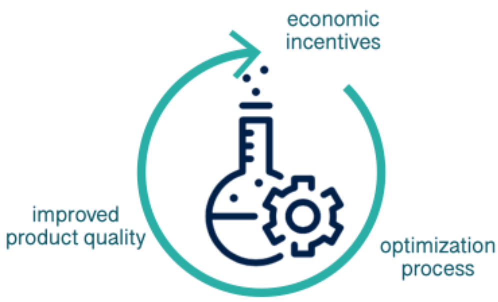


Figure 14-1: Interdependency of technology development and economic incentives.

Another critical comment arises from this line of reasoning: it can be argued that further development of the pyrolysis technology is not an interesting investment because of the uncertainty about the potential performance of the technology and the investments that are needed for R&D. This argument will be put into perspective in the following paragraph.

Stakeholder network

The further development of pyrolysis technology could also be encouraged by cooperation between stakeholders from various aspects of the composite waste issue. This was the last preliminary conclusion of the first phase of the research. However, the experts who were consulted indicated that at his moment there is a still lack of cooperation and transparency in the field of stakeholders. The advantages of more cooperation are explained in Chapter 0. On the other hand, working in cooperative networks always faces some challenges. For example, goals and expectations must be clearly identified and contracted together, to prevent disappointment and/or distrust. Also, an equal distribution of efforts and benefits must be secured, and the work needed to maintain the network should be limited and achievable for all participants.

Approach

A final remark on the results of this study concerns the approach. This study is conducted from the perspective of the PoR. It can be argued if the results would be different if the research question was approached from another perspective. For the PoR one of the main criteria assessing new business opportunities is that there is a link to the existing chain of activities in the PoR areas. But seen from the perspective of other organizations different criteria may be more leading. For example, for a provincial government, like Flevoland the clean decommissioning of Wind Turbines may be a focal point. From the perspective of a WTB production company, the main goal may be to secure a healthy and future-proof business. In these latter cases it can be argued that solutions lies at a broader scale then pyrolysis technology and for instance may need changes in the design of the WTB, whereas from the perspective of the PoR there was not much interest in this field of change, because at the moment there are not many relations between the current chain of activities in the PoR and the broader network of innovative stakeholders in the field of development and production of WTB.

14.3 Relevance of the study in the broader context

As was introduced in the introduction of this report, one of the main motives of this research is the worldwide transition towards a climate neutral economy, and especially towards a more circular reuse of the expected increase in WTB waste. The PoR aims to be carbon neutral in 2050 (Paragraph 1.2) in line with the goals of the Paris Climate Agreement of 2015, that was also signed by the Dutch government and aims at mitigating global warming.

It is believed that mitigating global warming goes hand in hand with a transformation of our current socio-technical system, including the way we provide ourselves with energy and the way we use the resources provided by the planet. This is a gradual transition that is taking place step by step on multiple levels (Geels, 2002) and is carried forward by intermediate technologies that could be identified as so-called “transition technologies”.

In climate policy a well-known distinction is made between adaptive and mitigating measures. Adaptation from climate change involves measures that take action to reduce our/human vulnerability to the consequences of climate change. Whereas mitigation from climate change includes measures to avoid the increase of pollutant emissions. In other words, it tries to solve the problem at its source.

Transition technology

In this research the attention was especially focused on the possible contribution of pyrolysis technology to reuse the composite materials in WTB in order to avoid the creation of a large waste issue. And although this study showed that it is not clear if this technology currently is able to solve this problem sufficiently, it can be discussed that that pyrolysis is a *transition technology*, an adaptive measure. It is currently a promising way to treat the waste that has been created and could form an early step towards the further development of technologies that will be able to successfully solve the composite waste issue in the future. And therefore, pyrolysis could be used and further improved in the coming years to be used in later years as part of the broader transition towards a carbon neutral and circular economy.

Long-term solution

Looking at the composite waste issue with a long-term perspective, the ultimate solution lies in measures that mitigate the problem at the source by avoiding the production of composite waste. It is believed that this transition towards a fully circular solution will be based on multiple and variable aspects of the larger social, technological and economic system, such as the availability of partners, knowledge, money, time, risk & benefits, scope and effective cooperation between a larger network of stakeholders. Geels (2002) described a multi-level-perspective (MLP) on technological transitions. According to Geels (2002): "Sociotechnical change is described as a process of shifting assemblies of associations and substitutions". This means that, changes in one network, can activate transformation of another (higher-level) system.

Figure 14-2 shows the attempt to grasp this broader *transition context* of the issue in a schematic figure. Where pyrolysis is a *current technology* that has the potential to become a *developed technology* by further technical improvement in the efficiency and circularity in the use of outcome products that may be accomplished on relatively short term in cooperation (5-10 years) with acquainted stakeholders. It is related to small potential benefits but also to small risks. Over time, the EoL solution changes gradually to a mitigating solution in a change in the design of WTB that is located in a higher-level system (Geels, 2002). It may transfortm towards a changed system in which (for example) the composite material for WTB is no longer owned used for a certain amount of time and at EoL returned to its owner, for instance, as described in the turntoo® model by Rau and Oberhuber (2016).

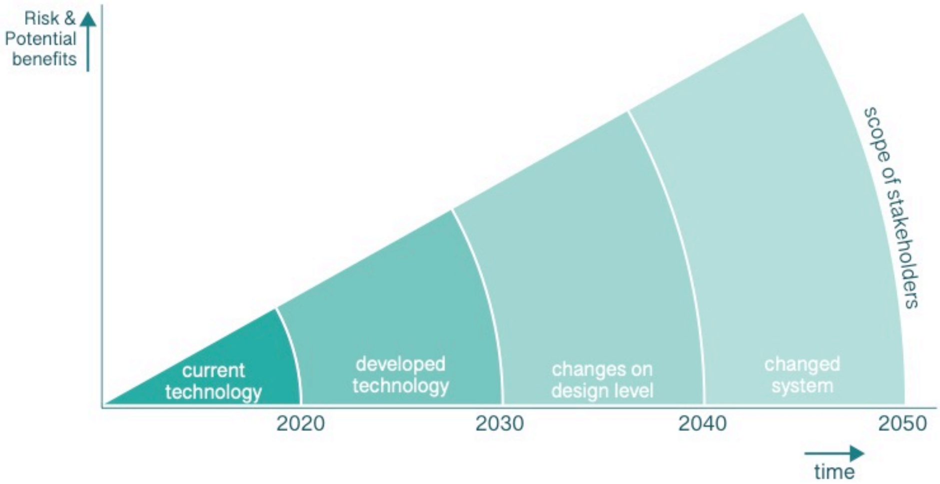


Figure 14-2: Schematic view of the transitional context between the current situation and a transformed, circular & carbon free system.

Perspective of the PoR

It can be discussed how the critical comments presented above relate to the future aspirations of the PoR. Based on this line of reasoning; recycling GFRC by means of pyrolysis will eventually be an outdated technology which presents a barrier to invest in it. Additionally, one of the main criteria for the PoR is that there is a link to the current chain of activities. The link between pyrolysis and the current chain of activities in the PoR is elaborately discussed, but the link between the current chain of activities and the activities in the follow-up stages, moving towards the design and production stage of the WTB lifecycle, can be debated.

However, as was indicated in Paragraph 1.2: the PoR is always trying to keep up with the changing world around them. The current overall tendency, towards a carbon neutral economy (Vos, 2018; Ministry of Economic Affairs and Climate, 2016), is expected to affect their current chain of activities by decreasing the fossil fuel related activities in the port. This means the portfolio makes room for newly emerging markets.

Besides, it can be discussed that entering the field opens up new business opportunities. By taking the first step, the PoR may become an early partner and influencer of the developments in this transitional field. This is invigorated by the observation that the early adoption of wind energy in Europe at the end of the 20st century now provides an opportunity to take on a pioneering role in developing technologies and business models for mitigating the composite waste from EoL WTB (Chapter 10). It is believed that becoming a pioneer in circular solutions for composites can deliver both commercial benefits and contribute to a more circular flow of materials in the PoR.

15 Recommendations

In closure of this thesis I want to give some final recommendations to improve my study and to continue the research in this field. The execution of this study has provided insight which areas require further investigation as well as potential opportunities for the PoR. Recommendations based on these insights are explained in this paragraph.

15.1 Further Research

Recommendations for further research can be given in two categories. First, recommendations are done in line with the aim of this study; finding out to what extent pyrolysis can deliver environmental benefits compared to other EoL solutions for GFRC from EoL WTB. Secondly, this study also revealed interesting directions of further research that could contribute to the overarching goal of a carbon-neutral and circular economy.

15.1.1 Recommendations in line with this research question

The clustered limitations of the comparison analysis given in Paragraph 13.3 provide a good basis for to build on for further research.

