MSc Program
Environmental Technology & International Affairs

An Assessment of Current Efforts Towards a Circular Economy - The Case of Chemical Recycling with Pyrolysis Processes

A Master's Thesis submitted for the degree of
“Master of Science”

supervised by
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Vienna, 30.05.2023

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Affidavit

I, **FELIX BRUCH, BSC**, hereby declare

1. that I am the sole author of the present Master's Thesis, "AN ASSESSMENT OF CURRENT EFFORTS TOWARDS A CIRCULAR ECONOMY - THE CASE OF CHEMICAL RECYCLING WITH PYROLYSIS PROCESSES", 99 pages, bound, and that I have not used any source or tool other than those referenced or any other illicit aid or tool, and
2. that I have not prior to this date submitted the topic of this Master's Thesis or parts of it in any form for assessment as an examination paper, either in Austria or abroad.

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Abstract

The accumulation of plastic waste in recent decades, caused by elevated levels of production and a short period of use in many cases, poses increasingly severe challenges to marine and terrestrial life. Therefore, attempts are being made to identify ways to reduce these quantities in order to counteract the problem. Circular Economy is a buzzword that is often mentioned in this context, under which many activities to extend the service lifetime are subsumed. Pyrolysis processes, as a form of chemical recycling, involve a technique often presented as a poster child and are subject to increased research. Consequently, this thesis will address the following research question in more detail: *In an attempt to create a more Circular Economy, what can chemical recycling in the form of pyrolysis offer?* To answer this relatively broad question more specifically, two sub-research questions have emerged: *(1) What qualifies pyrolysis processes to be classified as circular? and (2) What is holding companies back from pursuing larger-scale implementation of the pyrolysis technology?* The first part of the work provides an overview through literature research of the concept of Circular Economy, selected critical aspects of it, as well as an insight into plastic waste management and an in-depth examination of the functioning of chemical recycling in general and pyrolysis processes in particular. Subsequently, in the empirical part, the current implementation status is exploratively recorded with the help of expert interviews, targeted research, and statements from companies in the pyrolysis industry. On the one hand, the result presents a screenshot of the current efforts to bring pyrolysis processes to market and, on the other hand, an overview of the hurdles that still need to be overcome before widespread implementation is possible. These barriers are divided into five dimensions, namely technological, environmental, legal, economic and logistical. According to the analysis, pyrolysis can be classified as an initiative within the Circular Economy, as it pursues the goal of keeping materials in the loop with clear parallels to the general discourse on the concept. Nevertheless, in practice, the technology remains in its infancy and struggles to deliver on its high expectations.

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List of Abbreviations

ABS	Acrylonitrile-Butadiene-Styrene-Copolymer
bbl	Barrel of Crude Oil
BAT	Best Available Technology
CAPEX	Capital Expenditures
CE	Circular Economy
EESI	Environmental and Energy Study Institute
ELTs	End-of-Life Tyres
HDPE	High-Density Polyethylene
LCA	Life Cycle Assessment
LDPE	Low-Density Polyethylene
MFA	Material Flow Analysis
MMA	Methyl Methacrylate
MSW	Municipal Solid Waste
Mt	Megaton
OPEX	Operational Expenditures
PE	Polyethylene
PET	Polyethylene Terephthalate
PMMA	Polymethyl Methacrylate
PO	Polyolefin
PP	Polypropylene
PPA	Polyester, Polyamide and Acrylate Polymers
PPWD	Packaging and Packaging Waste Directive
PS	Polystyrene
PVC	Polyvinyl Chloride
RCB	Recovered Carbon Black
S-LCA	Social Life Cycle Assessment
SPI	Society of the Plastic Industry

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TCD	Thermo Catalytic Depolymerization
tpa	tons per annum
WCED	World Commission on Environment and Development
WEEE	Waste of Electrical and Electronic Equipment
WtE	Waste-to-Energy

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1 Introduction

“The paradox of the Circular Economy is that it seems to offer radical challenges to linear ‘take-make-waste’ models of industrial capitalism, backed by international legislation, but it does not actually give up on unsustainable growth. We need to tackle the plastics crisis at its root, dramatically reducing the global production of toxic and wasteful plastics.” This critical statement by Alice Mah (2021, 121) summarises the interesting double role of the circular movement that is under observation throughout this work. Without a doubt, plastic pollution is an urgent problem, considering, for example, the problem of the Great Pacific Garbage Patch (Lebreton et al., 2018). A prolonged lifetime of plastic emerges to be highly urgent, and any initiative to remedy this issue is commendable. Many of these initiatives are grouped under the scientifically and practically popular umbrella term ‘Circular Economy’ (CE). Thereunder, various approaches have been adopted to achieve the goals of waste management, namely resource conservation and environmental protection (Fellner & Brunner, 2022). One proposed approach to reaching an extended plastic reapplication is chemical recycling. In addition to mechanical recycling, it suggests another way to keep plastic in the loop for longer and thus establish more circularity (Thiounn & Smith, 2020). Meanwhile, it is also a solution of interest to the economy and potentially introduces new business opportunities. However, it is accused of distracting from changing the heavily increased production and consumption behaviour of societies across the globe and pretending to offer an opportunity for green growth (Giampietro & Funtowicz, 2020). Pyrolysis processes, a distinctive type of chemical recycling, have garnered particular interest and are considered extremely auspicious by some scientists and businesspeople (Dai et al., 2022). Therefore, pyrolysis is the primary focal point of investigation within this scholarly work and will be assessed exemplary for other initiatives under the concept of CE.

1.1 Research Gap

The current state of research on the technical applicability of pyrolysis processes is described and covered in great detail in the literature (Anuar Sharuddin et al., 2016; Butler et al., 2011; Dai et al., 2022; Lechleitner et al., 2020). Moreover, it is difficult to get a closer look at the technical status of the companies, as many are still in the research and development phase and therefore do not readily share their data. Hence, the focus of the empirical part of this paper will be set on the current state of implementation, developments, and its implications on other efforts of the circular movement. The aim is to find out what effect the implementation of the

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technology on the market has in the fight against plastic accumulation. Consequently, the overarching research question that has been derived is the following:

In an attempt to create a more Circular Economy, what can chemical recycling in the form of pyrolysis offer?

In this discourse, this work primarily discusses if the technology is truly circular, why there has not been a large-scale roll-out of pyrolysis plants, and what a smooth and cautious implementation can look like. Furthermore, it will be interesting to look at how the development in this area can be interpreted as an analogy for other developments within the realms of the CE. This has led to these two sub-research questions:

What qualifies pyrolysis processes to be classified as circular?

What is holding companies back from pursuing larger-scale implementation of the pyrolysis technology?

1.2 Relevance and Objective

Plastic waste accumulates and poses a threat to many living creatures. The use of this slowly degrading material needs to be reduced, and plastic needs to be reused or recycled. Furthermore, binding recycling rates are getting more ambitious, like for example in the European Union (European Commission, 2018), and solutions are required to achieve them. Therefore, the plastic waste management sector is in the spotlight. Various solutions have already been proposed in the recent past, mainly in the form of mechanical and chemical recycling. Alternative strategies and whether these would be better in line with the goal of a circular use of resources must also be considered.

The study acknowledges the urgent issue of plastic pollution. It explores how initiatives within the CE, such as chemical recycling, can reduce plastic waste and achieve greater circularity. The paper focuses on pyrolysis processes as a widely discussed solution, examining their technical applicability, the current state of implementation, trends, and their implications for the circular movement. The objective is to gain insights into the circularity of pyrolysis processes, identify impediments to their wider adoption, and provide recommendations for a cautious and effective implementation strategy. The work's relevance lies in addressing the urgent challenge of plastic accumulation while considering the broader objectives of resource conservation and environmental protection within the context of the CE.

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2 Methodology

2.1 Research Design and Approach

The research design can be broadly divided into two parts. In the first section, a profound literature research is conducted, which on the one hand, reflects the current state of the art and, on the other hand, is intended to lay the groundwork to synthesise existing knowledge for the empirical part. Thus, by means of various articles and publications from organisations, the concept of the CE is initially outlined, and its various facets are highlighted. Afterwards, the next chapter focuses on a critical examination of the discourse on the current use of the concept, as well as its implementation in practice. This is followed by a discussion of the problem of plastic waste and how CE is seen as a potential remedy. Chemical recycling, in particular, is assigned a promising role here. Therefore, the different forms of these reprocessing techniques are presented before the proponent in focus, the pyrolysis process, is discussed in more detail.

The second part presents selected companies that have entered or are in the process of entering the market using pyrolysis technology. This creates a better understanding of the current status of implementation of the technology and gives qualitative insights into the practical world. Moreover, current developments and trends in the industry are evaluated based on the list of companies working on the pyrolysis process published in the paper by Maisels et al. (2022). These quantitative findings and their graphical presentation describe how these companies operate, how advanced the process is, and where the average pyrolysis process is headed. Furthermore, open barriers that still need to be overcome are discussed, and the discourse is examined in a broader context. This section will integrate the insights gained in the conducted interviews. Different dimensions are analysed, namely the technological, environmental, economic and legal spheres. In this way, the introduction of pyrolysis processes serves as an example of CE measures from which recommendations for future efforts and a better assessment can be derived. With the help of these qualitative, quantitative and literature findings, the research questions will be answered in conclusion.

2.2 Data Collection

For the literature section, findings from existing literature were collected to gather the necessary background knowledge. Analysing scientific books and articles is the basis for a necessary understanding of the topic. For a better comprehension of the CE, seminal works (Geissdoerfer et al., 2017; Kirchherr et al., 2017; Murray et al., 2017) and a historical outline of the development (Wilts & Bröcker, 2022; Winans et al., 2017) are of assistance on the one

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hand but also works by scientists who look at the concept in a more critical perspective on the other hand (Korhonen et al., 2018; Kovacic et al., 2019; Mah, 2021). The accumulation of plastic and the problems associated with it are taken up in reports by management consultancies (Hundertmark et al., 2018; Rubel et al., 2019), but also by NGOs (Ellen MacArthur Foundation, 2019a-c) and public institutions (Quicker et al., 2017; Vogel et al., 2020). Regarding chemical recycling in the form of pyrolysis processes, several papers were particularly helpful in gaining an in-depth understanding (Al-Salem et al., 2009; Dai et al., 2022 & Lechleitner et al., 2020).

In the next step, best practices from some of the most important companies, which are currently or have already entered the market with pyrolysis processes, were contacted and asked for a written statement. The companies contacted were taken from the table in the paper *"Chemical Recycling for Plastic Waste: Status and Perspectives"* by Maisels et al. (2022). In this paper, the authors provided an overview of the developers of pyrolysis plants, projects, and operators in Table 1. Selected companies, who responded to the outreach, and their projects are presented in order to gain a clearer view of the scope and potential of these, as well as to get an additional angle of the status quo of implementation. The questions to be replied to were the following:

What contributions can your company make in the short-term and long-term, both nationally and internationally, towards improving plastic recycling and promoting circularity in the industry?

What barriers need to be overcome in order to scale up the use of pyrolysis technology on a larger scale (technologically, legally, economically, logistically, etc.)?

For the trend analysis, the second part of the empirical section, the list from Maisels et al. (2022)'s paper was used again, and the data was processed and compiled quantitatively. With the help of self-produced graphs, the trends provide information about the regional distribution of the companies and their installations, the capacity, the incoming material, the resulting products, the average process temperatures, the partners and the current status of implementation. This should provide a better insight into where the current pyrolysis processes evolve.

Furthermore, four interviews were conducted, two of them with scientists carrying out research in the field of chemical recycling and two with practitioners working for companies involved in pyrolysis technology. In addition to the written statements from the companies,

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the interviews were predominantly woven into the third empirical section on the barriers to the large-scale roll-out of pyrolysis companies. Furthermore, these interviews were used as a secondary source of information and were incorporated where appropriate. The full length of the talks or written exchanges could not be included in the paper, so the transcripts can be found in the appendix. The persons who were interviewed shall be introduced briefly:

- Dr. rer. nat. Franz-Georg Simon: He currently works at the Department of Materials and Environment (Dpt.4), Bundesanstalt für Materialforschung und -prüfung in Germany. His main field of research is in Environmental Chemistry and Environmental Engineering. The already addressed paper *"Chemical Recycling for Plastic Waste: Status and Perspectives"* (Maisels et al., 2022) that he co-authored, and the list of pyrolysis-oriented companies included in this paper was of significant relevance to this work as a starting point. The interview was conducted on 13 April 2023.
- Erik Moerman M.S. M.Eng.: He has been working for Indaver, a Belgian provider of waste management solution for industrial companies and the public sector, for over 20 years. Now, he is the Director of Sales and Development for the subsidiary Plastic2Chemicals, which operates in Antwerp. Mr. Moerman gave insights into P2C's operations but also into chemical recycling with pyrolysis processes in general. As he speaks in an official capacity for P2C, his statements are quoted under P2C. The interview was conducted on 13 April 2023.
- Dipl.-Ing. Dr.mont. Andreas Lechleitner: Like DI. Dr. Schubert, he also conducted research on chemical recycling at the University of Leoben and focussed on OMV's ReOil process. He is now a Senior Expert for Circular Economy Innovation at OMV. The interview was conducted in written form on 9 May 2023.
- DI. Dr. Teresa Schubert: She completed her doctorate at the University of Leoben, where she conducted research on chemical recycling. At present, she works for Wien Energie GmbH as a Senior Research & Development Specialist. The interview was conducted in written form on 24 April 2023.

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3 Literature Review

Now that the methodology has been outlined, the following section will present the already established literature. The first part of the literature section is an attempt to capture the concept of CE, followed by a critical assessment of the current discourse on it. Then, an outline of the challenges of plastic waste and an insight into how circular, but also non-CE measures are used to stop the accumulation of plastic is provided. The focus of the literature review, and of this thesis, is the subsequent section on chemical recycling, with an emphasis on pyrolysis processes, operating as an initiative in the field of CE.

3.1 Circular Economy: Capturing the Concept

CE is a concept that has gained traction and attracted interest from practitioners and scholars alike in recent years. The contemporary 'extract-produce-use-dispose' model is directed at the linear production and consumption behaviour that has been dominant since the beginning of industrialisation (Frosch & Gallopoulos, 1989). Economic and environmental insufficiencies arise when carrying on business as usual. Some examples include using unsustainable and scarce resources that will become more expensive in the future, a premature product-end-of-life, wasted end value and a missed opportunity to establish customer relations (Winans et al., 2017). On the contrary, a CE aims to reduce virgin input resources and waste output by establishing an alternative, cyclical flow model (Haas et al., 2015). The basic idea is simple and follows from the fact that raw materials and manufactured products are kept in circulation at the end of their use phase by being reintroduced into operation in the same or a modified form (Ellen MacArthur Foundation, 2023). In order to achieve a CE, it is vital to think in material circles with different stages, like the stage of product design in which already 80% of the product's circularity is decided (Wilts & Bröcker, 2022). According to the so-called Accenture Model, further vital stages are the procurement process with a circular supply chain, manufacturing, distribution, use, reverse logistics, sorting, recycling, and the reintroduction into the cycle (Bianchini et al., 2019).

While a CE constitutes an economy that differentiates itself from the 'end-of-life' concept, it has nonetheless very blurry boundaries, barely any common guiding principles for action and is hence hard to define generally (Kirchherr et al., 2017). Merli et al. (2018, 717) have concluded in their systematic literature review on how scholars approach CE that one reoccurring denominator is that it focuses on *"harmonising economic growth, environmental issues and resource scarcity"*. In literature, it does so predominantly by providing quantitative tools that rely on standardised and systematic methods, like Life Cycle Assessments (LCAs)

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or Material Flow Analyses (MFAs). While the idea of 'closing the loop' can be traced back to Boulding's early work in 1966, in which he highlighted the scarcity of natural resources for human activity, the first coherent conceptualisation of what is understood today as CE is attributed to Pearce and Turner (1989) (Andersen, 2007). Since then, several currents have shaped the concept and transformed it into this fluid and elusive construct that it is today. Geissdoerfer et al. (2017) listed some of these influences, namely cradle-to-cradle, laws of ecology, regenerative design, industrial ecology, biomimicry and blue economy.

The most prominent representative of CE is the Ellen MacArthur Foundation. The non-governmental organisation publishes articles, reports, videos and podcasts on the topic of CE and has been instrumental in its dissemination and relevance. The best-known contribution of the Ellen MacArthur Foundation is the publication of the Circular Economy System Diagram, better known under the name Butterfly Diagram (Ellen MacArthur Foundation, 2019a).