- Conducting a full LCA study

Both the limitations related to the *allocation of the burden* and the *system boundaries* could be overcome when a full LCA study would be conducted. This full LCA study should aim to look at the whole lifecycle of the material, including its application in secondary use and recycling. Preferably, such an analysis does not compare solely a CK and PYR pyrolysis, but also takes into account other existing technologies such as landfill and/or solvolysis.

- Considering different comparison cases

Because there are lot of uncertainties involved with the process, it would be advised to consider different comparison cases that for example distinguish different levels of technology optimization and implementation locations for all the considered EoL technologies. Based on a wider variety of comparison cases, different pathways could be plotted. *Additionally, looking at the problem from a different perspective is expected to give new insights*.

- Eliminate uncertainties

It is recommended to create more insight in the degradation of the mechanical strength of the fibres. More insights in the degradation process could provide new insights in the development of the pyrolysis technology and thus its economic viability.

- Application of product yield

In line with the previous recommendation in order to secure the economic viability of the technology, it would be interesting find out how these materials can be applied. Which existing virgin material could be substituted with pyrolysis products? There also might be an opportunity in the *Material Driven Design* method (Karana et al., 2015), that uses the material is the starting point for newly designed products.

15.1.2 Recommendations for research in a wider context

Following the research question of this study and the results in the perspective of the wider context, some recommendation based on the results from this study can be done.

- Design for End of Life

As was discussed in Chapter 14, recycling by the means of pyrolysis could form the first step of a bigger transition towards a carbon-neutral circular economy. It is recommended to look into mitigating solutions to the composite waste issue from an early stage on. This includes for example the design for reuse and the design for recycling.

- Socio-technical innovation

As was explained in the Paragraph 14.3, it is expected that the technological development of EoL technology for composite materials will be accompanied by a more social-economic transition. Towards a system with new types of business-models and more interlinked cooperation networks. It is recommended to the PoR to investigate how cooperation with a variety of stakeholders could enhance the transition and in particular with a focus on the future business strategy of the PoR.

15.2 Strategic advice PoR

The perspective of the PoR was leading for the approach of this study and therefore, one of the aims was to define an advice for the PoR on if and how pyrolysis could be implemented in the context of their company. A set of recommendations that is believed to be of value to the PoR is given in this paragraph.

- Participating role

First of all, it is recommended to make sure that PoR well informed about the predicted developments. The fact that the subject of the research rose and is further investigated in research by Bax & Company shows that the awareness for the issue is high. Based on the findings of this study, it is recommended that PoR takes on a participating role rather than an observing role in the (early) developments in this field. The following recommendations could help to formulate the concrete interpretation of this participating role.

- Enable technology optimization

In the previous paragraph the importance of further research into the pyrolysis technology is pointed out. This development could be stimulated by the PoR by giving room to newly emerging businesses that are involved with the technology development such as Suwotec.

- Early steps

While the developed pyrolysis technology will not be available for use instantaneously, preliminary steps that will release time pressure on the development of the pyrolysis technology can already be taken. PoR could look into the secondary and tertiary applications of composites materials in the PoR areas by for example, the application EoL composite material in quay reinforcements with the Windesheim technology (Appendix 0). This way, the PoR gathers the material on their territory which makes it easily accessible when the secondary applications reach their EoL and the (developed) pyrolysis recycling facility is in operation.

- Developing a relevant network

One of the findings of this study is that an expanded network could stimulate technology optimization. As mentioned in Paragraph 14.3, it is believed that within the broader context of the composite waste issue, the scope of the stakeholder network will expand over time. From this line of reasoning, it is recommended to by create a network of potential stakeholders in various aspects of the process, for example:

- Connect with the pyrolysis technology developers such as Suwotec and ECN to stay up to date about their progress and see where it is interesting to provide them with space and resources.
- Cooperating with stakeholders concerned with waste problems that pyrolysis could also provide a solution for, such as the artificial grass bulk or car tires. The established pyrolysis cluster in the PoR could be further expanded.
- Establishing relationships with product developers/start-ups that work with the product yield of pyrolysis. Creating room for innovation in this field could attract new business and activities in the port.

It is recommended to first create insight in what mix of stakeholders would be interesting for these networks, check if there are interesting partners in the existing database of clients of the PoR and to define what would be required for a successful mutual cooperation.

- Define the “Pioneering” role

Linked to the previous recommendation, it is advised to create a better understanding about this “pioneering role” and how advantages could be created. It would be interesting to investigate how the composite waste issue is perceived in other geographical regions and what the state of development is there. This could reveal what advantages a technological lead could provide for the PoR and how this can be linked to potential profits coupled with investments.

- Prepare for the future

The final recommendation is based on a long-term vision in which new business models are leading. It would be interesting to see what role the PoR could adopt in a situation like is sketched by the turntoo® model (Rau & Oberhuber, 2016), that for example considers material as a service.

16 Conclusion

This study aimed at providing an answer to the following question: “To what extent can the recycling of GFRC from EoL WTB material by the means of a pyrolysis process create environmental benefits within the context of the PoR in the coming 5 to 10 years?”.

This study identified recycling by the means of pyrolysis as a suitable Eol treatment for GFRC from WTB seen from the perspective of the PoR. However, the extent of the environmental benefits created by the implementation of this measure remains unclear but could be an early step in a larger transitional movement that allows for implementation in 50-10 years.

The first phase created a better understanding of the concepts embedded in the main research question. It confirmed that there is an existing need to develop an industrial-scale recycling option for the treatment of EoL GFRC waste that will flow from the wind energy industry in the coming decades. The predicted volume of blade waste reaches up to 100kt annually in 2030 and is expected to further increase in the following decades. About 80% is of this blade waste is composite material, often composed from glass fibre reinforcement and epoxy and polyester resin. The early adoption of wind energy in North West Europe entails that this area will also be the first part of the world to meet the composite waste issue. This provides an opportunity for PoR to play a pioneering role in finding a sustainable solution for this issue.

Several solutions for the treatment of GFRC blade waste, from different stages of the European Waste Gramework, are currently existent. Following the context of the PoR, this technology preferably links to their current chain of activities and is suitable to treat potential future materials from WTB such as CFRC or hybrid composites as well. To maintain the sustainable nature of the wind energy industry, this technology should be suitable to treat the GFRC with a minimal environmental impact. Although pyrolysis is not the first choice of EoL solution from an environmental perspective, this treatment was selected as technology of focus after taking into consideration the suitability for industrial-scale implementation and relation to the context of the PoR.

In order to find out to what extent environmental benefits could be created with the implementation of recycling by means of pyrolysis, the second phase of the research compared the pyrolysis scenario to the currently most matures scenario (the cement-kiln route) and a reference scenario (landfilling). This comparison did no deliver the expected result, because a variety of limitation hampered the comparison analysis. However, the pyrolysis technology is identified as a promising EoL solution whereas there is a potential re-use for all of the output products, the technology has a lot of room for optimization of process and product yield that would improve the quality and thus the economic viability. Compared to the other scenarios, the problem shift related to the pyrolysis technology is relatively low, providing that the recovered fibres and pyrolysis oil both find high-value secondary applications and that the combustion of the pyrolysis oil as fuel oil is avoided. It can be concluded that pyrolysis could deliver both environmental and economic benefits, but optimization of the technology and better understanding of the process is required. It is believed that this is feasible in the timespan of 5-10 years and fits within the context of the PoR.

Lastly, this study pointed out that an enhanced cooperation between stakeholders could contribute to the development and implementation of pyrolysis. This could include the exchange of knowledge and shared risks & benefits in R&D projects. This was primarily put forward by organizations from the field and can be confirmed when the results of the study are put into a broader context that also considers the long-term future (Paragraph 14.3). It is believed that including stakeholders from different clusters, such as other problem owners, potential product purchasers and researchers could stimulate the development of the pyrolysis technology. When pyrolysis is considered an early step in a larger transition towards this network is believed to further expand including stakeholders that become important in the following step.

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APPENDIX

A Desk Study

A.I Detailed information about the literature sets

Set	Goal	Subquestion	Subjects/included content	Search Terms	Search engine	Number of papers in the set
		What is the size of the issue? How much GFRC material is flowing from EoL WTB?				
1	Expand knowledge on technical characteristics of WTB	What are the characteristics of the predicted EoL material flow from decommissioned WTB? What is the material content of a WTB and what other materials, besides FRC are present? What are the predicted volumes of this EoL material flow?	the fibre reinforcement type and ratio (glass/carbon/hybrid), the supporting materials used in the blades, location of implementation, size of the blades, expected lifespan, future predictions for size and material	"composite waste"; "glass fibre reinforced"; "wind turbine blade waste"; "structure"; "materials"; "characteristics" "wind energy"; "wind turbine blades"; "manufacturing" "glass fiber composite recycling"; "composite recycling" "end of life"; "decommissioning" "wind energy industry"; "europe" "review"; "current status"; "outlook"; "developments"	Scopus TU Delft Library Google Scholar	8 to 10
		What are the details and possibilities of the pyrolysis technology?				
2	Expand knowledge on technical characteristics of pyrolysis	What are the technological characteristics of the pyrolysis of GFRC? What are the input requirements and what (by) products are produced? Are there any limitations to this technology? What is the predicted development of this technology in the coming 5 years and how can this be stimulated? Would the technology also be suitable for the treatment of CFRC?	chemical reaction, the input requirements, the output products, the limitations and bottlenecks of the process, predictions on the future development of the technology	"recycling"; "recycling technologies"; "pyrolysis"; "end of life" "composite materials"; "fibre reinforced polymers"; "glass fibre"; "polymer matrix composite"; "thermoset"; "epoxy" "mechanical properties"; "products"; "gas"; "oil"; "energy" "circular economy" "review"; "current status"; "outlook"; "developments"		8 to 10
		What benefits can be created compared to the current situation?				
3	Selection of environmental and economic criteria	Which impact categories should be considered in a scenario comparison? What is the business as usual scenario (BAU)? What is the new circular business scenario (NCB)?	Publications on LCA studies and economic assessment, similar to the case of Pyrolysis of GFRC from EoL flows. Providing data for the definition of both the scenarios to be able to compare them to each other. e.g. Data on Global warming potential, acidification, GHG emissions, energy costs, effiency etc.	"life cycle assessment"; "LCA"; "impact categories"; "environmental impact"; "comparative study" "cement kiln"; "recycling"		3 to 5
4	Collecting data for each selected criterium	To what extent does the NCB scenario create economic benefits compared to BAU? To what extent does the NCB scenario create environmental benefits compared to BAU?		"GHG emissions"; "CO2 equivalent"; "energy (use)" "wind turbine blade"; "materials" "landfill"; "inceneration"; "pyrolysis"; "current state"; "developments"		2-5 per criterium

B Field Study

B.I Overview of Field Study items

Date	Name	Contact Details	Organisation	Location	Subject	Type	Filed?	Hours	Verified?	Main take-away points
11/09/2018		website	Sirris Composites Workshop	Oostende		Conference Workshop	YES	5		
17/09/2018		Nienke Collée: collee@compositesnl.	Dutch Composites Platform Consultation	Bunnik		Consultation	YES	3		
04/10/2018		http://innovationexpo2018.nl	Innovation Expo 2018	Rotterdam		Exhibition	NO	6		
06/10/2018			Auto Recycling Nederland (ARN)	Tiel	"Weekend van de Wetenschap"	Presentation Plant tour	NO	3		
06/10/2018			Tejin	Arnhem	"Weekend van de Wetenschap"	Exhibition	NO	4		
18/10/2018	Wim Robbertsen	wr@businessinwind.com	Business in Wind / Lagerwey	Amersfoort	Wind energy market and current EoL situation	Informal conversation	YES	3	YES	
09/11/2018	Erik Hoeksema	e.hoeksema@milgro.nl; +31646761877	Milgro	Rotterdam	Waste management by Milgro	Informal conversation	NO	1		
13/11/2018	Martin Dijkstra (Wim Robbertsen	m.dijkstra@ewtdirectwind.com	EWT Business in Wind)	Enschede	WTB Production process and application	Informal interview Plant tour	YES	3	NO RESP	
15/11/2018	Frans van der Wel Arnoud Haffmans	vanderwel@fibercore-europe.com	FiberCore Europe	Rotterdam	Production and engineering of composite bridges	Presentation Plant tour	YES	3.5	YES	
21/11/2018		n/a	BRBS Recycling symposium 2018	Gorinchem	Branche update: Recycling in the Netherlands	Symposium	NO	3.5		
21/11/2018	Albert ten Busschen	a.ten.busschen@windesheim.nl 0651916870	Windesheim	Gorinchem	EoL: Reuse of composite material without the separation of the composite elements	Informal Interview	YES	1	YES	
22/11/2018	Julie Teuwen	J.J.E.Teuwen@tudelft.nl	TU Delft – Aerospace department	Delft	Recycling of WTB (earlier research)	Informal interview	YES	1	YES	
23/11/2018	Kees Joosten	k.joosten@baxcompany.com +31624365353	Bax and Company	PoR	Structure & tips of the study in general	Informal interview	YES	1	NO	
28/11/2018	Martin van Dordt	vandord@nrk.nl +31(0)623426593	NRK	Rotterdam	Current situation in the plastic industry, concerns for EoL	Informal interview	YES	2	YES	
11/12/2018	Novita Saraswati	novita.saraswati@tno.nl	ECN by TNO	Skype	Pyrolysis research project ECN; status and plans	Informal Interview	YES	1	YES	
06/12/2018	Richard Ijpma	richard.ijpma@suwotec.com	SuWoTec	Phone	Developed technologies at SuWoTec	*Unexpected phonecall*	NO	1	NO	
17/01/2019	Richard IJpma Lammert de Wit	richard.ijpma@suwotec.com lammert.dewit@suwotec.com	SuwoTec	Assen	Controlled clean pyrolysis	Informal Interview	YES	2		

B.II Main take-aways of attended events

Oostende Workshop Sirris - 09-11-2018

Main take-away points:

- Consortium of Agoira, Sirris, Go4Circle and OWI lab (from both wind and composite branche) aim to find out about the possibilities in 2-years
  - Very limited timeframe
- Cement-kiln route for recycling is perceived as good recycling technology fort his industry
  - Neowa, large mature company in Germany
  - Perceived as only possible solution today
  - Perceived to be always necessary; no other technology will be able to handle the full EoL material stream, as well ass cement will always be existent
- WindEurope emphasises on the prevention of waste material
  - Provided information:
    - FRP (used in WTB); 60-70% reinforcing fibres vs. 30-40% resins
    - Numbers of "aging WTB" in Europe and quantities composite material involved
  - There is a sustainability task force- publications can be found online

DCP Consultatie Nationale Agenda - 17-09-2018

Main take-away points:

- Focus for the industry defined by branch members:
  - mainly on the application of high-end know-how available in the Netherlands for key-technology of composites in the energy transition
  - New approach on valorization of technologies and products
  - Very little attention for the sustainability issue of composite material
- Sustainability brainstorm:
  - Relate to the general trend towards a circular economy (lengthen life span by repair and reuse) and local produce. Creative industry: modular designs
  - When a good recycling method is existent = very good business prospective
  - Recycling of composite material is a major bottleneck, especially when considering necessary innovation to stay ahead of other competing materials
  - No sufficient knowledge about indicators (LCA analysis, possibilities for sustainable development) present in the industry

B.III Main take-away points from informal interviews

Wim Robbersten, Business in Wind – 18-10-2018

Main take-away points:

- Basic knowledge (introduction) provided
  - Transportation accounts for a major part of the costs of commissioning a WTB, also for second-hand use; however, the transportation has no reduced price.
  - EoL possibilities
    - Wim estimates that only 20-30% of EoL WTB suitable for re-use, limited market will probably decrease in the coming years to possibly 5%
  - Material use/weight:
    - Carbon fibre attracts lightning, therefore necessary to carefully construct. However, CF for WTB is definitely possible.
    - Per blade; 50m = 9000kg; 68m = 19000kg → related to MW?
    - Nacelle nose is also made from GFRC; varies between 1000-1500kg

- Lead subjects/ useful contacts
    - Martin Dijkstra – EWT Enschede
    - Michel Alserda - GoGreen Logistics

Martin Dijkstra, EWT – 13-11-2018

Main take-away points:

- Lifespan
    - Most important design aspects are weight, length, lifespan, fatigue resistance and producibility
    - Economical EoL reaches first, second the designed lifespan
    - In practice; technological lifespan is dependent on circumstances and maintenance during usage-phase – EWT provides service contracts for 10-15 years
    - For larger WTB lifespan of 20-30 years is considered because intermediate transport is not economically viable
- EoL solutions:
    - Small market potential for second-hand turbines since transportation costs are same as for virgin WTB, the market is easily saturated and after purchase a shorter, less efficient lifespan is left for the product
    - EWT as manufacturer doesn't see EoL as their problem; no problem owner
    - Current solution is mostly shredding and cement-kiln; shifting the problem to 40 years later.
    - Decommissioning in NL: 80% of WT in Flevoland are going to be decommissioned in the coming years.
- Material use
    - Blade size: ~50-60
    - Epoxy and glass fibres; 50/50wt%, 2000kg
    - PVC foam as sandwich material
    - Difference in material costs available between industries; wind energy 10eur/kg vs. aviation 100 eur/kg; WTB high quality product for limited budget

Frans van der Wel, FiberCore – 15-11-2018

Main take-away points:

- Design
    - main priorities; stiffness (which directly assures strength), "comfort" of walking
- End of Life
    - Bridges designed for use of 100 years; so no clear EoL Strategy/statement (yet)
    - Delamination is main failure of these bridges, but InfraCore technology prevents this.
    - No clear other failure characteristics, only acoustic test.
    - Company aspires a lease-service for bridges, to assure the return of the product and material. However, their market does not seem ready for this.