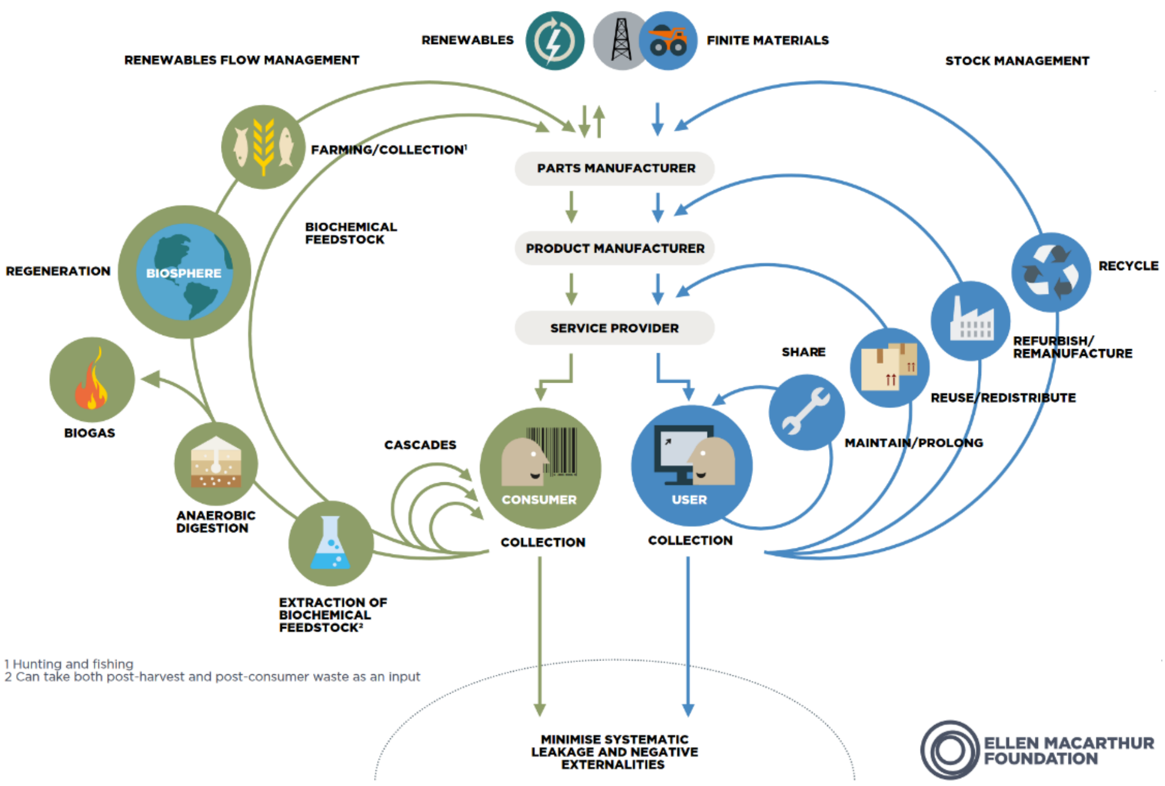

Figure 1: Butterfly Diagram (Ellen MacArthur Foundation, 2019a)

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Therein, material flows are divided into biological and technical cycles, pointing out how materials should be treated in order to prolong their lifetime. The left side of the butterfly describes the biological cycles and focuses on regenerative processes. The focus is on composting, anaerobic digestion to return nutrients to the cycle, and regenerative agriculture. The resulting microorganisms and biogas can be used as a source of energy. The aim is to turn biological waste into new products, biochemical feedstocks and healthy soils, as well as to maintain a thriving biodiversity (Ellen MacArthur Foundation, 2019b). On the right side, it is shown how the technical components, consisting of finite materials, can be kept in the loop for a longer time, preferentially eternally. The innermost circles are the most significant, starting with sharing, maintaining, reusing, redistributing, refurbishing and remanufacturing. Whilst all circles ensure that the product is not becoming waste, sharing, maintaining and reusing allow products to keep the same value. Redistributing is the process where products are still used but in different markets. Refurbishing and remanufacturing allow products to be restored and used again. Recycling means a product is broken down into basic materials and assembled into a new product. In doing so, the product value is lost, but the material remains in the cycle (Ellen MacArthur Foundation, 2019c).

What becomes evident from the Butterfly Diagram's technical cycle is that a so-called waste hierarchy is inherent to CE. To show this hierarchy, the actions that need to be taken to make products circular are divided into three groups that favourably lead to smarter product use and manufacturing, an extended product lifespan, and a practical application of materials. The result is a total of nine strategies, all of which begin with the letter R. Hence, the concept is called the 9R model (Kirchherr et al., 2017). As in any hierarchy, some strategies are to be preferred and therefore placed higher up, such as refuse, rethink and reduce. Even though recycling and recovering are often referred to in practice, this model highlights that these are the least desirable strategies and are closest to a linear economy.

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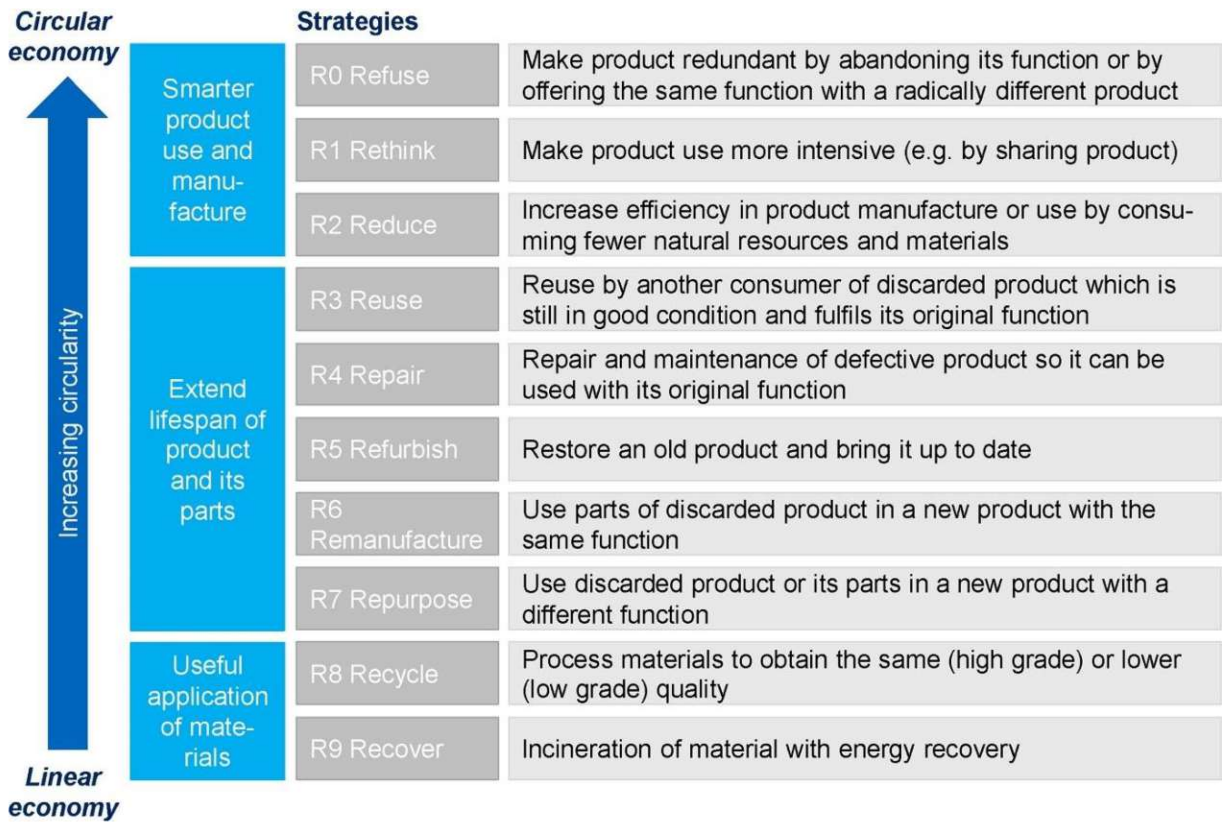

Figure 2: 9R Model of the Waste Hierarchy (Kirchherr et al., 2017, 224)

Moreover, it is essential to place the concept of CE in relation to the concept of sustainability to provide a better assessment. De Jesus & Mendonça (2018, 75) summarised that CE is *"not described necessarily as a disruptive concept, but rather as a workable socio-technical approach for attaining economic and ecological sustainability"*. CE can be seen as a tool to achieve sustainability (Fellner & Brunner, 2022). In general, CE, in contrast to sustainable development, offers a much more operational and implementable approach for a transition towards a regenerative system. While the former is often hard to grapple for companies and individuals due to its complexity, CE represents a business case and is inherently logical (De Jesus & Mendonça, 2018; Geissdoerfer et al., 2017).

Geissdoerfer et al. (2017) have identified similarities and differences between the two models. In both concepts, intergenerational commitments play an important role. They are both global in nature and ultimately aim at system transformation. Another similarity is that private companies and their innovation are central, but regulation and incentives are vital for proper implementation. Also, they equally define cooperation in a more interdisciplinary framework and technological improvements as prerequisites for success. With regard to differences, sustainability pursues an open goal that varies depending on the agent, while the goal of CE is a closed loop and a reduction of resource input and leakage. Moreover, CE prioritises and favours the economic system and its actors, whereas the sustainability movement focuses on a more holistic approach and the triple bottom line. As a result, the responsibility in CE lies mainly with private companies and regulators, while within the concept of sustainability, it is shared but not clearly defined (Geissdoerfer et al., 2017).

Merli et al. (2018) highlight that CE is a trending topic, as evidenced by the increased number of publications on the topic. This spike in interest in the topic is primarily evident in Europe and China. Content-wise, the main focus of these studies is either on the macro level, where systematic change through CE is discussed, or they support companies on the micro level to incorporate CE better. Another important finding of their work is that science strongly focuses on closing material cycles but slowing down cycles is hardly mentioned or discussed (Merli et al., 2018). However, the latter is also integral in current attempts to curb the excessive consumption of resources as much as possible.

It can be concluded that the CE framework continues to evolve, has no definite limits and should therefore be consolidated in the future. Like any concept that receives much attention, there is also criticism that CE encounters, which will be discussed in the following part.

3.2 Critical Discussion of the Circular Economy Concept

After introducing the concept of CE, the following subsection will deal with the critical discussion around this concept. Along with the meteoric rise of CE, an armada of critiques emerged, accusing the concept of not delivering what it promises. The most important points of criticism are discussed below. Only like this, misguided assumptions, incoherencies and false pledges can be debunked, and a new, more realistic understanding of CE unfolds. It is a collection of points of criticism from selected literature, which does not claim to be exhaustive.

Figure 3 describes five crucial points of criticism encountered frequently during the literature research. This section will discuss these points in more detail.

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Figure 3: Criticism of the Circular Economy (own graph)

3.2.1 Biophysical Boundaries of Economic Expansion

The first point of criticism goes back to an argument published in the book *"Beyond Growth. The Economics of Sustainable Development"* by Hermann Daly in 1996, who, together with his teacher Georgescu-Roegen is considered a co-founder of ecological economics. In his line of argument, Daly invokes the laws of thermodynamics and states that all economic activities, including those that fall under the category of being circular, require energy, increase entropy and lower exergy (Daly, 1996). It follows that all economic activities have an impact on the environment and its resources. With constant economic growth, the physical impact of the economy, measured in material and energy flows, increases. This blind spot remains widely unrecognised in debates on CE. For Daly, distinguishing between eco-efficiency and sustainability is essential in this context. No matter how efficiently the system is organised and structured, if the sustainable limit is exceeded and the burden on the supporting systems is excessive, even this supposedly optimised system will crumble. As Daly put it, *"optimally loaded boats will still sink under too much weight – even though they may sink optimally"* (Daly, 1996, 50).

Savini (2019, 676) even goes further, calling CE *"the beginning of the capitalist economy's structural adaptation to problems of waste accumulation and resource scarcity"*. According to Savini (2019), waste is upgraded into a resource and turned into an additional commodifiable product that can be traded to contribute to the economy's growth. Based on this, a narrative is created that is supposed to lead to green economic growth. Kovacic et al. (2019) make a coherent point in this regard, drawing on the butterfly diagram introduced above, that a CE can only succeed if it does not disrupt and jeopardise the interplay between the biosphere and the technosphere. On the one hand, the carrying capacity of the biosphere must not be exceeded by the demand for ecological resources; on the other hand, human activities must be limited to not destroy resource elements in the technosphere. Derived from this, the Ellen Mac Arthur Foundation allegedly follows a wrong assumption in aligning the technosphere with the biosphere within the Butterfly Diagram. It is argued that a redesign of the technosphere is needed so that resources in the biosphere are allowed to be restored and maintained (Kovacic et al., 2019). The biosphere, however, is a comparatively slow process governed by the laws of nature compared to the pace of a technosphere that is embedded in an increasingly ballooning economy. Therefore, Kovacic et al. (2019) conclude that a high degree of circularity, which allows the biosphere to regenerate, would decelerate material as well as energy flows and is inimical to economic growth.

3.2.2 Oversimplification

Another criticism of CE lies in the oversimplification of its operationalisation and its goals, which may result in a constrained perspective, as elaborated by Murray et al. (2017). Reductionist thinking leads to better comprehensibility of the matter and can thus reach more people. Nevertheless, care must be taken not to overemphasise certain aspects and neglect the omnipresent complexity in nature. Cycles in nature run on a holistic level, which makes it difficult to single out individual processes and thereby come to a simplistic but incorrect conclusion. Steenmans & Lesniewska (2023, 3) employ the term *"narrowly construed meta-narratives on certain environmental goals"*. One example of this is that a proclaimed goal of CE is to keep products in the loop for longer through a more durable design. A design that breaks down less quickly usually has a more complex chemical composition, consumes more helpful energy and can subsequently release more entropy, all leading to a more complicated reassembly (Murray et al., 2017). Another reductionist approach is biomimicry, in which one copies biological processes yet is not really biological. Individual processes are singled out that rarely have the same effect in isolation as they do in the overall ecosystem. Oversimplification indeed was important for CE in its steep rise to popularity. The idea is appealing and easy to comprehend, thereby capable of reaching a broad audience. However,

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in the process of simplifying, much information gets lost, and the remainder is often not telling the whole story (Murray et al., 2017).

3.2.3 Lack of the Social Dimension

As noted by Sala (2020), in attempting to assess sustainability, the complexity of the problem poses an obstacle. Different concepts are used to capture multidisciplinarity, such as the triple bottom line approach (Sala, 2020). In this concept, environmental, economic and social aspects are taken into account in order to derive informed policies and decision-making. In some other approaches, institutional and cultural dimensions are also considered. Taking a closer look at the definition of different types of capital, namely natural, economic and social capital, Pearce et al. (1994) deduced that there are strong and weak approaches to sustainability. The strong approach to sustainability considers certain natural capital and its functions not replaceable by man-made capital. This type of capital must be protected and preserved for future generations. A weak approach to sustainability holds that all capital has a price attached to it and is, therefore, substitutable. The Brundtland Report, which is still widely used today as the baseline for sustainable development, takes a strong approach by describing *"development which meets the needs of the present without compromising the ability of future generations to meet their own needs"* (WCED, 1987, 43). In this definition, the focus points to inter-generational equity and equity between different peoples currently inhabiting the planet. Thus, equity and social justice are central to the concept of sustainability (Murray et al., 2017).

Having introduced the concept of CE in section 2.1, it is noticeable that CE hardly addresses the social dimension, if at all. This remains intriguing as the issue of resource distribution and the forthcoming transformation of production and service processes will affect all strata of the population and thus also entail a social transformation. It will therefore be crucial for the success of CE whether social aspects are taken into account in the working methods and whether consideration is given to how the policies implemented will also ensure greater equality with regard to racial, gender and religious disparities. Winans et al. (2017) mention that community involvement, public education on the matter and broader media coverage are essential pillars to overcome this lack of addressing the social dimension and information asymmetries. Knowledge must also be regarded as a resource that is critical in being kept in the loop to reach as many people as possible for a wide-ranging and swift transition. If the spread of knowledge (on e.g. recycling routines) is constrained, bottom-up CE initiatives are prone to be unsuccessful (Winans et al., 2017). Redclift (1993, 18) outlines this relationship

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as follows: *"It soon becomes clear that we cannot achieve more ecologically sustainable development without ensuring that it is also socially sustainable. We need to recognise, in fact, that our definition of what is ecologically sustainable answers to human purposes and needs as well as ecological parameters"*.

Some scholars are trying to combat this issue by using a popular quantitative tool in CE, LCAs, to represent the social dimension better. The developed Social-LCA (S-LCA) follows the standard steps of LCA: target definition, life cycle inventory, life cycle impact assessment and interpretation. It aims to include social impacts along the supply chain. However, this method is not yet mature and requires further recognition and widespread implementation (Sala et al., 2015).

3.2.4 Global Net Sustainability and System Boundaries

Data from the Environmental and Energy Study Institute (EESI, 2021) show that in 2020 about 80% of energy production came from fossil fuels such as coal, oil and natural gas (EESI, 2021). All fossil fuel projects are part of the linear throughput economy: Dead resources stored in the bedrock for thousands of years are mined and subsequently processed, used and converted into greenhouse gases. The fossil cycle is a very slow one, but humanity is consuming these resources at an increasing rate, contradicting all principles of CE. It becomes clear how difficult it is to implement a functioning and honest CE.

Therefore, Korhonen et al. (2018) introduce the concept of global net sustainability, which aims at comparing an entire situation before and after a set action or project implementation. It is essential to define system boundaries, both in time and space. In the case of spatial system boundaries, the whole supply chain, value chain and product life cycle are included. In times of globalisation, climate-damaging activities are regularly outsourced to other countries, and the problem is simply shifted locally. In this way, a local increase in efficiency and social and environmental improvements can be achieved, while in other parts of the world, it yields the contrary effect (Korhonen et al., 2018). Temporal system boundaries also pose a frequent balancing act for decision-makers. While there is a trade-off between short and long-term impacts, it must also be taken into account that some impacts are not yet assessable or certain technologies are not yet developed. Usually, attention is overwhelmingly paid to minimising short-term impacts. Each decision leads to a so-called lock-in, which allows little or no adjustment for the coming years (Goodman, 2009). In the energy sector, for example, such decisions have an impact for the following 30-40 years, which is mainly due to slow amortisation rates. In CE, as in other sustainability concepts, impacts are either oversold or

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underreported because local and temporal system boundaries are not set appropriately (Korhonen et al., 2018). This needs to be addressed in future.

3.2.5 Efficiency without sufficiency

In section 2.1, the 9R model and the resulting waste hierarchy were discussed in detail. Kirchherr et al. (2017) found in their analysis of CE definitions that only one-third of all authors included the waste hierarchy in their definitions. In their view, this can lead to a distorted understanding of CE because companies and other agents that only undertake small changes can already count themselves as part of the circular movement. CE should be understood as a fundamental systemic change that can first and foremost be brought about by implementing the upper strategies of the waste hierarchy (refuse, rethink, reduce). Lower strategies in the waste hierarchy (recover, recycle) lead to improved efficiency, mainly economic efficiency (Kirchherr et al., 2017). A

As Berkhout et al. (2000) found, higher economic efficiencies are always subject to rebound effects. This mechanism works as follows: Efficiencies lead to lower prices, resulting again in more consumption. The increase in consumption makes up the efficiency gains and, in many cases, even offsets the initial environmental improvement (Berkhout et al., 2000). A similar effect occurs when a wealthy country achieves increased eco-efficiency and better nature protection by moving its environmentally harmful activities to a neighbouring country that is dependent on foreign investment and hence, accepts the environmentally degrading activity within its borders (Mayer et al., 2005). In the neighbouring country, biodiversity decreases, and other environmental aspects deteriorate. Consequently, the ecosystem in the wealthy country will also be harmed by the lack of species migrating into the country, worse air currents from neighbouring countries, and other issues. Mayer et al. (2005, 360) call this phenomenon the *"boomerang effect"*. Therefore, paying attention to the adverse effects of efficiency increases when adopting the CE is necessary.

Brauner (2022) describes that not only efficiency but also sufficiency is needed to initiate the necessary systemic transformation. In concrete terms, this means that when implementing CE measures, the focus must increasingly be placed higher in the waste hierarchy rather than on the lower, less effective strategies, as has been the case to date (Steenmans & Lesniewska, 2023). A significant lever for this would be changes in consumer behaviour, such as the wider use of models that follow the principle of the sharing economy. This point of criticism is similar to some extent to the first subpoint, discussing the biophysical boundaries of economic expansion, with the difference that, in this case, the focus lies not on the economic system as a

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whole but instead on the widespread lack of agreement on what CE should look like in implementation and what the resulting consequences entail.

In conclusion, some work must be done before the concept can be considered mature. The biggest problem at present is the need for more agreement on what CE does and does not encompass. This ambiguity is frequently exploited to use CE as a concept to futureproof capitalism and thus carry on with business as usual. At the heart of the concept should not be the creation of new business models by commodifying waste but a holistic rethinking of how humanity engages with its limited resources. Likewise, improvements will not be accomplished if the social dimension of the triple bottom line is not taken into account and if spatial and temporal system boundaries are set so narrowly that they only capture a segment of the whole picture. In order to bring the scientific concept closer into practice, the following section takes a closer look at the circular ambitions at the example of plastic waste management.

3.3 Circular Economy in the Field of Plastic Waste Management

Due to its diverse application, attractive characteristics and economic benefits, plastic has become indispensable in households and industries. Before World War II, plastic was mainly used by the military in the form of synthetic plastics, like Bakelite. Starting in the second half of the twentieth century, plastic production experienced rapid growth (Geyer et al., 2017). Jambeck et al. (2015) found that while plastic accounted for less than 1% of Municipal Solid Waste (MSW) in 1960, it increased to more than 10% in 2005 in middle- and high-income countries, also taking into consideration that MSW generation has simultaneously grown extensively over this period. According to Shamsuyeva & Endres (2021), this development can be traced back to improved processing and performance properties, like rheological, mechanical, thermal, structural, morphologic, and optical properties. Maier & Schiller (2016) explain that the reasons for this enhancement of the material are mainly due to additives, such as stabilisers, colourants, plasticisers, antioxidants and others, which have been increasingly added to plastics. Some benefits include better protection against degradation, easier processability, stabilisation against UV-induced degradation and modification of the material to an extended range of properties (Maier & Schiller, 2016). The proliferation of plastic waste and its components has become so universal that it has been proposed to be used as a geological indicator of the human-dominated Anthropocene era (Zalasiewicz et al., 2016).

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The widespread distribution of plastic and its accumulation has also increased pressure on the environment and organisms, including humans. Barnes et al. (2009, 1985) report a high-paced accumulation and fragmentation of plastic debris *"in terrestrial environments, in the open ocean, on shorelines of even the most remote islands and in the deep sea"*. Some of the consequences thereof encompass a threat to animal species by starving or choking, a spread of toxic chemicals, and a breaking down of mega and macro-plastics into tiny particles known as micro-plastics that are unconsciously consumed (Barnes et al., 2009). Another issue comprises the fossil-fuel-based energy source, serving as the feedstock of plastic, which makes up approximately 4% of the overall use of oil and gas. In addition, another 3-4% of this budget accounts for the manufacturing process of all plastic products. Barnes et al. (2009) state that plastics consist almost exclusively of monomers such as ethylene and propylene, made of fossil hydrocarbons and are not biodegradable. Most of the products are aimed at being short-lived and disposed of after single use (Hopewell et al., 2009).

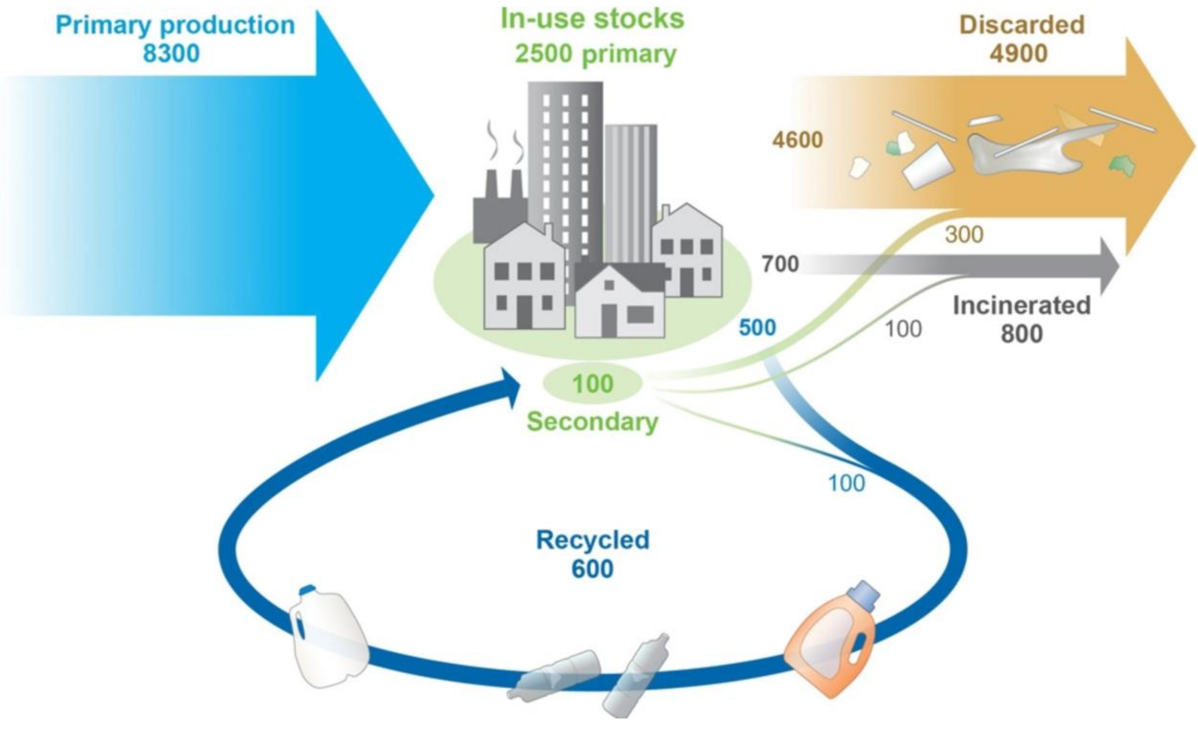

Figure 4: Production, use and fate of all plastic that has ever been made between 1950 and 2015 (Geyer et al., 2017, 2)

In their article, Geyer et al. (2017) analysed the production, use and fate of all the plastic that has ever been made between 1950 and 2015 and is displayed in Figure 4. While the primary production of virgin plastics amounts to 8300 Mt, with the most significant share produced

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after 1980, only 2500 Mt are still in use. Secondary production (recycling) accounts for 600 Mt, of which 100 Mt are still in use (assessment date: 2015). The most likely fate of plastic has been a withdrawal from the system by either being discarded (4900 Mt) or incinerated (800 Mt). Assuming steady use patterns and anticipated waste management trends, Geyer et al. (2017) forecast production to increase to 26000 Mt of resin, 6000 Mt of PP&A fibres and 2000 Mt of additives by 2050. According to a report by the Boston Consulting Group (Rubel et al., 2019), these estimates might go up even higher, with an overall primary production of 9000 Mt assessed in 2019 already and 7000 Mt calculated to have gone to waste, which indicates an even more pronounced production speed than Geyer et al. (2017) predicted.

Looking at the quantities produced and the projected quantity that will be created in the coming years (Geyer et al., 2017), it becomes clear that solutions are needed to tackle this growing problem. In this context, CE is often discussed as a potential remedy to this issue. Just as there is a general waste hierarchy for CE (Figure 2), there is one that has been derived and adapted for plastic waste management (Rubel et al., 2019). Here, too, the most objectionable way of dealing with waste plastic starts at the bottom, namely, to dispose of it in the environment or to landfill it. This resembles following the linear economic model and throwing the product away after production and (single) use. Open landfilling can be found this low in the pyramid because it poses environmental harm that is calculated to be 23 times higher than the effect of CO2, mainly by releasing large qunatitites of CH4 (Babaremu et al., 2022). There are huge regional differences in the amount of waste that ends up in landfills, ranging from countries such as Austria, Germany or Sweden with below 5% to countries such as Mexico, where this practice is still applied to 78.54% (Lima et al., 2014; Babaremu et al., 2022). Many factors depend on which waste system a country has established. Countries with a poorly developed waste system tend to send more of their waste to landfill. In contrast, countries with more advanced waste systems rely to a greater extent on thermal recovery and mechanical recycling in order to reuse secondary resources and energy gained from the process (Lechleitner et al., 2020). Incineration is one step up the waste hierarchy. It refers to the process corresponding to the most common waste-to-energy (WtE) method, which ultimately produces heat or electricity that can be used for various purposes (Sahin & Kirim, 2018). As utilisable end products are obtained, and it minimises waste, WtE is often categorised as a strategy in the scope of CE, according to many policymakers (see, e.g. Asian Development Bank, 2020). However, this classification is disputed because no long-term and sustained closure of the cycle can be achieved. At the next stage above this in the hierarchy, chemical recycling follows, where plastic waste becomes the feedstock for new products

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(Ragaert et al., 2017). These technologies are discussed in section 2.4 in more detail. Even further above in the ranking, mechanical recycling can be found. This process includes a sequence of steps that should be kept as low as possible due to their cost and energy intensity. The most critical stages are collecting, sorting, washing and grinding the material (Al-Salem et al., 2009). Schyns & Shaver (2021) explain the functioning of mechanical recycling like this: Plastic undergoes heating via extruders to attain malleability and facilitate further processing. However, the thermal response of distinct plastic types differs, and they exhibit varying softening behaviour. In the case of non-uniform plastic mixtures, such heterogeneity presents a challenge, as it may result in extruder damage and contamination of the output. These contaminants, analogous to crystal lattice defects in minerals, introduce flaws that cause material fractures (Schyns & Shaver, 2021).

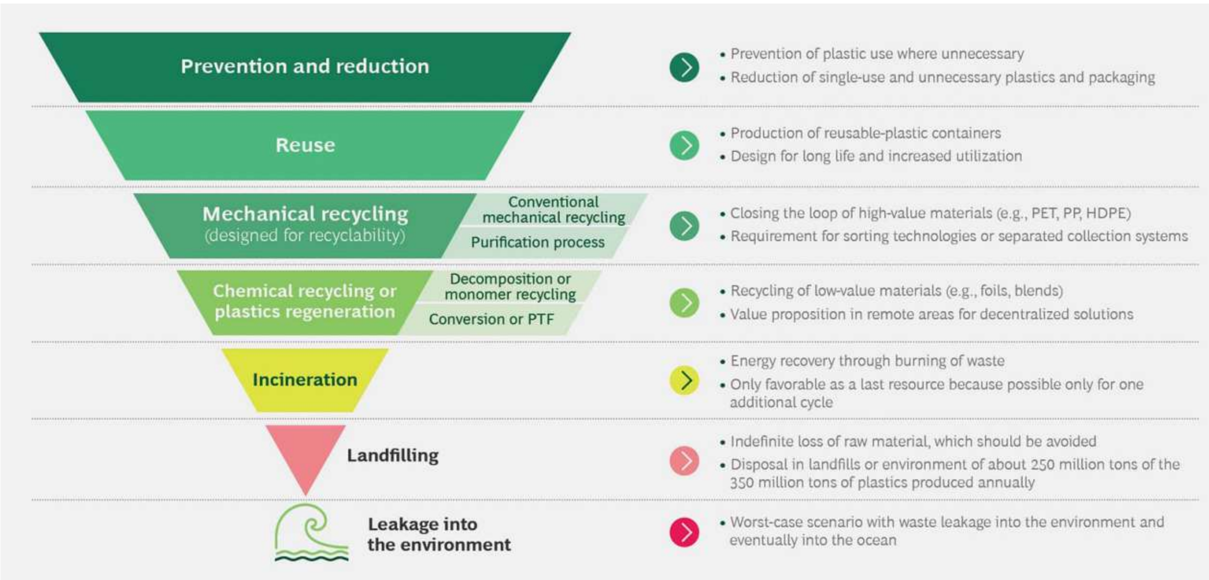

Figure 5: The Plastic Waste Hierarchy (Rubel et al., 2019, 9)

Currently, mechanical recycling is the most common form of reprocessing. Depending on the type of plastic, it can recover high-quality plastic, as can be seen in the example of PVC and PET (Al-Salem et al., 2009). Furthermore, it should not be overlooked that mechanical recycling must remain price competitive with the use of virgin material to be widely implemented. This is made more difficult by the high expenditures on separation and sorting since these costs are also reflected in the price of the recycled product (Lechleitner et al., 2020). So, with the help of mechanical recycling, it is possible to reduce the use of virgin plastic and process waste. Nevertheless, due to differing degradation steps across polymers, a

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high financial effort and difficulties in collecting and sorting the material, mechanical recycling faces many problems that need to be tackled in the future (Schyns & Shaver, 2021). What should also be taken into consideration is the fact that mechanical recycling is increasingly connected to water contamination, being a point source of microplastic pollution (Suzuki et al., 2022). In the waste hierarchy, in Figure 5 (Rubel et al., 2019), the largest focus is again on conserving resources, reusing products and their components or reducing their use. In science and practice of plastic waste management, however, these strategies are usually not the top priority but instead recycling and lower ranked strategies because these constitute a business model. Thus, with assumed constant production and consumption patterns, mechanical and chemical recycling will become the *"lynchpin"* (Schyns & Shaver, 2021, 2) in determining the extent of the multiple negative impacts that can result from plastic pollution.