Albert ten Busschen, Windesheim – 21-11-2018

Main take-away points:

- EoL solutions:
    - At Windesheim research focus on solutions that make use of the attached composite materials.
    - It is believed that; Separation of matrix and reinforcement degrade both the elements to such extent that it is not worth the effort, doesn't deliver benefits.
- Wind Turbine Blades:
    - Extra attention for high-quality shear parts of the load carrying structure.

- Think about the “shave” of strokes and bars of the composite material, these could be re-applied in marine high-impact products.

Julie Teuwen, TU Delft Aerospace – 22-11-2018

Main take-away points:

- Project; 2 elements (working towards tender @RVO)
  - Julie/TU Delft focus on the design developments of WTB
  - ECN (by TNO) focus on EoL solutions
- Examples/learning from Aircraft recycling:
  - AELS aircraft solutions; each aircraft is individually assessed to see what solution fits that part the best,
  - Combination of solutions to account for changes between WTB and over time
- Material use (resin)
  - Epoxy has better mechanical properties for WTB
  - Polyester shrinks more, should be taken into account in the design
  - Material innovations/R&D
    - Coating of fibres (easier to come loose from matrix or prevent degradation by heat)
    - Resins easier to recycle
    - Use of thermoplastics for aerodynamic blades (non-shear load parts)

Martin van Dord, NRK – 28-11-2018

Main take-away points:

- Martin van Dord indicates that Pyrolysis should be the end of a long cascade of the material in various products.
- Nevertheless; PoR seems like an interesting party to research their possibilities in this field of practice, because of knowledge and experience in this field and the investment possibility and experience already existent in the chemical cluster in the Botlek

Novita Saraswati, ECN by TNO – 11-12-2018

Main take-away points:

- The relevance of the development of an EoL technology for WTB is confirmed by the wind energy sector at ECN by TNO. To be ready for the increased volumes in 20-25 years, R&D is necessary now.
- The focus at ECN lies on the development of the pyrolysis process and the supporting chain of activities in a subsidized project. Other EoL technologies will be investigated too, but the highest hopes lie on the pyrolysis technology.
- The coming year a new subsidy application will be handed in by RVO. Therefore, the project aims to have a plan for a demonstration project (pilot plant) and sufficient partners to support this goal
- Current partners exist of Shell and some of the members of the GROW consortium. There are currently talks with a recycling/trading companies that would be valuable to add to this list of partners.
- It might also be interesting for the PoR to join this partnership, since the relation with offshore wind and chemical industry are close. Also, ECN is considering locations like Vlissingen, Eemshaven and Port of Rotterdam for a beforementioned pilot plant.

Richard IJpma & Lammert de Wit SuWoTec – 17-01-2019

Main take-away points:

- Social entrepreneurs with innovation skills who share the same vision on a sustainable circular World.
- Multiple inventions among which a non-corrosive electrode that can be programmed for a specific functions
- Theoretical technology of Controlled Clean pyrolysis
- Three steps plan towards pilot project for Controlled Clean Pyrolysis.

Field Study Overall

Most important – leading take-aways

- In the composite industry the awareness of the sustainability is increasing. However, it seems that there are no clear EoL plans at manufacturers and a feeling of responsibility for the EoL material is not always present. This might change however, due to increasing awareness and upcoming opportunities. Visible solutions will show people their opportunities.
- Validation the urge to start with the development of Pyrolysis
    - For PoR pyrolysis is very interesting (2x named)
    - Pyrolysis is a lower-end treatment technology of composite material, valuables are lost. However, it seems like a solution that cannot be undermined (?).
- One should wonder whether focusing solely on pyrolysis is the way to go. Also, attention for higher-end solutions, working together with the complete cascade flow to optimize the pyrolysis process → “Hub” idea

C Composite using industries

C.I Aviation

According to Karataş and Gökkaya (2018), an increasing number of aircraft parts are made out of Carbon FRC because of the preferred characteristics such as high strength and stiffness, low eight and high fatigue resistance. Figure C-1 shows that FRC are used in a wide range of applications of the Airbus 350 aircraft. Applications vary from small parts such as doors and clips to big structural components of the plane such as wing flaps and the main body (Karataş and Gökkaya, 2018). In aircraft industry, the main reason for FRC application is the reduction of weight of structural components. Weight reductions contribute to fuel efficiency and the load bearing capacity of airplanes (Karataş and Gökkaya, 2018).

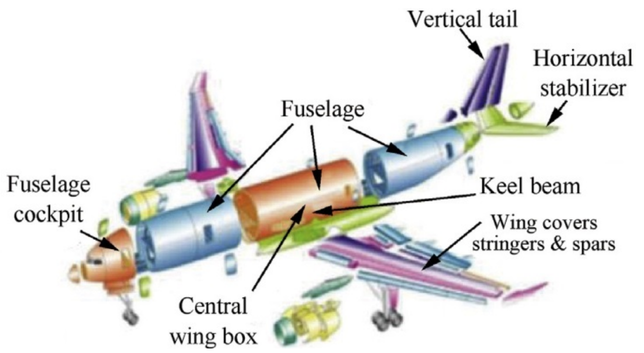

Figure C-1: Elements of the Airbus 350 that FRC are applied in (Karataş and Gökkaya, 2018).

Reported by Sauer et al. (2017) is that both Airbus and Boeing, the two main aircraft manufacturers are increasing applying the carbon FCR materials, with a growth rate of 8% recorded between 2015 and 2016. It should be noted that the quality of FCR used in the aviation industry is often valued at a higher price according their higher quality standards and considered higher approval costs of the material, due to safety considerations (Sauer et al., 2017).

C.II Automotive

The automotive industry is the second largest FCR demanding industry (Sauer et al., 2017). An increasing number of car producers is using FCR materials in the design of their vehicles. The successful application carbon fibre composites in automotive applications is possible is demonstrated, also for high impact parts (Regenfelder, 2014).

There are multiple explanations for the increased interest in FCR materials in the automotive industry in the last few decades. According to Balakrishnan and Seidlitz (2018), car safety performances require much higher standards than before as European standards have been redefined. Secondly manufacturers are facing the challenge to become more resource efficient. Since 2000, they have to deal with extended producer responsibility for end-of-life vehicles (ELVs) imposed by the European union (Regenfelder, 2014). In line with this, vehicle manufactures are encouraged to also produce environmentally friendly cars in terms of emissions. FCR, with glass or carbon fibres can reduce 20-30% weight compared to traditional materials due to the light-weight properties of the FCR materials (Balakrishnan and Seidlitz, 2018). For the same reason emerging trend of E-mobility is intensifying the use of FCR materials in the automotive industry (Sauer et al., 2017).

According to Balakrishnan and Seidlitz (2018), the most commonly used composite materials in the automotive industry use a polymer matrix which can be either a thermoset or thermoplastic and are reinforced with glass or carbon fibres. These composites have high strength and good damping properties compared to traditionally used metals. Besides, the carbon composites have high mechanical performance under cyclic loading. Cyclic loading is continuous and repeated application of a load on a material or on a structural component.

C.III Wind Energy

The wind energy industry has a large demand for FCR because the wind turbine blades are generally produced out of this material. According to Nijssen (2013) and Beauson & Brønsted (2016) the majority of wind turbine blades are produced from polymer composite materials reinforced with mainly glass fibres. To some extent carbon fibres are also used and more frequently also carbon fibres in hybrid combination with glass fibres. The matrix material used in wind turbine blades is generally a thermoset polymer such as epoxy, polyester and vinyl ester (Nijssen, 2013).

The demand for composites in the wind energy industry is growing for two different reasons. Firstly, the market is a growing due to the so-called Energy Transition that is taking place in the energy industry. It comprises the transition from fossil fuel-based energy carriers towards renewable energy forms. The driver of this transition is the goal to reduce the emission of GHG that cause the current global issue of global warming. In line with these developments, the European Union has set the target to produce 27% of its required energy with renewable sources in 2030 (Arantegui et al., 2018). It has led to a higher growth rate in the utilization of renewable energy in the electricity sector, especially from solar and wind sources, compared to the growth rate in the rest of the economy in Europe and world-wide (Arantegui et al., 2018). Since 2005, the cumulative installed wind energy has significantly increased from 50 GW to almost 450 GW in 2015 (Fig. X) (Arantegui et al., 2018). Secondly, not only the number of wind turbines is growing, also the size of wind turbines has increased significantly, with a corresponding growth in composite material requirements for wind turbines. In 1990 an average wind turbine had a power of 600 kW and blade length of 18m, in 2015 7 MW turbines with blades of 85m were already existent (Beauson and Brønsted, 2016). And the prediction is that these sizes will continue to increase (Sauer et al., 2017).