For the following discussion, it is necessary to be aware of the various kinds of plastic and to consider them separately. The seven most relevant types of plastic resin have been listed by the Society of the Plastic Industry (SPI) in 1988 and are listed below in Figure 6:

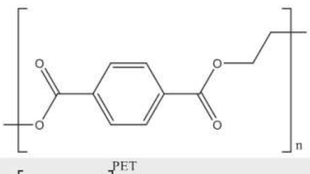
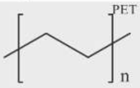
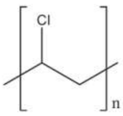
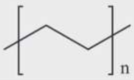
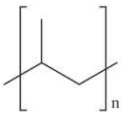
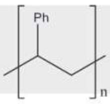
SPI Code	Polymer	Structure	Uses
1	Poly(ethylene terephthalate) (PET)		Soda bottles, water bottles, medicine jars, and salad dressing bottles
2	High density polyethylene (HDPE)		Soap bottles, detergent and bleach containers, and trash bags
3	Polyvinyl chloride (PVC)		Plumbing pipes, cables, and fencing
4	Low density polyethylene (LDPE)		Cling wrap, sandwich bags, and grocery bags
5	Polypropylene (PP)		Reusable food containers, prescription bottles, and bottle caps
6	Polystyrene (PS)		Plastic utensils, packaging peanuts, and styrofoam
7	Other		

Figure 6: SPI Code Identification Number of Polymer Resins in Plastic Products, Structure and Use (Thiounn & Smith, 2020, 1348)

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Butler et al. (2011) state that the main fraction of plastic in MSW of, about 60% is made up of polyolefins (POs), which include HDPE, LDPE and PP. From a chemical perspective, POs are long-chain alkanes consisting of high concentrations of carbon and hydrogen. Compared to PET (with oxygen) or PVC (with chlorine), POs have no halogens or other undesirable elements in their main structure. Also, they have high energy contents and are therefore well-suited to be turned into liquid fuel feedstock, as discussed later. PS and PET make up smaller fractions of plastic in MSW (Butler et al., 2011).

The different types of plastics not only have different areas of application, properties and characteristics, but it also plays a role in further processing when the initial product's lifetime has come to an end, especially in the case of mechanical recycling (Schyns & Shaver, 2021). Even before the recycling process itself, plastic waste reprocessing efficiency depends on sorting and pre-treatment processes. The types of plastic introduced in Figure 6 need to be carefully separated and singled out not to deteriorate the recycled product's quality (Thiounn & Smith, 2020). Fellner and Brunner (2022) also point out that special attention should be paid to hazardous legacy additives, which will either be transferred to secondary plastic products or, ideally, removed from the cycle. In the former case, if these substances that include heavy metals, and persistent organic pollutants, like brominated flame retardants, cannot be detected, separated, and safely disposed of, there is a risk that they will remain in the newly recycled products and thus pose a threat to the end users (Fellner & Brunner, 2022). Next to the practical issues, like collecting, sorting and pre-treating, also other factors influence the complexity of plastic recycling rates, above all, technical considerations, such as chemical reactivity (Thiounn & Smith, 2020).

It becomes clear that mechanical recycling is already well researched and widely used in practice. Figure 7 by McKinsey (Hundertmark et al., 2018) shows the global polymer flows in millions of metric tpa in 2016. 16% of all flows are collected and prepared for recycling, with an estimated loss of four % throughout the process resulting in a recycling rate of 12%. Recycling efforts are predominantly mechanical, with less than one per cent being chemically recycled. 40% of waste plastic is transported to landfills, 25% is incinerated, and 19% end at unmanaged dumps or leaks without being observed.

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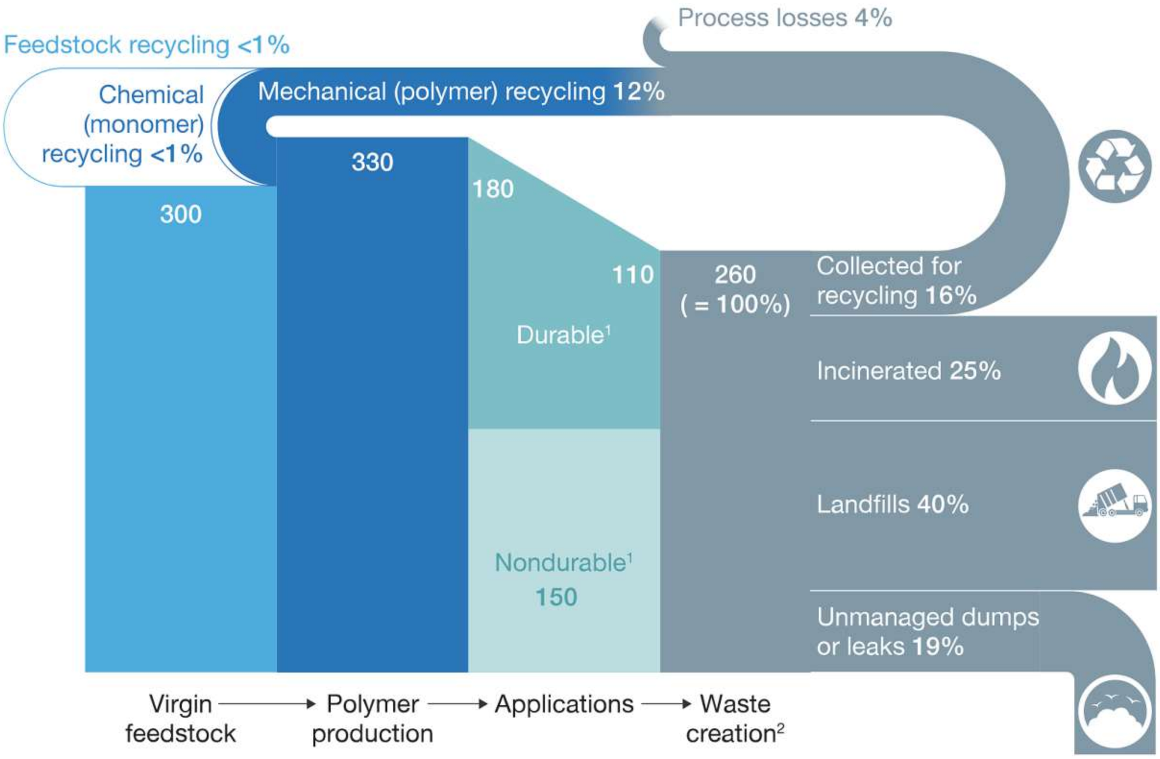

Figure 7: Global Polymer Flows, millions of metric tpa, 2016 (Hundertmark et al., 2018)

3.4 Overview of Chemical Recycling

Now that an insight into the CE in plastic waste management has been given, the next section focuses on chemical recycling, the different types, and its advantages and challenges. Lechleitner et al. (2020) explain that in mechanical recycling, the polymer structures are not changed from the ground up but are transformed into secondary products by simply melting them down (Lechleitner et al., 2020). Chemical recycling, in contrast, which is the subject of this upcoming section, separates the polymer chains, recycles the chemical building blocks obtained and polymerises them into new products (Ragaert et al., 2017). Chemical recycling is a general term for several approaches to recycle plastic waste. So, there is more than one general formula for how chemical recycling works (Solis & Silveira, 2020). However, the principle is always similar and aims to recover the building blocks of the material (Vogel et al., 2020). Exposure to heat, catalysts, solvents, hydrogen, and a partially oxidative atmosphere, breaks down the polymer chains into shorter hydrocarbons. Thus, monomers, petrochemical base materials and synthesis gas can be recovered from waste streams, with the classification depending on the forces acting to split the chains (Lechleitner et al., 2020; Shamsuyeva & Endres, 2021). The following section will discuss the pros and cons of chemical recycling (in comparison to mechanical recycling).

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3.4.1 Advantages of Chemical Recycling

Chemical recycling is currently seen as a complement to mechanical recycling (Ragaert et al., 2017). This is because it is possible to work with plastics that can otherwise only be separated with great technical effort, if at all. From this point of view, it is an attempt to save plastic from incineration to give it a new lease of life (Al-Salem et al., 2009). In Section 2.3, we have already read that the main disadvantage of mechanical recycling is that in order for plastic to be recycled, it has to be separated in a way that is costly and energy-consuming before such a processing operation can even take place. Chemical recycling can remedy this issue and does not require such an effort for separation to this extent. However, according to Al-Salem et al. (2009) the input requirements of the different chemical recycling processes also vary significantly (Al-Salem et al., 2009).

The Fraunhofer Umsicht (2023) Institute found that chemical recycling has the additional advantage of better handling impurities in plastics, such as glass, metals, fibres, pigments, additives or flame retardants, which limit cyclability in mechanical recycling. With chemical recycling, obtaining new chemical base materials for different plastic products from this process is possible. Especially in sensitive product areas, such as baby toys or food packaging, it is important to remove contaminants and return them to clean base materials (Fraunhofer Umsicht, 2023). Also, in the medical sector, wide fields of application occur if the virgin-like quality of the recycled material can be achieved (Ragaert et al., 2017).

Vogel et al. (2020) also point to another reason why chemical recycling is seen as a promising technology for the future. It can potentially keep the carbon in the plastic in circulation. This means that if plastic is the basis for new plastic, reprocessing the plastic waste can be regarded as a secondary carbon source. Thus, decarbonisation of the plastic industry could occur, and chemical recycling could contribute to reducing greenhouse gas emissions. However, the ultimate suitability as an ecological solution has not yet been conclusively confirmed technologically and tested on a large scale (Vogel et al., 2020).

Producing an equivalent to virgin plastic in various forms from high-quality recycled raw materials is the ultimate goal and advantage of chemical recycling, when executed correctly, compared to mechanical recycling (Maisels et al., 2022). Successful use of chemical recycling would eliminate the deterioration in the quality of plastic products that occurs with every recycling process and thus remove the quantitative cycle limitation (Fraunhofer Umsicht, 2023). Like this, the value chain from plastic waste to new products would be fully closed.

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3.4.2 Challenges of Chemical Recycling

On the contrary, according to Shamsuyeva and Endres (2021), one disadvantage of this type of recycling consists of the nature of its required complex facilities and the need for special solvents. These factors make it difficult for small companies to start such a project. Therefore, chemical recycling plants are mainly operated by large groups of companies, often with a background in the chemical or petrochemical industry, which also produce virgin plastic. As long as this virgin material is cheaper, these companies will have an incentive to produce this rather than recycling. Furthermore, the complexity and required know-how result in the form of centralism of the process, which in turn naturally hampers any attempt to implement more small-scale, bottom-up solutions (Shamsuyeva & Endres, 2021).

Moreover, based on the available data, Vogel et al. (2020) assume that mechanical recycling is currently superior to chemical recycling in both ecological and economic terms, if applicable. The main reason is that fewer processing steps must be incorporated. This means that in mechanical recycling, fewer additives and less energy must be added, leading to lower costs and less environmental impact (Vogel et al., 2020). Therefore, mechanical recycling should be preferred to chemical recycling whenever possible and should always be used, especially when single-variety, uncontaminated plastic waste is collected for processing. This fact is also consistent with the findings from the plastic waste hierarchy of Rubel et al. (2019).

Chemical recycling has yet to prove itself feasible for implementation on a large scale and a wide range of plastic types, as it has been chiefly used for post-consumer PET, PE and PP until now (Ragaert et al., 2017; Thiounn & Smith, 2020). With the multiple techniques of chemical recycling, additional individual problems arise that must be illuminated and evaluated for each approach separately. Hence, it is currently difficult to determine its future role in the recycling industry and the CE altogether.

3.4.3 Types of Chemical Recycling

The best-known processes are briefly presented in Figure 8 before discussing the pyrolysis process in more detail. The five most important ones include hydrocracking, thermocatalytic cracking, pyrolysis, solvolysis and gasification (Lechleitner et al., 2020).

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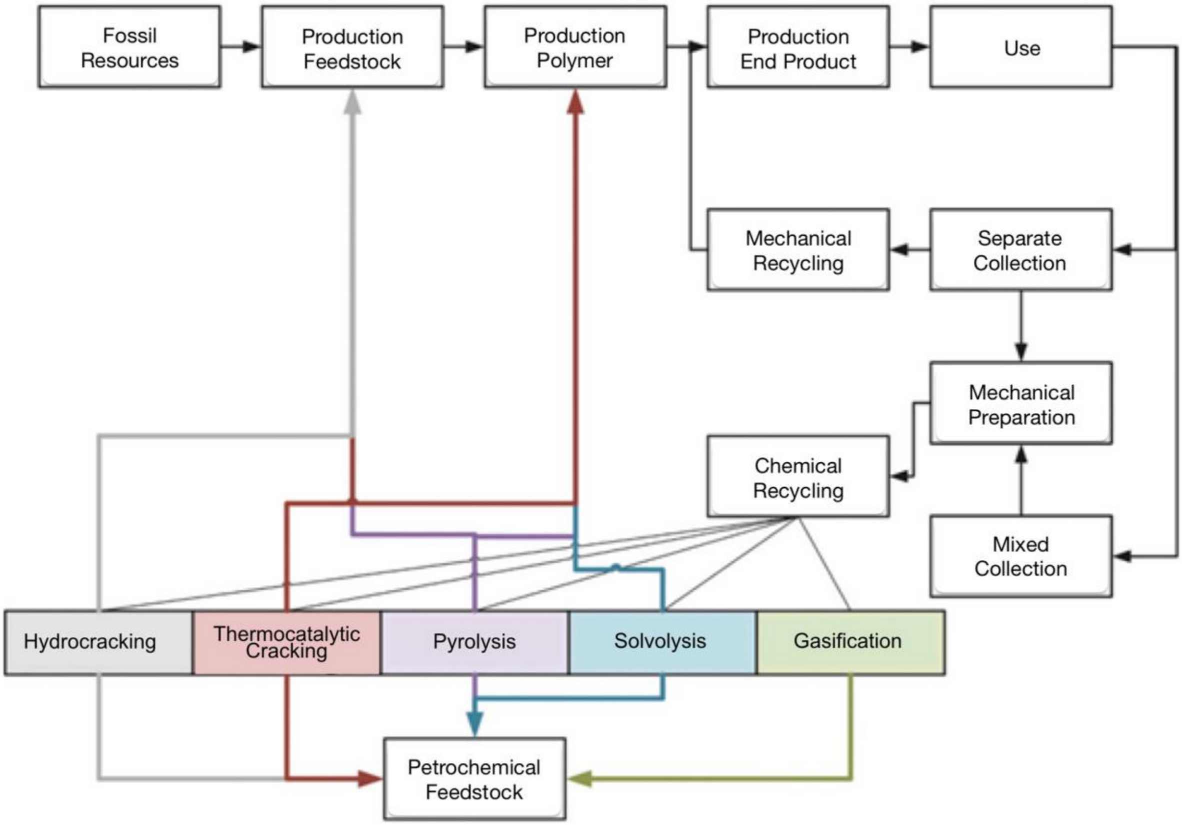

Figure 8: Options for chemical recycling in the life cycle of plastic products (Lechleitner et al., 2020, 51, translated)

Hydrocracking is the first way of converting waste plastic into shorter hydrocarbons that is presented. Munir et al. (2018) highlight that the materials are exposed to elevated temperatures, hydrogen at partial pressures and a biofunctional catalyst to achieve the desired separation resulting in various products (Munir et al., 2018). Lechleitner et al. (2020) describe that in the process of hydrocracking, the formation of unsaturated compounds is prevented to ensure a higher product quality on the one hand. However, on the other hand, there is a reduced tendency of the saturated hydrocarbons to polymerise again (Lechleitner et al., 2020). There is much research on hydrocracking, but the implementation has failed due to funding. The biofunctional catalyst and the provision of hydrogen entail disproportionate additional effort and are not financially competitive. Therefore, an attempted implementation of a large-scale project was shut down again in 1999 (Lechleitner et al., 2020).