Considering these developments in both market and technology of wind energy, an increase in waste material flowing from this industry is expected. Wind turbines are generally designed with a lifespan of 20-25 years (Beason and Brønsted, 2016; Larsen). The first offshore wind park near Ravnsborg in Denmark was installed in 1991 and thus reached the age of 25 in 2016 and is ready of dismantling (Beauson and Brønsted, 2016). Based on the lifespan and information of the installed capacity over the last 25 years an estimation of the material flow can be done. Figure 3.7 shows how a material flow prediction was done by Albers et al. (2012). Reflecting on the sustainability of wind energy production, it is important to consider this (growing) end-of-life material flow and the waste treatment possibilities and capacity of our current economic system.

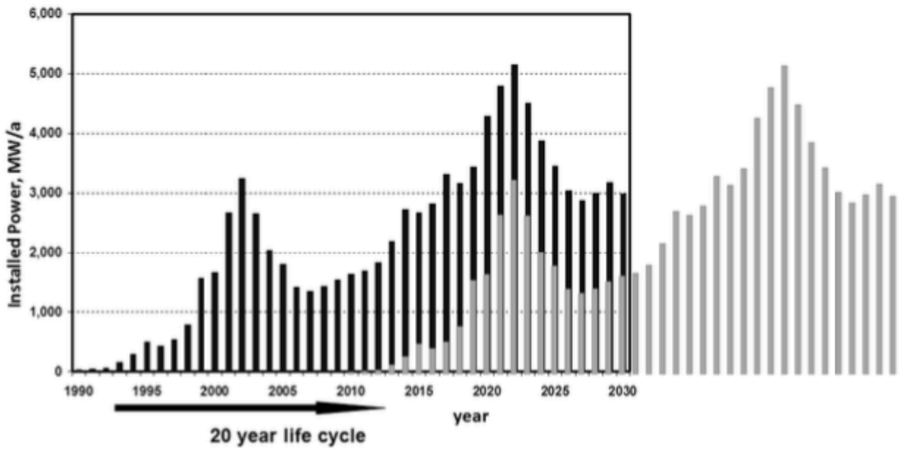

Figure C-2: Material Flow production, based on lifespan of 20 years (Albers et al., 2012)

C.IV Construction

According to Krivoshapko (2017) the last three decades there has been considerable growth in the use of FRC in (among others) the construction industry. Again, in this industry the advances of the material can be found in their high strength-to-weight ratio and versatility and the ability to combine different materials to meet specific requirements. Also, in the construction industry, FCR are gradually replacing conventional materials in different applications.

Wan (2014) mentions the application of FRC as concrete reinforcement and as structural members subject to corrosive environments. Since the late 1980s FRC have been used as reinforcements for concrete buildings, especially in highway bridge decks. Their main characteristic suitable for this application is their high resistance to corrosion, especially compared to the conventionally used material steel. The application of FCR for this purpose has taken flight the last few decades because of reduced costs of manufacturing (Wan, 2014).

Furthermore, more recent developments of application of FCR in the construction industry are based on multiple advantages of FRC materials over conventional materials. First is the fact that the materials can easily be moulded into complex shapes. Shapes can be curved, corrugated or ribbed and all in a variety of ways which gives the architect a large form-freedom (Krivoshapko, 2017). Secondly, the low weight, high strength and the simplicity of production allow for prefabricated panels to be used during construction, which is generally a time-saving measure. Additionally, the panels can be designed for a specific purpose in terms of transmittance of heat and light for example, allowing controlled indoor temperatures (Krivoshapko, 2017).

Multiple of more innovative FCR-applications were evaluated by Krivoshapko (2017). The material is mainly applied in designs with organic shapes. Figure C-3 shows four examples of these architectural designs. All make use of the beforementioned advantages of the FCR materials. Firstly, the Chanel Contemporary Art container designed by Zaha Hadid. In 2008 this project was a showcase for a new direction of the use of plastics in architecture. It was a so-called piece of mobile art that travelled between expositions all over the world. It was relatively easy to transport because it was built up from a steel frame combined with detachable panes. Similarly, the Thematic pavilion on the expo 2012 in south Korea also existed of detachable panes, 108 in total. FCR materials are also very suitable for the construction of domed structures. The “composite superstructure” Avatar Meher Baba’s Samadhi is a 13.4m tall by 6.1m diameter glass-reinforced, egg-shaped shroud dome, almost completely built from FCR materials (Krivoshapko, 2017).

Figure C-3: Examples of architectural projects that make use of FCR materials. [clockwise] a) Chanel Contemporary Art Container in New York's Central Park in 2008 designed by Zaha Hadid; b) Thematic Pavilion EXPO 2012, Yeosu, South Korea; c) Avatar Meher Baba's Sa

According to Sauer et al. (2017), the growth of the market for carbon FRC for the civil construction industry will grow less fast than for other industries such as automotive and wind energy. However, they acknowledge the fact that this market comprehends a very large application potential with comparatively very large numbers and quantity available. Thus, if these applications are further developed and more widely applied, their prediction would not be valid anymore.

D Wind energy in the Netherlands

Wind energy has proven itself to be one of the most promising renewable energy sources as alternative to fossil fuels (Paragraph 7.3). Both in Europe as well as in the Netherlands in particularly, the wind energy industry has been expanded significantly over the last decades. Figure D-1 shows the wind energy capacity on land (blue) and on sea (offshore, purple) in 2015 (CBS, 2015). The industry is expected to further expand over the coming decades. The Dutch target points for respectively 6000 MW onshore wind in 2020 and about 4500 MW offshore wind energy capacity in 2022 are also depicted (Figure D-1). Figure D-2 gives an indication of the onshore wind energy hotspots in the Netherlands in 2016. Figure D-3 shows the currently existing offshore wind parks (dark green) and the plans for tenders of new offshore wind parks (light green).

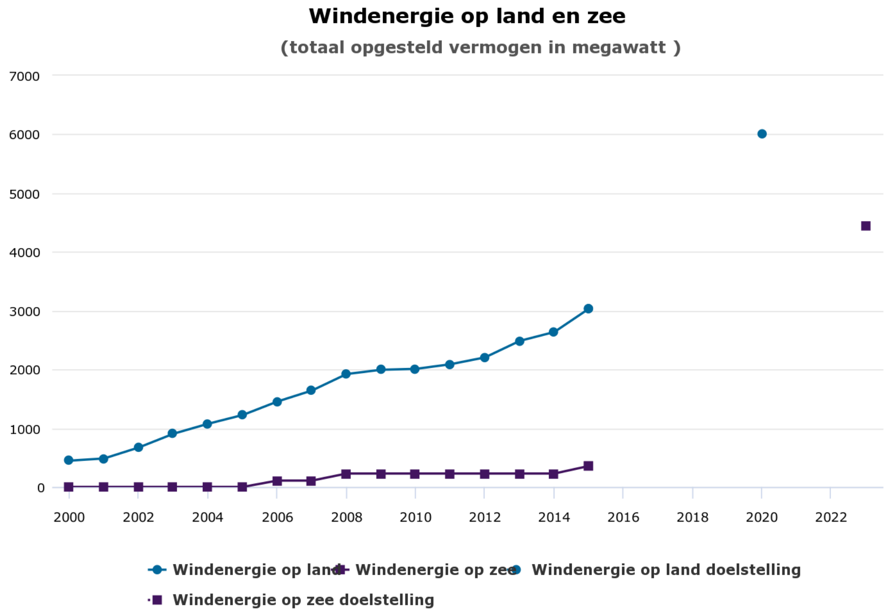

Figure D-1: Wind Energy on land and Sea in the Netherlands (CBS, 2015)

Figure D-2: Wind Energy on Land in the Netherlands in 2016. Each red dot indicates a wind turbine installed onshore (Geopraxis, 2016).

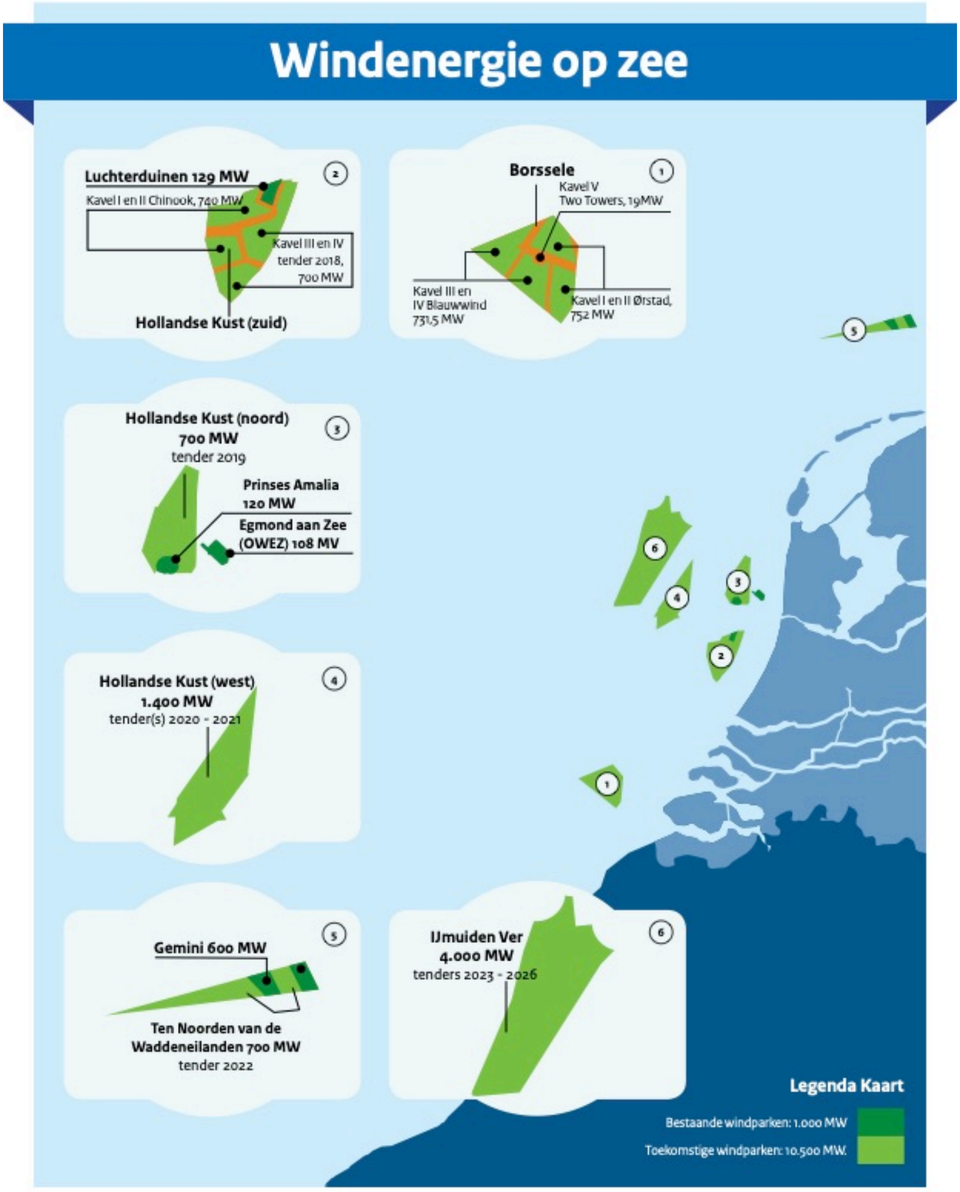

Figure D-3: Current and planned offshore wind energy capacity near the Dutch Coast (RVO, 2018)

E Design Guidelines for recycling by means of Pyrolysis

This study gives insights in the working principle of pyrolysis and what the consequences are for the reinforcement material. With these acquired knowledge, some recommendations for further research to enhance the potential “design for pyrolysis” are given in this appendix:

Generally, it can be recommended to investigate the different pyrolysis requirements and characteristics of different (combinations of) resins and reinforcements such as:

- Temperature
- Heating time
- Composition of the pyrolysis oil
- Mechanical quality of the fibres
- Composition of the gaseous content.

Furthermore, the suggested research above could be supported by measures such as:

- Work with standard resin materials
  Preferably optimized resins for pyrolysis, that yield the right composition of pyrolysis oil and gases. Besides it could prevent pollution and potentially allow bulk processing of WTB produced from the same resin material.
- Material passport
  To create insight in the resin and reinforcement material such that with reference data a choice can make whether a certain combination of materials would deliver pyrolysis oil and recovered fibres that could be processed in a secondary product.
- Pre- or post-treatment of the reinforcement material.
  This was explained in the main report. Pre- and post-treatment of the fibrous part of the composite could protect the fibres for degradation by heat or simplifies the decomposition of fibre from resin, such that temperature and heating time could be reduced (for example).

F Repurposing composite material by Windesheim

As was mentioned in Paragraph 8.1, at the university of applied sciences Windesheim, research is done into the potential to repurpose existing composites to produce new composite material.

They use strips and flakes of composite material from WTB and GFRC boat hulls as reinforcement element for sheet pile walls (Figure F-1 and Figure F-2). The fragments and flakes are inserted in a new mould with enough overlap between them (Figure F-3), that is then infused with a new matrix (Ten Busschen, 2018).

This way, the new composite gains advantage from the mechanical characteristics of the existing composite. Besides sheet pile walls, this technology can be used for various other purposes such as to replace hardwood bog mats (ground protection for heavy duty construction) or mooring dolphins.

Currently, Windesheim is cooperating with Demaq, the company that offers on-site mechanical decommissioning of WTB and other large composite structures.

Figure F-1: Strips and flakes of EoL composite material from WTB and boat hulls used as reinforcement in new composite material (Ten Busschen, 2018).

Figure F-2: Section of the sheet piling walls with fragments and flakes of EoL composites as reinforcement, produced by Windesheim (Ten Busschen, 2018).

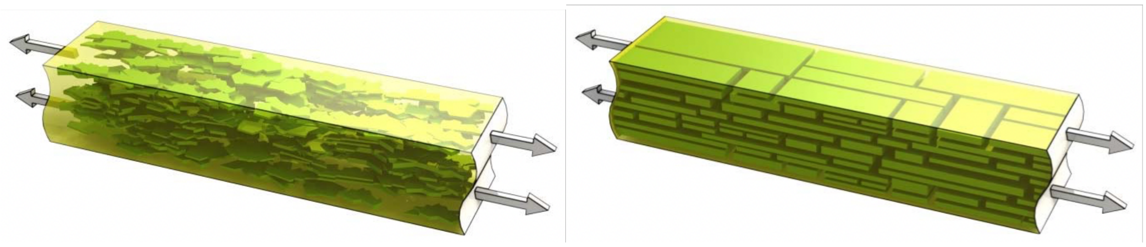

Figure F-3: Alignment of the flakes and strokes of secondary composite material in a new composite part, the loose elements require enough overlap between them to transfer the forces (Ten Busschen, 2018).

G Comparison Case Details

Transport

- Transport per truck: 0,07 kg CO_2eq per tkm; 1,0 MJ/tkm

[Idemat2018 Truck+container, 28 tons net (min weight/volume ratio 0,41 ton/m3; C.010.06.103]

- Transport over water: 0,01kgCO_2eq per tkm; 0,1176 MJ/tkm

[Idemat2018 Coaster; C.070.01.103]

- Although based on these data transport over water would be beneficial, for the equality of the comparison both distances are considered transport by truck.

Noteworthy, when assessing EoL WTB arriving from offshore decommissioning, this will be favourable for any technology applied within the Rotterdam port areas.

Table G-1: Overview of the GHG-emissions and Energy use related to different transportation routes, all calculated for 1 tonne of GFRC from the hypothetical decommissioning site near Lelystad..

GHG-EMISSIONS				
Traject	± km	Type	kgCO2eq/tkm	Total kgCO2eq/t
Lelystad – Bremen	300	Truck	0,07	21
Lelystad - Bremen	420	Water	0,01	4,2
Lelystad – Rotterdam	160	Truck	0,07	11,2
Lelystad – Rotterdam	200	Water	0,01	2
ENERGY USE				
Traject	± km	Type	MJ/tkm	Total MJ/t
Lelystad – Bremen	300	Truck	1	300
Lelystad - Bremen	420	Water	0,12	50,4
Lelystad – Rotterdam	160	Truck	1	160
Lelystad – Rotterdam	200	Water	0,12	24