Thermocatalytic cracking refers to the process where plastic waste is thermally split in the presence of a catalytic agent. Miskolczi et al. (2017) describe that, as with pyrolysis, the temperature, the reactor type, and the present pressure are the most important parameters for obtaining the desired product. Here, however, the type of catalyst also comes into play as a

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further adjusting screw. Even though this process is similar to pyrolysis in many respects, it has the advantage over it in that the catalyst lowers the activation energy and speeds up the separation process (Miskolczi et al., 2017). This means that even smaller plants can be set up and become economically viable earlier. On the contrary, problems can arise because catalysts sometimes react sensitively, coking can occur, and the separation of catalysts is technically complex (Lechleitner et al., 2020).

Pyrolysis processes are the main subject of this paper and will be discussed in more detail in the following section.

Solvolysis, also referred to as chemical depolymerisation or chemolysis, involves dissolving polymers in organic solvents, if necessary, under elevated temperature and pressure. Unlike solvent-based mechanical recycling processes, in which the molecular structure of the polymers is retained, in solvolysis, they are broken down into their basic building blocks (Vogel et al., 2020). Ragaert et al. (2017) explain that technically, this is the reverse reaction of polycondensation. Therefore, such technology only applies to polycondensation plastics such as polyesters and polyamides, whose synthesis is based on eliminating water or other compounds. Unfortunately, polyolefins, which make up a significant proportion of plastic waste, are not amenable to solvolysis (Ragaert et al., 2017). By dissolving, separating colour and impurities and further purification before re-polymerisation, high levels of purity can be ensured, which also allows for safe use in contact with food. However, according to Lechleitner et al. (2020), as the mechanism is limited to a small part of the emerging plastic waste volumes, the polycondensation plastics, this approach offers only limited potential to boost recycling rates (Lechleitner et al., 2020).

In gasification, the partial oxidation of carbon-containing materials takes place at high temperatures (700 to 1600 °C) and pressures between 10 and 90 bar (Lechleitner et al., 2020). In the chemical industry, synthesis gas can be used as a basic material to produce a wide range of chemical products. Gasification requires little feed preparation, which is one of the advantages of the process, along with the versatility of the end product gas. At the same time, the output only produces low-molecular products, and oxygenation occurs, leading to a reduced product value. For waste as a feedstock, in particular municipal waste, the techniques have not been able to establish themselves, even though repeated attempts have been made in the past decades in this direction (Lechleitner et al., 2020; Vogel et al., 2020).

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3.5 Focus on Pyrolysis Processes

This section is dedicated to discussing pyrolysis in more detail. The pyrolysis process is not an innovative technology per se but one that is already centuries old. Quicker et al. (2017) states that the technique has already been applied in charcoal production and in the coking of hard coal in the past. The thermal decomposition of these materials depends on the input material and leads to reaction products in all three aggregate states (Quicker et al., 2017).

Conventional pyrolysis, also referred to as thermal cracking, describes a technology for processing waste plastic that is undertaken under relatively high temperatures, above 300 °C (Lechleitner et al., 2020), and in the absence of oxygen, in an inert atmosphere. In simple terms, heat and pressure break down long polymer chains into less complex molecules. The valuable outputs of the pyrolysis process are variously composed hydrocarbon mixtures, mainly oil, gas and char, which can then be further processed in production and refineries, such as feedstock in the chemical industry (Anuar Sharuddin et al., 2016; Vogel et al., 2020). The design of industrial pyrolysis processes varies significantly depending on the targeted plastic type and product fraction. Typically, such processes involve feedstock preparation and feed-in systems, followed by depolymerisation of the molten plastics using thermal energy. This step can occur in various reactor types, with or without catalysts, in tubular reactors, stirred tanks, or fluidised beds. Subsequently, the resulting products are separated from any unconverted material and subjected to further processing, upgrading, and refinement (Schubert, personal communication, 2023).

Solis & Silveira (2020) describe that the product, which will be formed in the end depends on two factors. The first is the mixture of plastic introduced into the process. Based on the composition of the plastic waste, the moisture content, fixed carbon, volatile matter and ash content will differ. The quantity of the most desired product, pyrolytic oil, mainly depends on the latter two factors, volatile matter, and ash content. While high volatile matter benefits oil production, a high ash content has an adverse effect and fuels gas yield and char formation. Studies found that for all plastics, the amount of volatile matter is relatively high and ash content relatively low, making it a suitable input to produce liquid oil (Anuar Sharuddin et al., 2016; Solis & Silveira, 2020). Before the oil can be used, it often demands further treatment. It can be either added to crude oil streams in cracking plants or utilised as raw material in chemical production after fractionation (Maisels et al., 2022; Solis & Silveira, 2020). In several steps, it is possible to come back to obtain monomers from which plastic can be produced again. By saturating the hydrocarbons through hydrogenation, it is possible to make more stable compounds for fuels or chemical feedstocks (Lechleitner et al., 2020).

The second factor are process parameters that include, according to Anuar Sharuddin et al. (2016, 312), *“temperature, type of reactors, pressure, residence time, catalysts, type of fluidising gas and its rate”*. Each of those can be adjusted in order to achieve a desired outcome. Temperature is an especially important factor, as it directly affects the vibration of the molecules inside a system and can consequently speed up or inhibit the cracking reaction of a polymer chain. If a chain breaks, it depends on whether the Van der Waals forces that are holding together the molecules or the enthalpy of the bond that is increased by temperature is stronger. In general, lower temperatures, between 300 and 500 °C, lead to more liquid output and higher temperatures, above 500 °C, will deliver more products in the gaseous spectrum and enhance the production of char. Moreover, the reactor type plays a vital role in the question of how to engineer a process in order to achieve desired products (Anuar Sharuddin et al., 2016).

In the following part, the benefits and drawbacks of the pyrolysis process are listed. As mentioned, it is hard to reduce all pyrolysis processes to a common denominator since they vary due to several factors.

3.5.1 Advantages of Pyrolysis Processes

The main advantage of pyrolysis lies in its ability to revert relatively far back in the chain, bringing one closer to the original substance, crude oil (Dai et al., 2022). Simon (personal communication, 2023) explains that by regenerating the polymer, one can proceed towards the desired application by employing appropriate stabilisation techniques. While the polymer has not yet been wholly burned into CO2 and water, it yields pyrolysis gas (CO and hydrogen) and pyrolysis oil. From CO and hydrogen, it is indeed possible to synthesise polymers again, as it is referred to as synthesis gas in the chemical industry. This gas can be used to produce fuels and synthesise any desired monomer, enabling the production of plastics once more (Simon, personal communication, 2023). Hence, pyrolysis has the potential to create a variety of products like fuels and chemicals. Pyrolysis requires no additional resources or materials; it only needs energy input in the form of heat. Even though the exothermic energy required for the pyrolysis process is relatively high, the process is equally relatively straightforward in terms of the initial conditions, in that it requires only heat and the absence of oxygen (Anuar Sharuddin et al., 2016).

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Additionally, the technology is relatively tolerant with regard to impurities and mixed plastic waste, making a variety of plastic types, especially POs, appropriate for recycling (Lechleitner et al., 2020). POs consist of hydrogen and carbon atoms and do not add organically bound impurity atoms to the process. Like other common types of plastic, for POs, the pyrolysis process can be referred to as a *"radical chain reaction"* (Schubert, personal communication, 2023). This well-known process, pyrolysis, is supposed to broaden the recyclability. It is not targeted at feedstock, which can be processed in mechanical recycling plants. Pyrolysis uncovers a lot of impurities that need to be considered, from big stones to exotic molecules. After uncovering them, they can be separated using methods usual for refineries. Synergies to mechanical recycling need to be considered, as neither can cover the whole amount of plastic, *"but the full Circular Economy system should"* (Lechleitner, personal communication, 2023).

Some distinct advantages emerge when pyrolysis processes are compared to the other well-known types of chemical recycling, solvolysis and gasification, as elaborated by Schubert (personal communication, 2023). In contrast to solvolysis, no solvents are used in pyrolysis. This circumstance simplifies the process, removing complexity and reducing costs simultaneously. In addition, the possibilities in the solvolysis process are limited in terms of the types of plastics that can be introduced into the process. Thermal processing can handle a much wider range of plastic types (Vogel et al., 2020). In contrast to gasification, pyrolysis as a form of chemical recycling offers a distinct advantage due to the absence of oxygen during the process. This condition facilitates intermediate and end-product formation without requiring additional oxygen. The resultant reduction in energy requirements represents a notable benefit, rendering the process more efficient and cost-effective (Schubert, personal communication, 2023).

Furthermore, Schubert (personal communication, 2023) describes that an increasing urge can be foreseen in the future to process compound materials in waste plastic materials and states carbon fibre-reinforced plastics from wind turbines as an example. As these materials are increasingly utilised and will gain importance due to their advanced properties, the growing demand for reprocessing these materials arises. Pyrolysis, which can reassemble plastic monomers and recover other components, can play a major role in this process (Schubert, personal communication, 2023).

3.5.2 Challenges of Pyrolysis Processes

However, certain drawbacks exist that must be considered when utilising the pyrolysis process. Lechleitner et al. (2020) specify some of the most pronounced technical

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disadvantages. The process necessitates a relatively high endothermic energy input. Heat transfer and mass transfer throughout the process are both made more challenging by the low thermal conductivity of plastics and the high viscosity of the melt. Some plastics, like PVC, might also contribute to corrosion issues within the reactor or demand for dechlorination procedures. Heteroatoms can also lower product quality, which can cause problems with subsequent procedures. Terephthalic acid, which can clog systems due to precipitation, is also produced during the thermochemical processing of PET. These are some of the most important but only exemplary technical problems that can occur in the process and show that in pyrolysis, many things have to work together to ensure successful operation (Lechleitner et al., 2020).

Vogel et al. (2020) describe another controversial point being the categorisation of the different applications of the pyrolysis process products. In addition to the direct use of the products of chemical recycling as feedstock for the chemical industry, recycling into liquid energy carriers/fuels is also sometimes included under the term chemical recycling. However, it must be noted that, from an environmental point of view, no clear ecological advantages can be demonstrated over direct thermal or energy recovery in waste incineration plants, substitute fuel power plants or cement works, especially if high product qualities, as required for the production of fuels, are necessary (Vogel et al., 2020).

Concerning MSW, the heterogeneity of the waste also presents a challenge with pyrolysis processes. As explained earlier, this problem is less pronounced with plastic waste, and pyrolysis can handle more variability than mechanical recycling. Still, even with plastic waste, a high level of homogeneity ensures consistent reaction conditions and a predictable product yield. This becomes especially important if a certain quality of the final products is to be achieved (Quicker et al., 2017). Given the intricate nature of the depolymerisation reaction, it is imperative that further research will be conducted to improve the understanding of the fundamental reactions and interactions, particularly in the context of plastic mixtures and their interactions with impurities and contaminants, taking into account different process conditions. Schubert (personal communication, 2023) points to the importance of recognising that the resulting waste streams will change as materials evolve. Therefore, the effects of pyrolysis on novel materials such as biobased plastics and high-tech compounds need to be studied in more detail to enable effective process development for future waste streams. A more detailed study of the mechanisms underlying these reactions is needed to provide

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valuable insights into how pyrolysis can be optimised to extract maximum value from a wide range of waste materials (Schubert, personal communication, 2023).

4 Empirical Findings

4.1 Lessons from Practice

In this chapter, based on literature research, statements (see Appendix A.2 Company Statements) and information from the respective homepages, projects are presented in which attempts are made to enter the market with the pyrolysis process. This qualitative method is intended to show the variety of different initiatives, what makes them relevant and what can be deduced from them. Considering the large number of companies and projects, this is only a small part and by no means an exhaustive list. It should also be noted that in this active field, changes can occur constantly, new approaches emerge, and others are abandoned.

4.1.1 Resynergi

Resynergi's mission is to use sensitive scanners to collect and sort piles of abandoned plastic waste into seven types of plastic, mainly from the sea, before shredding usable plastic, which includes HDPE, LDPE, PP and PS, into small pieces that are fed into an oxygen-free microwave reactor (Resynergi, personal communication, 2023). The plastic is rapidly heated and converted into gas using microwave energy in the purpose-built Continuous Microwave-Assisted Pyrolysis Reactor. According to the company, pyrolysis with microwave energy works 100 times faster than in traditional reactors. The gases are then condensed into liquid hydrocarbons such as usable oil, fuels and other products that can be reused to make new pure plastics. Ultimately, one tonne of plastic waste is converted into about 750 litres of fuel (Quackenbush, 2020). The all-electric system runs on 480 volts, involves no combustion and produces no smoke or other volatile organic compounds. On its homepage, Resynergi claims to produce products with 68% less carbon intensity than conventional industry-standard methods (Resynergi, 2023).

Resynergi (personal communication, 2023) specialises in smaller plants because of the many problems other companies are encountering as they try to move to plants that can convert about 200 tonnes per day. The company calls this approach modularisation, which understands upscaling horizontally rather than vertically. These plants, capable of transforming about five tonnes per day, are technically proven, faster to deploy and can be set

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up close to the point source. In the past, many pyrolysis companies have failed to deliver on their promises, making it hard to receive funding and gain trust from governments and investors. Their failure was partly due to difficulties in sourcing high volumes of feedstock, especially at a high enough quality. This can be traced back to a lack of reliable sorting systems, which will be solved in the future by robotic sorting systems.

The takeaways from Resynergi's experience are:

- Upscaling does not necessarily have to go along with larger plants but can also come in the form of many small plants (modularisation).
- Using microwave energy is an efficient and fast way to break up the hydrocarbons and turn them into gas.
- The biggest problems stem from a historical technology failure and a logistical problem in sorting and transport.

4.1.2 Bioland Energy Ltd.

Bioland Energy is a renewable energy provider that, in addition to PV parks, will also pursue pyrolysis with a planned plant in Limassol, Cyprus. The plan is to recycle material from end-of-life tyres (ELTs) and generate energy from them at the same time (Bioland Energy, 2023). However, the plant is still under construction after years of research and development as well as obtaining permits. It is expected to process 67,000 tonnes of ELTs per year when operations start (planned for 2026). According to Bioland Energy, this approach can be classified as a WtE and recycling project at the same time. In addition, the group assures that the project will comply with the strictest emission standards while being economically viable and bringing environmental benefits (Bioland Energy, personal communication, 2023).

The company sees barriers in the lack of quality parameters and standards for using recovered carbon black (RCB) for many applications, which leads to a limitation in its marketing. In addition, the European Green Agenda is criticised for failing to promote an integrated approach combining waste-to-energy and recycling as such, but for classifying it as inadequate for all respective objectives (WtE, recycling, reducing waste deposits, renewable energy) (Bioland Energy, personal communication, 2023).

The main lessons learned from this case are:

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- It is possible to use pyrolysis in order to recycle ELTs and produce electricity from them.
- Waste-to-energy and recycling are not necessarily contradictory objectives.
- European legislation, and missing quality parameters for RCB, are hindering the scale-up of such projects.

4.1.3 Neste

Neste (personal communication, 2023) is trying to produce crude oil from waste plastic, aiming to produce 1 million tpa by 2030. Neste specialises in post-consumer plastic, such as coloured, multi-material, and multilayer packaging waste, precisely the kind of plastic that mechanical recycling cannot process. In 2020, Neste announced that it had liquidated a first batch of 800 tons of plastic (Neste, 2020). To be able to process a larger capacity, Neste has entered into partnerships with committed investors and offtake partners. Thus, it tries to combine expertise from several companies across the value chain and harness synergies. For example, in 2021, Neste announced that it would work with Ravago, a leader in mechanical recycling, to combine Alterra Energy's proprietary liquefaction technology with its in-house expertise in hydrocarbon processing. The first project is an industrial plant at the North Sea Port in Vlissingen, in the Netherlands, with a capacity of 550,000 tpa of mixed plastics (Neste, 2021). Neste is a minority shareholder of the US-based company Alterra Energy and has also secured Alterra's technology rights for Europe. In addition, Neste reports having recently received €135 million from the EU Innovation Fund for its PULSE project at the Porvoo refinery. Of particular note for the company is the wide range of applications, as well as the ability to reintroduce recycled content through pyrolysis into even sensitive applications, such as the food or medical sectors (Neste, personal communication , 2023).

The most important learnings from Neste's case are:

- Many pyrolysis companies have very ambitious goals. However, they have often run only test series and no large-scale plants in operation.
- Partnerships along the value chain are an essential asset that can help merge expertise and accumulate funds.
- Public innovation funds and diverse other funding opportunities should be explored in order to raise valuable funds.

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4.1.4 Plastic2Chemicals (P2C) – Indaver Group

Plastic2Chemicals (P2C) is a subsidiary of the Indaver Group, a renowned waste management company. P2C does not cooperate with a petrochemical group like many other pyrolysis companies but has evolved from a waste company. Indaver's P2C project aims to process 65,000 tpa of end-of-life plastic. The plant is not yet in operation. However, P2C has already invested €80 million in demonstration and pre-treatment plants (P2C, personal communication, 2023). Petrochemical companies that also operate in this field primarily run smaller plants with around 15,000 tpa. P2C sees clear potential for economies of scale because chemical recycling plants resemble petrochemical plants. Nevertheless, according to P2C, no concrete plans exist in Europe to build a larger plant, for example, in the range of 200,000 tpa. The obstacles are, on the one hand, the legislation, which many are waiting for, but which is still questionable in its form and scope, and on the other hand, technical problems in upscaling, such as an important purification step, especially in the processing of PO. P2C works with PO and PS, whereby it sees clear advantages in recycling PS since there are fewer steps in the processing and thus fewer losses. On its homepage, P2C claims to save 225,000 tpa of CO2 with its process once the plant is in operation (Plastic2Chemicals, 2023).

The lessons learned from P2C's example include:

- Pyrolysis companies are not necessarily collaborating with petrochemical companies but sometimes have a background in waste management.
- There is potential for economies of scale with pyrolysis plants. Still, no concrete plans for a large-scale facility are planned in Europe.
- Different forms of plastics require different treatment steps; therefore, some are to be prioritised over others when introduced into a pyrolysis plant.

4.1.5 Rudra Environmental Solutions India Ltd.

Rudra Environmental Solutions Ltd (personal communication, 2023) is an Indian company researching a technology to convert plastic waste into fuel since 2009. Since then, three generations of plants have been installed to process plastic waste from around 12,000 households, businesses and hotels. It mainly processes non-recyclable thin plastic waste that otherwise has no monetary or recyclable value. Rudra works with a technology they call Thermo Catalytic Depolymerization (TCD) technology. This process does not require separating different types of plastic. It is energy efficient and eco-friendly, producing no toxic

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gases. By accepting many different types and grades of plastic, the waste that would otherwise end up in landfills in India can be recycled.

One plant can process between 50 and 500kg per shift (8hr) (Rudra Environmental Solutions India Ltd, 2023). Rudra is following a very different approach from many of its commercial competitors. In fact, together with the Keshav Sita Trust, the company is trying to raise awareness of plastic separation and form bonds with its customers as part of its project by letting the customers hand in the separated plastic directly. Via this bottom-up approach, the company has gained trust and recognition among the population. This decentralised approach can be replicated in its format and applied in more communities. Rudra has found that the bottleneck in countries like India is already in the plastic separation process, which is why a lot of plastic waste ends up in landfills. Larger facilities require more CAPEX and also a large volume of freshly separated waste (Rudra Environmental Solutions India Ltd, personal communication, 2023).

The key lessons from Rudra's approach are the following:

- Some pyrolysis companies adopt a bottom-up approach by engaging in awareness-raising measures and collecting the waste directly from their customers. This approach involves building trust with the community and encouraging them to participate in the plastic separation process.
- While CAPEX and high upfront investment costs are often financial burdens that hinder companies from a scale-up, a lack of waste separation in countries like India restricts high-volume plants from being built.

In order to follow up on these findings, the most critical exploratively derived trends are examined in section 4.2.1. These include the geography of the companies and their installations, the capacity, the incoming material, the resulting products, the average process temperatures, the partners and the current status of implementation.

4.2 Developments and Trends in Implementing Pyrolysis Processes

Even though the pyrolysis process is receiving attention and enormous effort is being put into research and development, the implementation status remains in its early stages. Maisels et al. (2022) estimate the capacity of plastic waste going into pyrolysis processes at around 1 million tpa in 2021. By 2030, this capacity is projected to quadruple at least. This implies that,

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even though the process has ambitions to multiply its current capacity in the coming years, it is relatively minor in relation to the amounts of plastic waste that have been generated so far and will be generated in the future, as listed in section 2.3 (Maisels et al., 2022). Nevertheless, it must be ascertained that there are increasing efforts to bring this number into the significant range.

This chapter is going to quantify the status of development in the field of pyrolysis processes at the market level, building on the data from the paper by Maisels et al. (2022). The data should act as a sort of screenshot of the current implementation status. As a result, trends that will help to provide information on the development of pyrolysis processes in the future shall become visible.

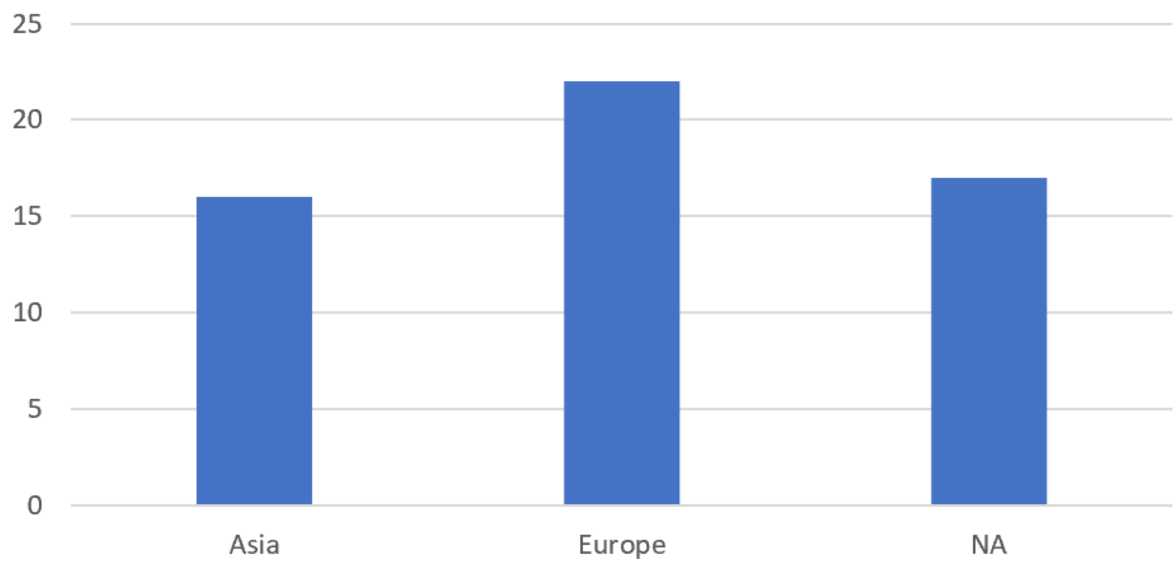

Figure 9: Geographical Distribution of Pyrolysis Companies (Continent) (own graph)

Figure 9 shows the geographical distribution of the activity of companies working on pyrolysis technology. It becomes apparent that the activity is limited to the three continents of Asia, Europe and North America. The largest share of companies can be found in Europe, with 22 out of a total of 55 companies. North America has 17, and Asia has 16 each. However, this distribution says nothing about capacity, which will be discussed later, but only about location. The fact that Europe and Asia are pioneers here correlates with the finding that research on the topic of the CE is predominantly undertaken on these continents.

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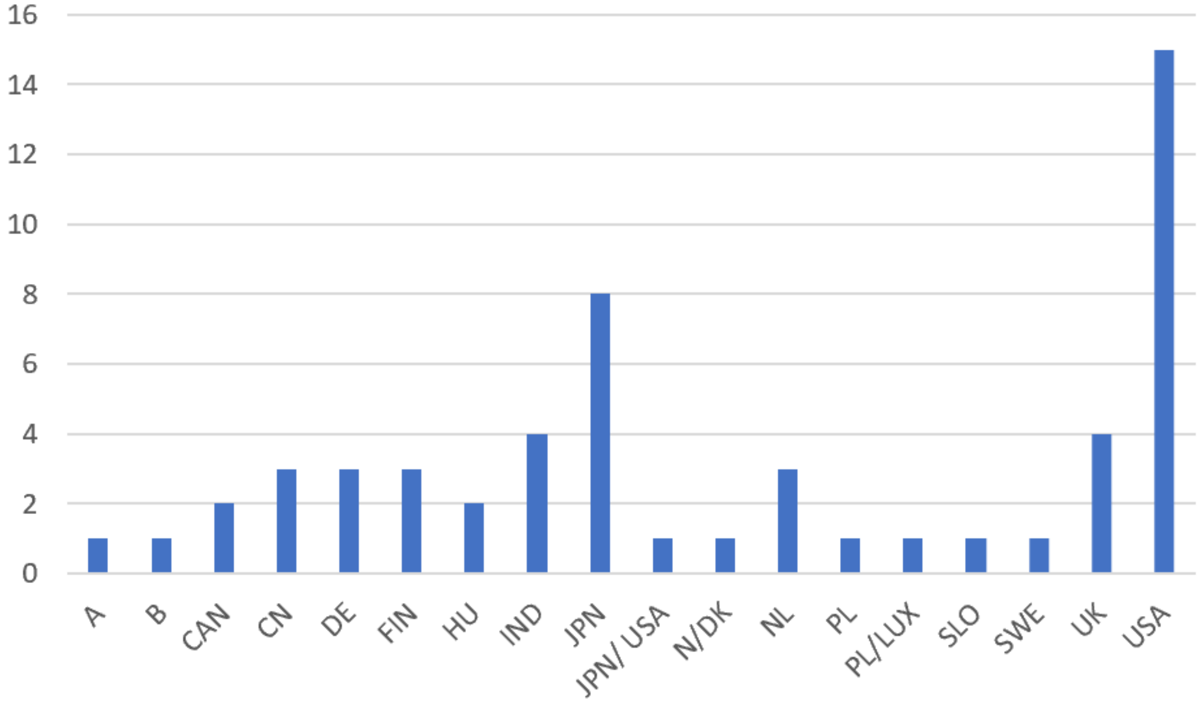

Figure 10: Geographical Distribution of Pyrolysis Companies (Country) (own graph)

Figure 10 further details and shows the geographical distribution of companies working with pyrolysis technology. The country with the most activity is the USA with 15 companies. Thus, with the exception of two companies in Canada, the USA accounts for nearly all activity in North America. The second most active country is Japan, with eight companies, which thus accounts for half of all companies in Asia. There is also a US-Japanese joint venture (Sapporo Plastics / Klean Industries). Among the remaining pyrolysis companies, India is home to four companies, while China hosts three. The activity in Europe is very fragmented and spread over many countries. There are four companies in the United Kingdom and three each in Germany, Finland and the Netherlands.

However, the USA and Japan are not only the countries with the largest number of companies but also the locations with the companies with the largest capacities. According to Maisels et al. (2022), the company New Hope Energy in the USA, which cooperates with Chevron Phillips as its primary customer, has a capacity of 340,000 tpa. In Japan, Nippon Steel Engineering has the largest share of national pyrolysis capacity at 200,000 tpa. Nippon Steel states that this represents about 30% of the national collected plastic waste (Nippon Steel Engineering, 2023).

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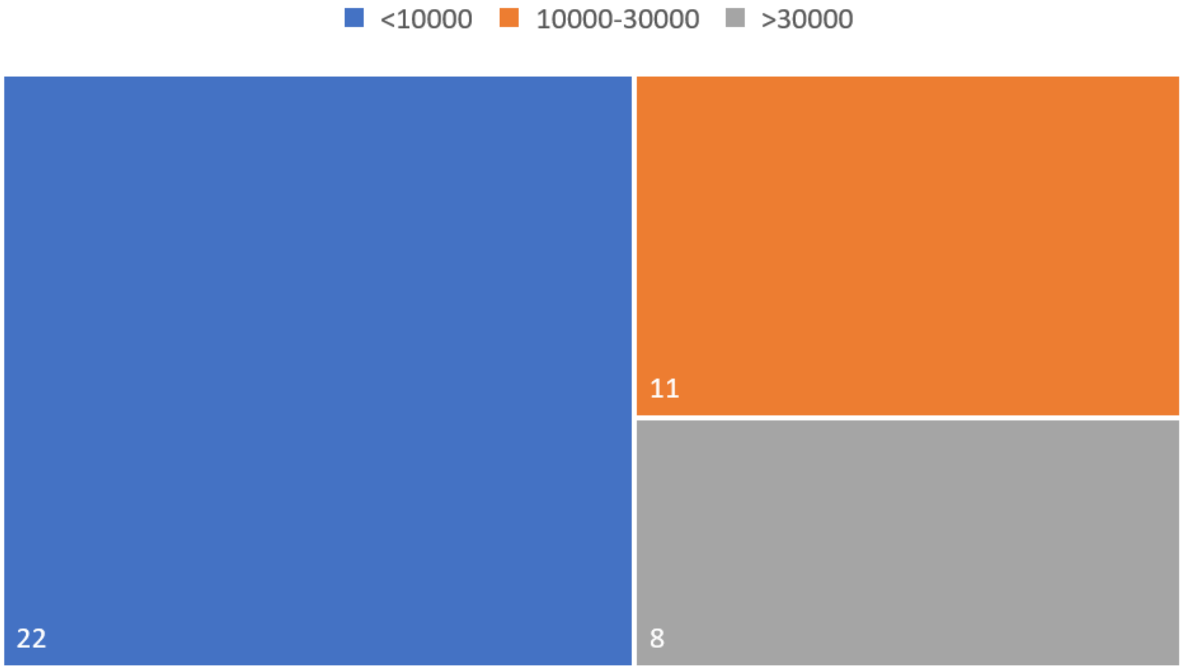

Figure 11: Capacity of Current and Planned Plants (own graph)

Nevertheless, looking at the capacities of current and planned plants, as shown in Figure 11, these large-scale projects are a glaring exception. Of the 41 companies that indicated the capacity to process plastic waste annually, more than half, 22 companies, are below the 10,000 tonnes per year threshold. Only eight companies can process more than 30,000 tonnes per year. It should be noted that not all facilities need to process enormous capacities, depending on the use case. In general, the capacities of the plants vary from less than 10,000 tpa for research purposes and the provision of diesel fuel to 10,000-30,000 tpa for classic commercial plants that transform local plastic waste into liquid products for further use, to 30,000 tpa and more for plants that produce capacities that are also of interest to the chemical industry.

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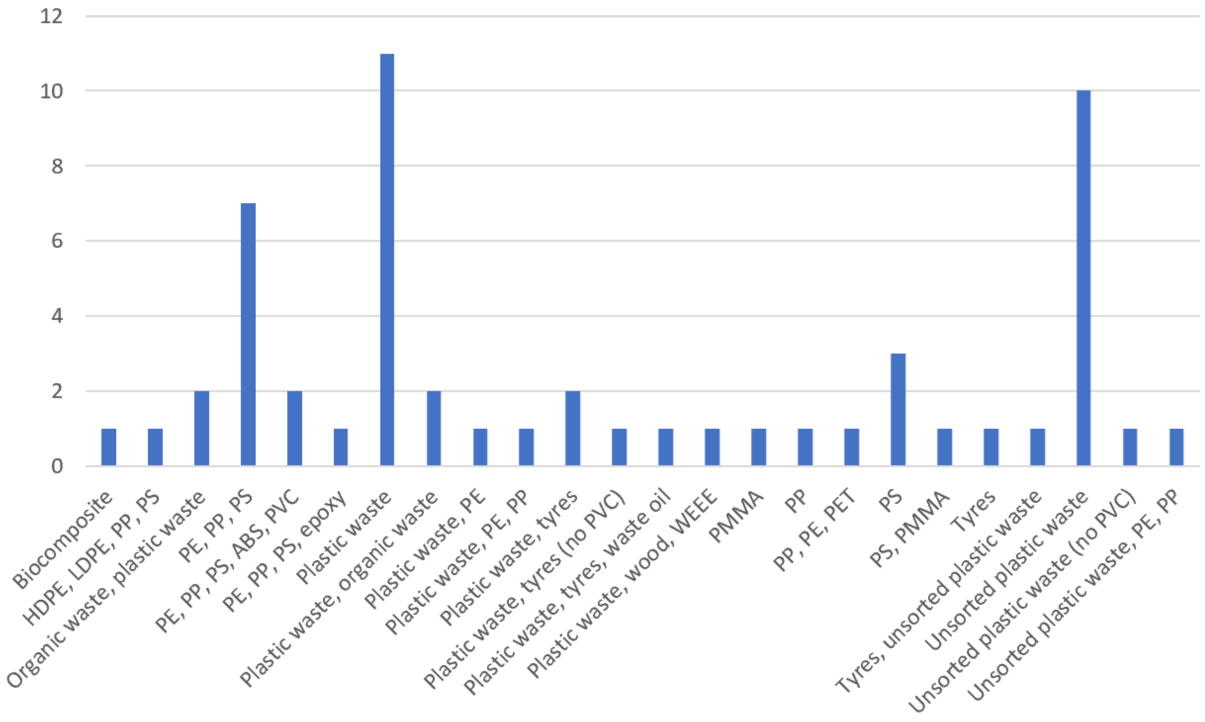

Figure 12: Materials to be recycled (entire input) (own graph)

Besides the capacity, it is interesting to observe which types of plastic can be included in the processing. Different pyrolysis projects specialise in recycling different materials. Figure 12 provides an overview of the input materials considered in the process, encompassing all the materials that can be effectively processed. What is striking is the large number of raw materials that can be treated with different reactors/processes and the few overlaps between the process types. This is another indicator of their heterogeneity and the lack of synergies being used in the industry. An exception is a large number of projects that specialise in general plastic waste or even unsorted plastic waste. Of these, there are several companies, but in these cases, modern plants must be flexible in sorting before and dechlorination after pyrolysis. The quality is naturally less stable, less homogenous and produces only broad specifications of the end product (Maisels et al., 2022). The remainder of the companies often focuses on single types of plastic, such as Encina Technologies, on processing PP or a defined mixture, leading to relatively stable products by simple processes. Others can introduce a plurality of types into the process, such as seven companies that can recycle PS in addition to PE and PP.