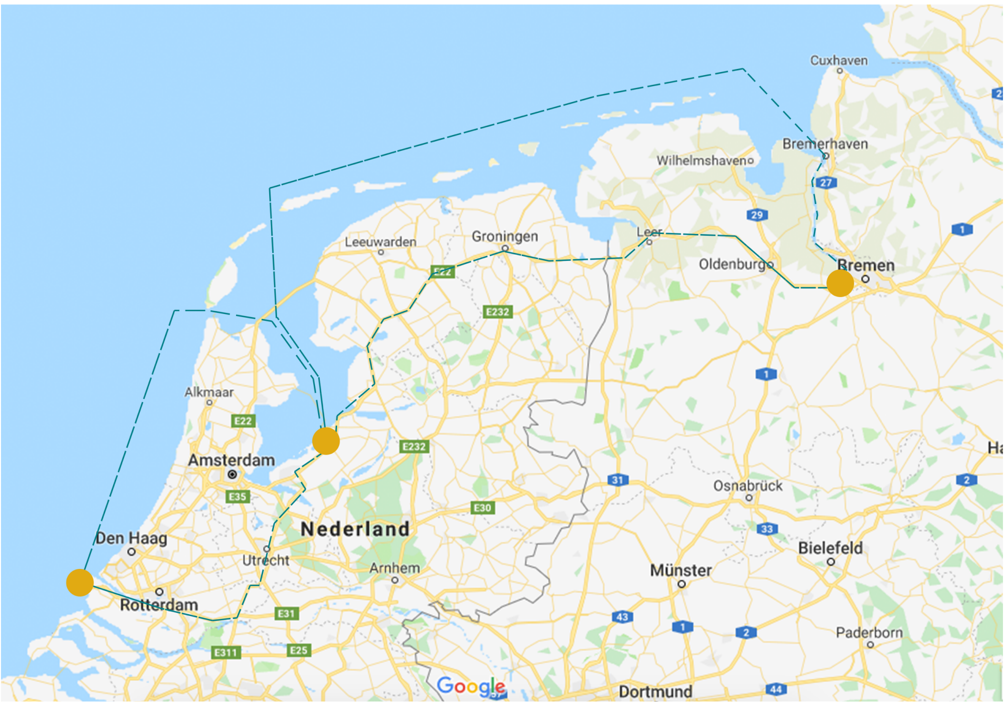

Figure G-1: Potential road and water transportation routes for the CK scenario (facility located in Bremen) and the PYR scenario (facility located in PoR)

H Quantitative criteria assessment

H.I Specifications of the cement-kiln process

Table H-1 gives the specifications that were adopted for the cement-kiln process, based on literature and general knowledge.

Table H-1: Specifications of the cement-kiln process.

Distance to facility	300 km	Neocomp
Energy Requirements	3100 MJ/$t_{clinker}$	Schneider, 2011
Carbon footprint of Portland cement	0,9 $kgCO_2eq/kg$	Idemat 2018, Farfan et al.
Calorific value of coal	30 MJ/kg	Engineeringtoolbox.com
Calorific value of the resin	12 MJ/kg	Job, 2013

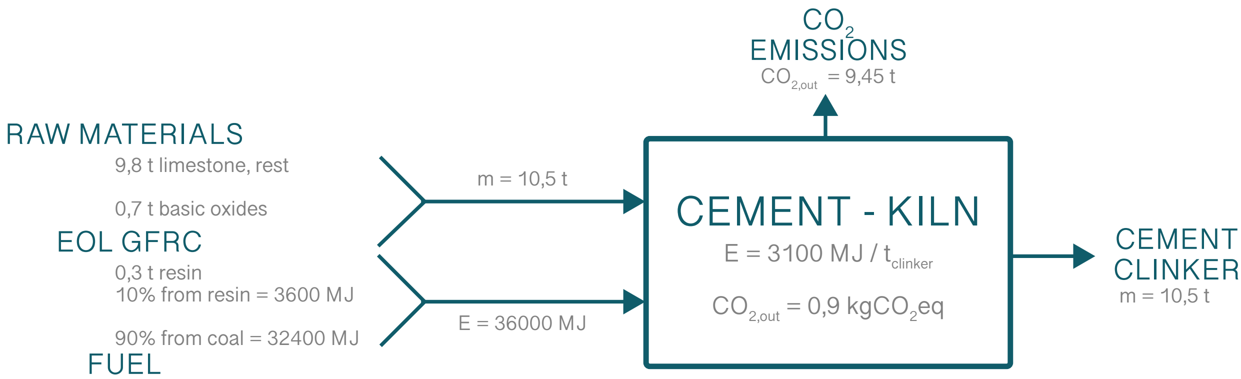

Figure H-1: Schematic overview of the cement-kiln route including the results of basic calculations.

Based on these specifications basic calculations are conducted, the results are depicted in Figure H-1.

- One tonne of GFRC contains 30% resin, 300kg of resin which delivers 3600 MJ (10%). No more than 10% of the fuel input can be substituted with GFRC (Oliveux, 2015).
- This means that total energy used in 36000 MJ, rest of energy comes from coal (32400 MJ).
- Coal is the main fuel for the cement-kiln process (Schneider, Deschamps). Based on energy requirement by Schneider and the law of conservation of mass, it can be calculated that 11t of cement clinker is produced.

Note that the mass of the released GHG-emissions is considered negligible compared to the masses of other system products.

To put these numbers in perspective; the total global cement production capacity (production facilities) in 2016 = 3746 Mtcement/annually. Europe 7,3% = 275,4 Mt/a (Farfan et al., 2019). According to the calculation above, 10,5 t clinker is produced per t of GFRC waste. The predicted GFRC waste from wind turbine blade waste = 100kt in ±2030 in Europe. This means that when substituting all of this GFRC in cement, 1050kt or 1,05Mt of cement clinker would be produced, which only accounts for 0,4% of the total European capacity. This indicates that there is plenty of room for co-production of the recycling of GFRC in the cement industry.

H-II Specifications of Pyrolysis process

Table H-2 gives the specifications that were adopted for the pyrolysis process (assuming 100% pyrolysis), based on literature and general knowledge.

Table H-2: Specifications of the pyrolysis process

Distance to facility	160 km	Lelystad-Rotterdam
Energy requirement	13,5 MJ/kg_{GFRC}	Wong et al (2017)
GCV pyrolysis oil	40MJ/kg	Phase 1
GCV gaseous yield	15MJ/kg	Phase 1
Density CO_2	1.842 kg/m^3 0,55 m^3/kg	https://www.engineeringtoolbox.com/gas-density-d_158.html
Density CO	1.165 kg/m^3 0,86 m^3/kg	
Density CH_4	0.668 kg/m^3 1,5 m^3/kg	
CO_2 equivalent of CH_4	1kg CH_4 = 25kg CO_2eq	https://climatechangeconnection.org/emissions/co2-equivalents/

According to Wong et al (2017): A pyrolysis system for CFRC (different reinforcement but similar resin, = similar decomposition) varies between 2,8 MJ/kg to 30 MJ/kg. This variance might be determined by the batch/continuous etc. Average value is taken considered for the calculations; Energy requirement for the process is 13,5 MJ/kg.

Based on these specifications basic calculations are conducted, the results are depicted in Figure H-2.

- The product yield is as indicated in Figure H-2.
- The energy requirement to process 1 tonne GFRC is 13500 MJ.
  - One part of this requirement is delivered by the combustion of the gaseous product. The 100kg of gaseous product with a GCV of 15MJ/kg delivers 1500 MJ.
  - The rest (12000 MJ) is delivered by renewable energy sources.
- GHG-emissions are emitted with the combustion of the gaseous content.
  - The gaseous product is composed of a variety of gases (see Table H-3)
  - 100kg of gas is produced of which approximately 30vol% is CO_2 and 15vol% is CH_4 (see Table H-3). The volume of 100kg gas is unknown since the exact composition of the gas in unknown and depends on the chemical composition of the resin.
  - Compared to other abundant gas-compounds such as CO and CH_4, CO_2 has a high density. This means that the volume percentage of CO_2, is lower than the weight percentage of CO_2 (engineeringtoolbox). Assumed is that about 30-50wt% is CO_2, which means that for 100kg of gaseous product, 30-50 kg of CO2 is released.
  - CH_4 has a low density and therefore a higher vol% than wt% (engineeringtoolbox). It is assumed that about 10wt% CH_4, which means that for 100kg of gaseous product about 10kg of CH4 is released. 10kg of CH_4 is 250kg CO_2 equivalent (climatechangeconnection.org).
  - Both these emissions add up to about 280-300 kgCO_2eq per tonne of GFRC treated.