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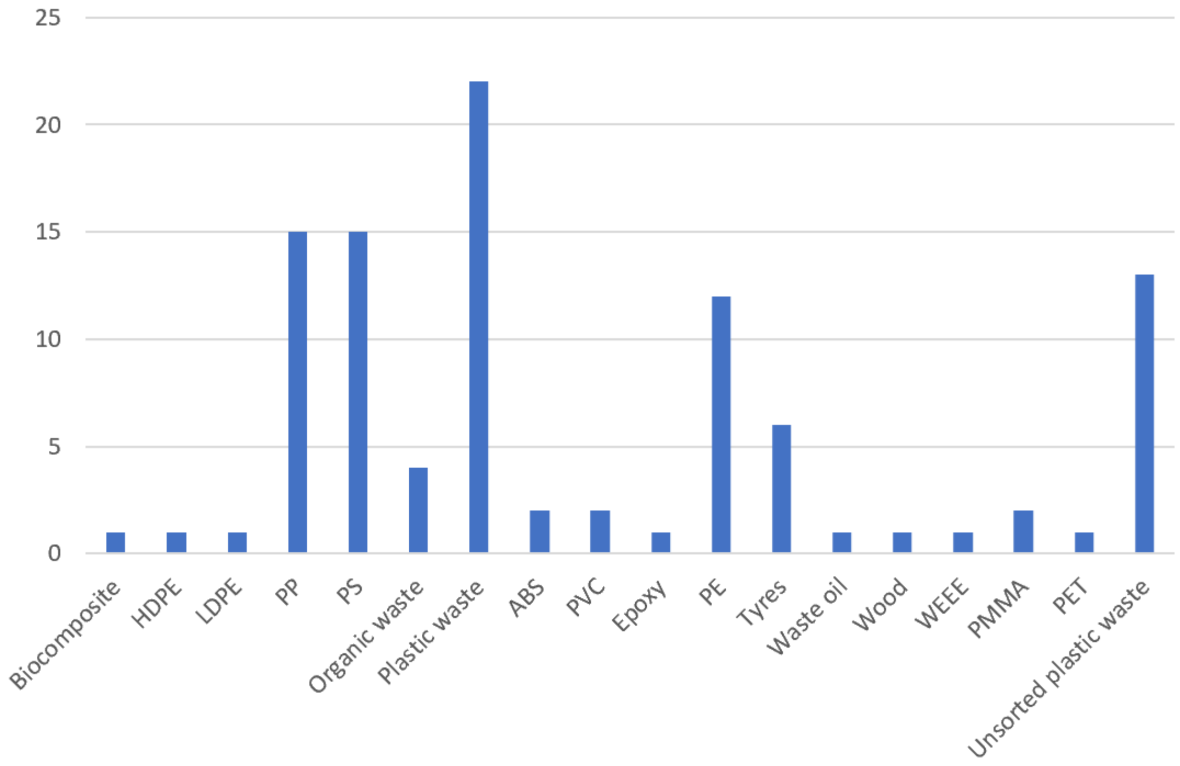

Figure 13: Materials to be recycled (single Input) (own graph)

Figure 13 looked further, not at what composition plastic can be processed, but at how many projects can process what type of plastic. Most of the companies in this view did not specify their capabilities of processing input to more than 'plastic waste' and 'unsorted plastic waste'. Fifteen companies stated they could process PP and/or PS, and twelve included PE in their pyrolysis process. Six projects also include ELTs, as presented in the Bioland Energy project. Another four companies stated that they pyrolyse organic waste, and another two may operate with ABS, PMMA and PVC each. In addition, one respective company indicated that they feed biocomposite, HDPE, LDPE, epoxy, waste oil, wood, WEEE or PET into their pyrolysis plant in order to process these materials. This breakdown into the multitude of materials clearly shows the wide range of applications for pyrolysis processes and, at the same time, the disagreement about where the industry is heading.

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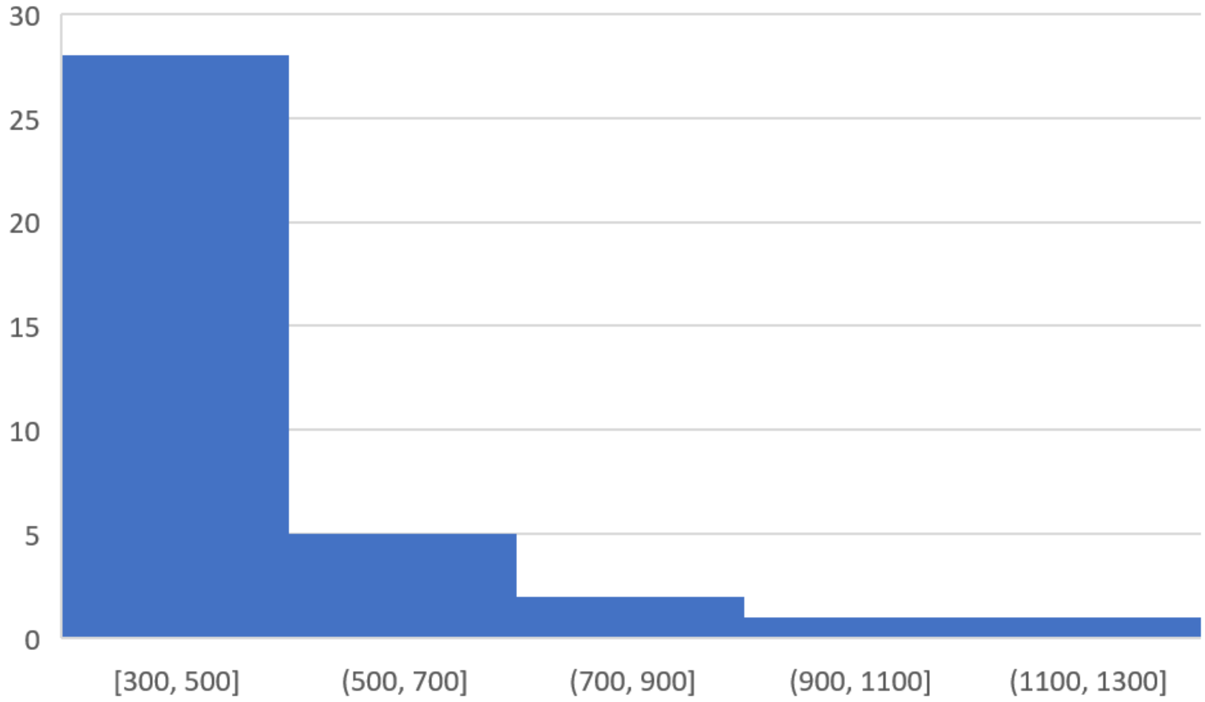

Figure 14: Temperatures in Pyrolysis Processes (own graph)

Besides the raw material, the temperature reached in the process is a decisive component. On the one hand, this determines how quickly the pyrolysis process takes place and, on the other hand, which end products are formed. In section 2.5, in which the general facts about pyrolysis processes were described, it was already explained that a characteristic of them is that they take place over 300 °C in order to be classified as such. Figure 14 shows that the vast majority, 28 out of 37 projects that reported their process temperatures, work with temperatures between 300 and 500 °C. A clear trend can be seen here. Nevertheless, we got to know, for example, during the presentation of the company Resynergi, that there are also other approaches. This company works with microwave-induced pyrolysis at much higher temperatures, around 1000 °C. On the one hand, the higher temperature is much more energy-intensive, but the process is also considerably faster.

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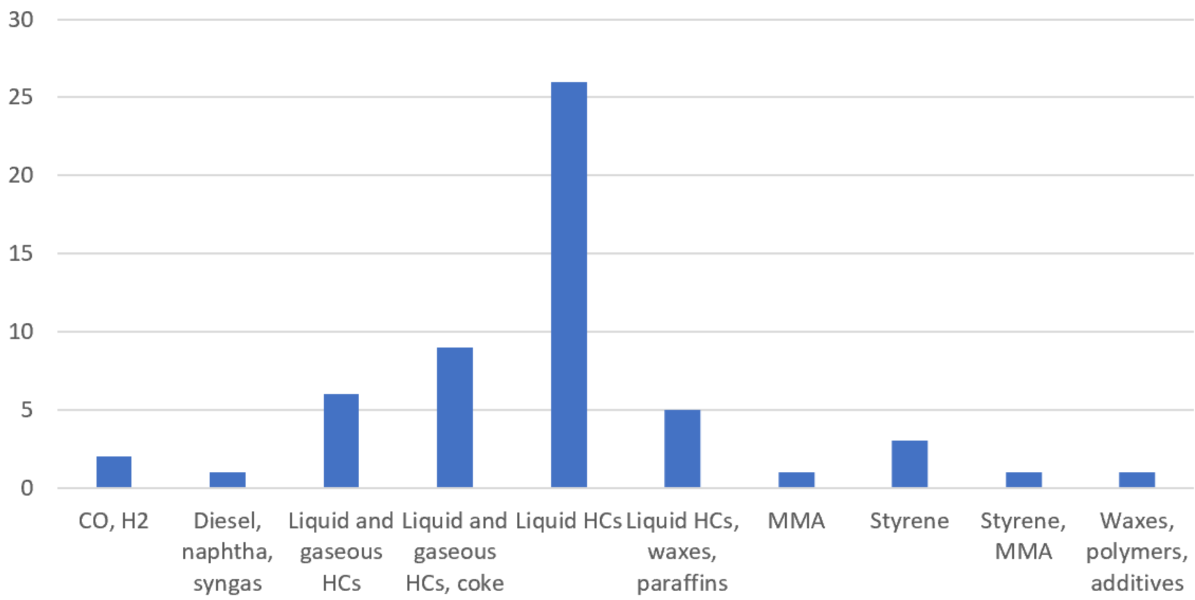

Figure 15: End products of Pyrolysis Processes (own graph)

The end products already mentioned vary greatly, as shown in Figure 15. It should be noted that this graph does not indicate how much of each end product is produced, but only how many processes produce a proportion of it. Although it is rarely achieved, the most circular result is when pure monomers emerge again after pyrolysis, such as styrenes or methyl methacrylates (MMA). More often, there are mixtures of gas, liquid and solid products, with the liquid products being produced most frequently. An increase in liquid products can be interpreted as a sign of high quality, as these are best suited for further processing and are increasingly produced under ideal conditions. Maisels et al. (2022) highlight that liquid yields of up to 90% can be achieved under optimised circumstances. In exceptional cases, H2/CO mixtures are also produced due to higher market prices. However, elevated temperatures of 800 °C and more are needed to obtain a high yield. In turn, this makes them more challenging to implement and more energy-intensive.

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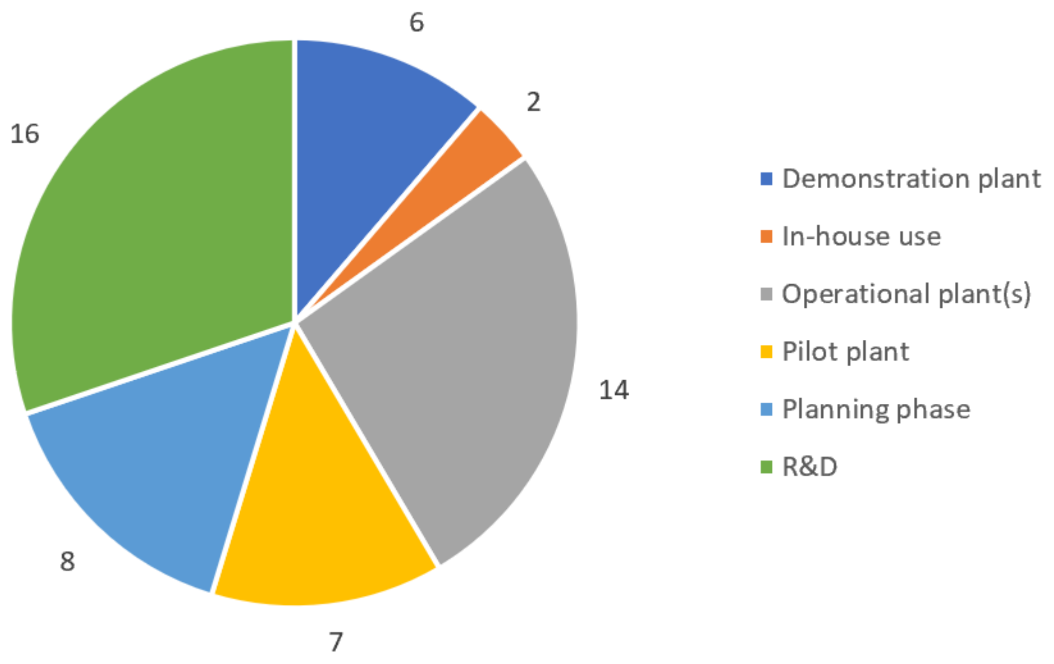

Figure 16: Current Status of Implementation (own graph)

Figure 16 analyses the current implementation status of the 53 companies working on or with the pyrolysis process. Out of this number of companies, only 14 are already operational and run one or more plants. Another two companies operate pyrolysis processes but do not work with plastic waste from outside. These companies process the waste generated in the industrial company itself. Seven other companies have installed a pilot plant but have not yet started a commercialisation attempt. Six projects have built a demonstration plant to show that their approach is feasible, but these companies are still far from entering the market. Eight companies are still in the planning phase and have not yet built a demonstration or pilot plant, let alone an operational plant. The majority of the projects listed are still in the research process or have set themselves the goal of building a commercial plant. Therefore, it is clear that despite enormous efforts, this technology is still in its infancy. The number of companies that can already keep plastic in circulation to date is small, and their capacity for processing plastic waste is minimal. On a more positive note, it is an emerging technology that needs time to gain widespread effectiveness. The growing number of companies trying out pilot and demonstration plants suggests that the volume of recycled material will increase in the coming years.

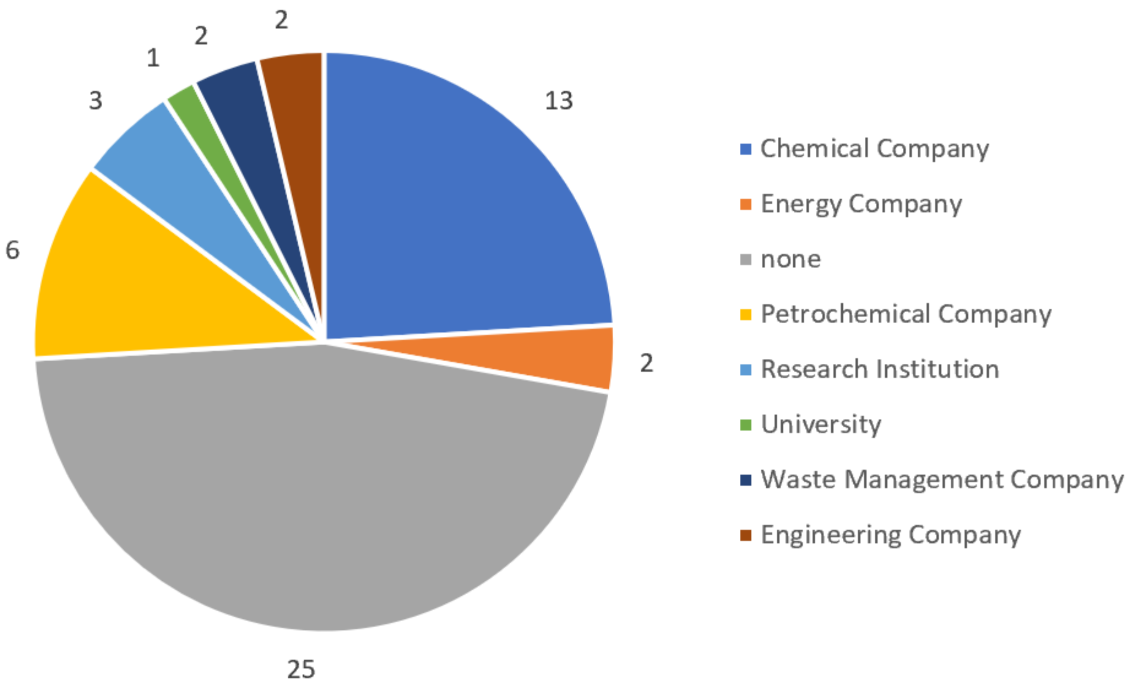

Figure 17: Cooperation Partners (own graph)

These companies themselves are operated on the one hand by inventors, start-ups or spin-offs on a smaller scale (< 20,000 tpa), by waste management companies, engineering companies, up to petrochemical companies and big chemical companies, which, however, often cooperate with smaller technology providers. The evaluation showed that 25 out of 54 companies work without a partner. Thirteen projects were started in cooperation with a chemical company and six with a petrochemical company. The synergies with these groups and companies obviously make sense, as their plants have a similar structure and function similarly. Three projects were started together with research institutes that contributed their theoretical know-how. In addition, there are two projects in cooperation with energy companies, waste management companies (such as the example of P2C with Indaver) and engineering companies. The Resynergi project in the USA, which was also presented, has entered into a partnership with a university, which stands ready as a sparring partner for them.