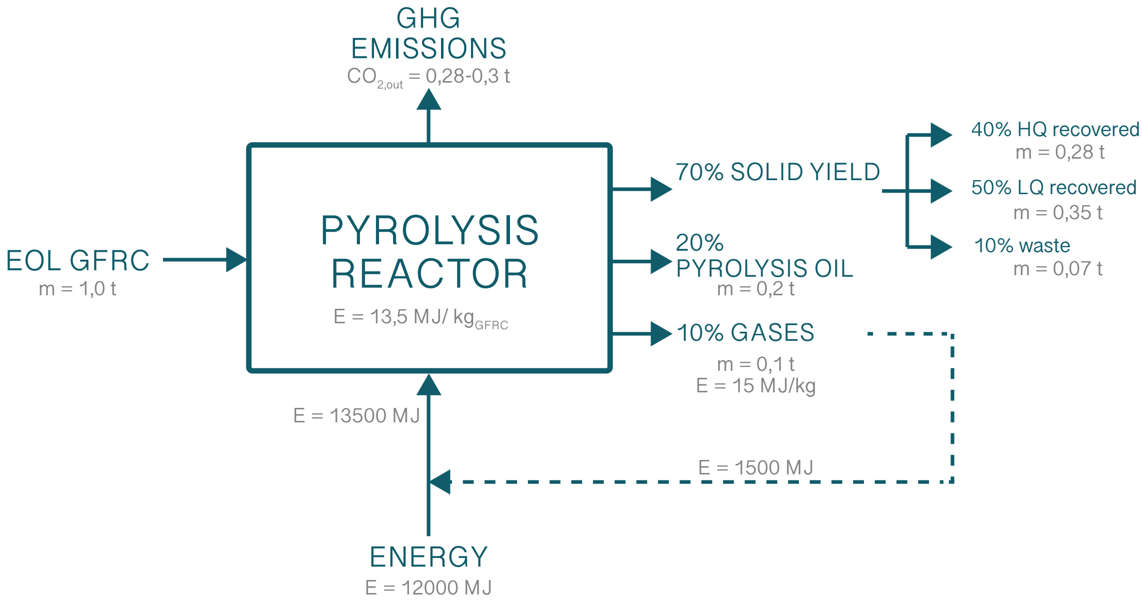

Figure H-2: Schematic overview of the cement-kiln route including the results of basic calculations.

Table H-3: Chemical composition and gross calorific value (GCV) of the gas produced by pyrolysis of GFRPs scraps at different process temperature (Giorgini et al., 2016).

Pyrolysis gas components (vol%)	Process temperature (°C)		
	500	550	600
H_2	5.8	7.5	11.5
CH_4	10.6	15.4	20.7
CO	24.2	24.0	21.8
CO_2	32.6	26.0	20.4
C_2H_4	4.8	5.0	5.2
C_2H_6	2.8	3.3	3.7
C_3	1.4	1.4	1.3
C_4	2.6	2.7	2.5
Others	15.2	14.7	12.9
GCV (MJ/m^3)	31.1	33.1	34.1

To put these outcomes in perspective; a 100% pyrolysis scenario would mean in 2030: FRP composites from EoL WTB in 2030 between 150-325kt annually; 100kt GFRC in 2030 waste results in: 28kt HQ recovered fibres, 35kt LQ recovered fibres, 10kt waste, 20kt pyrolysis oil (which is a very small fraction of the current virgin use) and 10kt gaseous yield.
However, it is not realistic to assume that within this short timespan the pyrolysis technology has both been fully developed and implemented. Therefore, the 60% PYR scenario can be considered. In which pyrolysis only covers part of the EoL WTB waste material. The rest of the EoL GFRC is considered to follow the same route as the CK scenario. In the alternative 60% PYR scenario is assumed that in 10 years, about 60% of the material will be treated with pyrolysis and the remaining part in the cement-kiln route. The results for this adjusted scenario are given in Table H-4.

Table H-4: Overview of quantitative results for the CK, 100% PYR and 60% PYR scenarios.

		CEMENT - KILN	PYROLYSE 60%	PYROLYSE 100%
GHG-emissions	[kgCO2eq/t]	9.454,2	3.782,9	±280-300
Transport Lelystad- Bremen		4,2	1,7	-
CK process		9.450,0	3.780,0	-
Transport Lelystad - Rotterdam		-	1,2	2,0
PYR process		-	-	*±280-300*
Energy Use	[MJ/t]	32.450,4	20.194,6	12.024,0
Transport Lelystad- Bremen		50,4	20,2	
CK process		36.000,0	14.400,0	
CK yield		-3.600,0	-1.440,0	
Transport Lelystad - Rotterdam			14,4	24,0
PYR process			8.100,0	13.500,0
PYR yield			-900,0	-1.500,0

H-III Specifications of the Landfill scenario

Table H-5 gives the specifications for the LF scenario, additional to the first transport step from decommissioning site in Flevoland to the PoR of Rotterdam over water (same as for the PYR scenario).

Table H-5: Specifications of the LF scenario.

Disctance to landfill facility Idemat2018 Train, freight electric Europe (tkm)	Max 200km 0,04 kg CO_2eq 0,8 MJ	Idemat2018, C.050.01.102

Based on these specifications, the additional transportation impacts for the LF scenario are:

- GHG-emissions: 200*0,04 = 8kgCO_2eq
- Energy Use = 200*0,8 = 160 MJ

H- IV Cost and value of output of both processes

Table H-6 gives an overview of the data that was explored for the financial criteria costs and product value. However, due to the limitations and uncertainties concerning these data, they were not used to formulate a conclusion.

Assumptions:

- Investment costs for CK process are low, because GFRC is used as substitute and does not require the process to change.
- Investment costs for pyrolysis are high, because a purpose-specific plant should be developed.
- The GFRC included cement-clinker has the same price as conventional cement clinker, because the GFRC fuel content is 10% and should therefore not affect the quality.
- The pyrolysis oil is considered to have the same value as fuel oil (refer to Paragraph 9.2).
- It was assumed that the pyrolysis process would decrease both the high- and low-quality glass fibre products with 50% of their original price.

Limitations:

- It turned out to be difficult to give an estimation of the costs of the process, especially for an emerging technology like the pyrolysis of GFRC there are many unknowns on the financial. Both processes require energy, but CK process also requires input materials.
- Comparison of values was hampered because price indications vary from significantly from source to source (wholesalers, web shops and platforms). There might be a wide variety between the accuracy and the embedded costs (profit margins etc) of the different sources. Interestingly, online web shops gave similar prices for virgin chopped GF and virgin GF yarn.

Table H-6: Overview of data retrieved for the financial criteria.

$1,00 (UDS)	€0,87	At 01-02-2019
Price fuel oil	$400/t	https://shipandbunker.com/prices/emea/nwe/nl-rtm-rotterdam 01-02-2019
Assumed price reduction of secondary yield 25%	$300/t = €260/t	
Price for coal	±100$/mt = 87€/t	https://tradingeconomics.com/commodity/coal
Price for grinded cement	€3,60/25kg = ±€150/t	https://www.bouwmaterialenkopen.com/cement/portland-cement-25-kg-seibel-klasse-cem-I-42-5-r
Price of chopped strand glass fibres	$1400/t	link
Price for yard glass fibres	$1500/t	link
Limestone	$20-50/t	http://www.mountaingatequarry.com/category/limestone/
Energy price	Av. €60/MWh €0,017/MJ	; https://www.energiemarktinformatie.nl/beurzen/elektra/
Transport per truck	±€70/t per 750km €0,1 tkm	link

I Qualitative criteria assessment

Table I-1: Qualitative criteria assessment rubric

	●○○○○	●●○○○	●●●○○	●●●●○	●●●●●
Link to chain of activities	No link with chain of activities. There is no potential relation to any of the three system stages.	Weak link with chain of activities. Potential link to at least one of the system stages.	Intermediate link with chain of activities. Potential link to at least two of the system stages.	Intermediate link with chain of activities. Potential link to at least two of the system stages.	Strong link with chain of activities. Potential link to all of the three product stages, with at least one underpinned with e.g. experience from practice.
Problem shifting	No problem shifting. The output products are used for the same type of application as the input material was used for. They will eventually go through the same EoL again	Minor problem shifting. The output products of the system are used in new products, for which a recycling technology is available, but this is a downgrading process.	Moderate problem shifting. The output products of the system are used in new products, for which a recycling technology is available, but this is a downgrading process that involves the use of some harmful additions such as chemical and high energy use.	Significant problem shifting. The output products are used in materials that are not recyclable. OR Harmful additions such as chemicals or excessive amounts of energy are necessary for the process.	Major problem shifting. The EoL does not reduce the waste or the output products are used in materials that are not recyclable. AND Harmful additions such as chemicals or excessive amounts of energy are necessary for the process.
Future potential	No future potential. The technology is fully matured AND is not suitable for future materials such as hybrid FRC and CFRC.	Limited future potential. The technology is either fully matured OR is not suitable for future materials such as hybrid FRC and CFRC.	Moderate future potential. The technology offers low potential to be further developed and optimized but high potential to be suitable for future materials such as hybrid FRC and CFRC. OR The technology offers high potential to be further developed and optimized but low potential to be suitable for future materials such as hybrid FRC and CFRC.	Significant future potential. The technology offers moderate potential to be further developed and optimized but high potential to be suitable for future materials such as hybrid FRC and CFRC. OR The technology offers high potential to be further developed and optimized but moderate potential to be suitable for future materials such as hybrid FRC and CFRC.	High future potential. The technology offers high potential to be further developed and optimized AND shows high potential to be suitable for future materials such as hybrid FRC and CFRC.