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4.3 Barriers to Upscaling Pyrolysis Processes

Now that the trends have been assessed, the next section will use qualitative interviews to shed light on how these trends will be understood. For this analysis, it is essential to identify the barriers that must be overcome to implement pyrolysis technology on a large scale. The barriers were divided into five categories: technological, legal, environmental, economic and logistical. Of course, these are mutually influential, but an attempt is made here to look at them separately.

4.3.1 Technological Barriers

In the interviews, three out of four experts pointed out that the widespread introduction of pyrolysis processes faces several technological obstacles. Lechleitner (personal communication, 2023) states, *"I personally see the challenges less on the technical side"* and suspects the hurdles mainly in the other dimensions discussed in the following sections. He says that while mechanical recycling processes lead to a loss of quality and thus to a *"downcycling"* (Lechleitner, personal communication, 2023) of the products, pyrolysis processes can overcome this limitation. Therefore, chemical recycling is proposed as a reset button to keep hydrocarbons in the CE. Already today, chemical recycling allows the production of materials with as-new quality suitable for industries with strict quality requirements, such as food packaging and medical products. In terms of quantity, he points to their first commercial ReOil® plant that will be upscaled to a size of up to 200,000 tpa. Although he admits that it does not sound like that much compared to the total waste generated worldwide, he clarified that they are only at the beginning. The synergies with mechanical recycling should be taken into account (Lechleitner, personal communication, 2023).

P2C (personal communication, 2023) agrees with Lechleitner that pyrolysis is a technology that is still in its infancy even though it is described as *"not innovative"* (personal communication, 2023) because it has been in use for a long time in India, for example, where they produce pyrolysis soup under differing safety conditions and efficiencies resulting in fuel. Concerning their own company P2C, constant work is being conducted to refine the processes, the technology and the supply chains. A step-by-step approach was adopted due to the complexity and associated uncertainties, meaning upscaling takes place relatively slowly. Whilst this iterative process allows for continuous improvement and careful implementation,

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at the same time, it highlights the long period that will be needed to overcome the technological barriers associated with pyrolysis processes.

Schubert (personal communication, 2023) highlights the challenge of the energy balance in pyrolysis processes. Since a large amount of energy is required for the cracking reactions, covering the energy demand through the internal use of short hydrocarbons is a possibility. In order to achieve material cycles, the energy use of the obtained products should be minimised. Nevertheless, the overall energy balance depends on the types of plastics, the process conditions and the installation. Furthermore, she also refers to the need for further research in this field, which is vital to understand the complex reaction mechanisms and interactions during depolymerisation (Schubert, personal communication, 2023).

More research is also called for by environmental organisations, such as the Global Alliance for Incinerator Alternatives (Rollinson & Oladejo, 2020), who suggest that although pyrolysis is well understood for simple feedstocks such as coal and wood, there is little knowledge about contaminated, poor-quality mixed plastic waste. As most operations so far have not taken place in real-world conditions but mainly in the laboratory or in pilot plants, there is little information on practicality. What is more, if ever larger quantities of plastic are to be processed by pyrolysis, larger quantities of unsorted, contaminated plastic will inevitably enter the process, also against the background that the separated, clean plastic is to be recycled mechanically (Rollinson & Oladejo, 2020).

Simon (personal communication, 2023) reports that the pyrolysis process is often idealised in theory but fails in large-scale implementation. He sees the reasons for this in the fact that while the process is portrayed as simple heating in the absence of oxygen, with the end product being a usable gas mixture, there is no mention of oils of different consistencies, as well as coke, which is pure carbon. In the long run, the latter leads to clogging, which is particularly problematic in larger plants. Consequently, this leads to reduced yields, and other manifold problems that have so far prevented upscaling from being successful. Even if the reaction equations look simple on paper, the problem remains in the details. In addition, over time, interfering substances, in the most straightforward case metals, enter the reactor and have to be removed again. Therefore, Simon sees the *"crux"* (Simon, personal communication, 2023) in that it is challenging to keep the process running over a long period. He also complains that there are few alliances and no exploitation of synergies. Companies would work in secrecy, which could end up leaving no one to overcome the technological problems. More open discussions, participation and cooperation would be needed here.

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From a technological point of view, upscaling attempts of pyrolysis processes failed partly because the technology has not been researched for so long and with such intensity, and partly because many small details can cause problems, such as clogging side products. Also, the energy balance must not be disregarded, which already has to be considered on a small scale and leads to disproportionately high energy input on a large scale if internal hydrocarbons cannot supply the energy demand.

4.3.2 Environmental Barriers

Detrimental environmental impacts are another barrier to the widespread roll-out of pyrolysis processes. A major roadblock is the sourcing of external energy for pyrolysis processes. The energy intensity makes the process very challenging to be environmentally sustainable, even though some of its energy comes from burning the end products created during pyrolysis. In order to split the plastic into liquid, gaseous and solid products, the pyrolysis process requires much heat, which means mostly external energy. In addition, the energy required for polymerisation into new plastic is not to be neglected. To date, there is no plant that is self-sustaining in terms of energy (Rollinson & Oladejo, 2020).

Even though pyrolysis takes place in the absence of oxygen, Simon (personal communication, 2023) highlights that a significant disadvantage of pyrolysis is its close chemical proximity to combustion. Plastic experiences oxidation, which turns the hydrocarbons into unwanted CO and CO2 instead of retaining them as hydrocarbons. The consequence is a loss in overall energy potential due to a decreased carbon content in the end products. Therefore, the carbon footprint of pyrolysis facilities needs to be monitored to keep them environmentally sound. Environmental organisations, too, raised concerns about the similarities of pyrolysis and other thermal treatments to combustion processes, other WtE processes and their accompanying production of Greenhouse Gases, mainly CO2. It is vital to minimise the carbon footprint to gain public acceptance for pyrolysis procedures by society and policymakers to make them advocate for its upscaling. One potential remedy for this problem is the capturing and sequestering of CO2 that is generated during the process before it gets released. The initial creation, however, remains an issue (Simon, personal communication, 2023).

In the end, only via LCAs, it is possible to thoroughly compare the impact of these processes to landfilling, incineration or mechanical recycling. This includes the recycling process and the final use of the recycled product. P2C (personal communication, 2023) mentions the

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number of steps that need to be conducted for different polymers during chemical recycling. Each step entails losses, which potentially bring about leakages of CO2. In their paper, Dai et al. (2022) summarised several case studies on LCAs, comparing different types of plastic waste (PET, PO, HDPE). During the pyrolysis process, all outperformed landfilling, combustion and hydrocracking in the release of Greenhouse Gases, mainly because they reduce the use of fossil-based raw materials. Yet, after the pyrolysis process itself, the conversion of the plastic pyrolysis oil needs to be considered. There is a broad consensus among policymakers and environmental organisations that waste-to-fuel is, from an environmental aspect, not within the scope of chemical recycling and hence, does not fulfil the criteria to be considered circular (Dai et al., 2022; Rollinson & Oladejo, 2020).

While more energy needs to be invested for the separation and pre-treatment during mechanical recycling, its lower energy consumption generally leads to a lower carbon footprint. In practice, the choice between these two recycling types is often not based on the environmental impact but more on the technical feasibility (P2C, personal communication, 2023). Simon (personal communication, 2023) underlines that the ability of chemical recycling to handle contaminants, such as plasticisers and other toxic additives, is advantageous from an environmental standpoint. Whether chemical or mechanical recycling is used needs to be decided on a case-by-case basis and needs more research, especially into Greenhouse Gas production of mixed plastic waste. This can only be achieved through more transparency of the operators or waiting for the first large plants to be built and their GHG measurements to be taken.

4.3.3 Legal Barriers

The legal situation and the associated uncertainty are also a hurdle that needs to be overcome in order to provide a framework for pyrolysis processes to be rolled out on a large scale. Although it is difficult to consider all national or transnational jurisdictions together due to their respective differences, an attempt will be made here to summarise general problems in the legal situation. The basic consensus in the interviews and from the online research is that the legal situation for chemical recycling is generally very sparse. Open questions remain, which subsequently lead to uncertainties, among other aspects in accountability and classification.

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Lechleitner (personal communication, 2023) explains that there are fundamentally two different types of recycling targets. On the one hand, there is the recycling quota and, on the other hand, the recycling content target. The former refers to the amount of plastic waste that is recycled. The latter refers to how much recyclate is contained in the final product. It is essential to distinguish between the two. Simon sees recycled content targets as an actual silver bullet, as they can open up the market to specified quality standards. This can ensure a closed-loop system where plastics are used again in a similar application without constantly producing new material. The danger of recycling quotas is that recycled plastic is only used to make inferior products, and virgin plastic is used for most products (Lechleitner, personal communication, 2023).

Furthermore, P2C and Lechleitner (personal communication, 2023) refer in this context to the Packaging and Packaging Waste Directive (PPWD), which has recently been presented as a draft by the EU Commission, in which recycled content targets for contact-sensitive applications (Non-PET) are presented for the first time in the European Union. They see the Directive as the kick-off for an enormous demand for chemical recycling, as the targets therein can be described as highly ambitious and cannot be achieved without considering chemical recycling. Nevertheless, in other fields of application and regions where recycling quotas are the main tool to increase recycling rates, chemical recycling will likely be used more extensively since also waste streams will have to be processed in the future, which are not within the scope of mechanical recycling. As a first step, chemical recycling will have to be legally accepted as part of meeting recycling quotas. *"If there are no clear targets for contact-sensitive applications and no acceptance of chemical recycling for the recycling quota, it is rather unlikely that a market will be established and subsequentially, no chemical recycling plant will be built, no matter if based on pyrolysis or some other technology"*, states Lechleitner (personal communication, 2023).

Uncertainties in accountability, classification, and waste management hinder the growth of chemical recycling. P2C, which operates in Belgium, points out that there is currently restraint throughout the industry. Currently, no large-scale plants are planned and built (in Europe) as companies and investors are waiting for clear legislation and favourable conditions. Once this is achieved, it will give a big push to the upscaling process of pyrolysis plants (P2C, personal communication, 2023). The legal aspects have implications for the following two dimensions: logistical and economic.

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4.3.4 Economic Barriers

Bringing pyrolysis processes to market on a large scale also needs an economic appeal for companies and investors to get involved. As already discussed, a clear legal basis is needed at the outset that takes chemical recycling into account and creates demand for it in the market in the first place. Once this is in place, investors on the supply side will follow suit and actively commit money to this technology on a larger scale (Lechleitner, personal communication, 2023).

Simons (personal communication, 2023) explains that certain companies already invest in the technology, even though legislation is not in place because they know they will have to remodel their business strategy to remain relevant. Many companies that work with fossil fuels, such as oil and gas, need to change their strategy from the ground up. Since pyrolysis and petrochemical plants are very similar, this change is logical. Taxes and levies are used to make these processes economically viable. The reason for petrochemical and chemical companies to enter into chemical recycling via pyrolysis is not based on their high economic aspirations. In addition, these companies often depend on hydrogen sources that they also need for other purposes (Simon, personal communication, 2023).

The basic idea of accepting plastic waste, heating it, melting it down and reselling it as fuel sounds like a lucrative business opportunity. However, Schubert (personal communication, 2023) points out the high costs involved, including capital expenditures (CAPEX) and operational expenditures (OPEX). Simon underlines that the plant construction drives up costs and pronounced personnel costs. This also involves a lead time of several years, which must be invested in research and development to develop the process. Pyrolysis plants are capital-intensive and require expensive technology, qualified personnel and high operating costs (Schubert, personal communication, 2023).

Furthermore, in the case of pyrolysis oil, Simon (personal communication, 2023) notes that what matters most is whether its price is competitive compared to the price of crude oil from naphtha, which can vary greatly. The example is given of 2020, where the oil price was at 50 US$/bbl, compared to 2022, where it stood at well over 100 US$/bbl. While in 2020, it would not have been commercially competitive, in 2022, it had a clear advantage over the price of crude oil. Therefore, the economic profitability and the associated increased adoption of pyrolysis processes dependent highly on the oil price and its volatile development (Simon, personal communication, 2023).

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Another determining factor as to whether a pyrolysis process is financially profitable is the capacity of plastic that can be processed and the associated quantity of output products. As found in sections 4.1 and 4.2, this industry knows different business models. On the one hand, there are start-ups that try to operate innovatively on a small scale due to a lack of investment, whereas other companies try to process large amounts of plastic waste in cooperation with experienced partners from the chemical industry. P2C (personal communication, 2023) states that, in principle, it makes sense to build large pyrolysis plants, as these have a high financial advantage in economies of scale. This is the result of chemical recycling plants having similarities with petrochemical plants, as mentioned above (P2C, personal communication, 2023).

Moreover, an essential interface for these large-scale plants and their economic viability is the availability of specific types of plastic waste in a certain quantity in order to be able to process at the scale the plant is built for. Therefore, the following section deals with logistics.

4.3.5 Logistical Barriers

If the legal and social situation continues to evolve towards more (chemically) recycled plastic waste, pyrolysis processes will be used extensively. On the one hand, regulations mandating a certain recycled content will lead to millions of tonnes of plastic waste being used for this purpose. On the other hand, there is also increased pressure from consumers pushing companies towards more recycling. To make this development possible, some logistical hurdles need to be overcome. The biggest obstacle, and therefore potential barrier, is undoubtedly the provision and availability of usable feedstock (Lechleitner, personal communication, 2023).

Innovation must be encouraged throughout the supply chain of the waste management system. The quantities of plastic that go to waste currently being produced are enormous, yet there are problems with returning them to the recycling plant. According to P2C (personal communication, 2023), even in Europe, which sees itself and is seen by others as a front runner, the appropriate feedstock is unavailable, leaving aside countries where plastic waste is incinerated without safety and environmental precautions or ends up in landfills. Even if efforts are made to process plastic waste and use it for other purposes, several factors impede these efforts. The main factors involved are inadequate collection systems, insufficient waste sorting, problems in storage or pre-treatment, or difficulties in the pyrolysis process. *"If*

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plants are built in the future that can process 100,000 tpa of plastic waste and more, then 100,000 tpa must first be delivered there" (Simon, personal communication, 2023). What adds to the problem is that losses are often not considered in the various steps. Therefore, emphasis must also be placed on increasing efficiency and reducing losses (P2C, personal communication, 2023).

5 Discussion

5.1 Answering the Research Questions

Plastic waste accumulation is an increasing problem for the environment and all living creatures, including humans. Solutions are constantly being sought for this pressing issue, which on the one hand, tries to stop the proliferation of plastic debris, and on the other hand, prevents the economy from collapsing because consumption is reduced. CE seems to be a tried and tested means that claims to guarantee economic growth by changing business models, transforming waste into resources and, ideally, extending or even closing life cycles. Chemical recycling, discussed here in more detail for pyrolysis processes, shows how technologies are being commercialised under the guise of CE. This has resulted in the following exploratory research question:

In an attempt to create a more circular economy, what can chemical recycling in the form of pyrolysis offer?

In order to specify this relatively open question, the following two sub-questions were introduced, which will be addressed and answered to the extent possible in this section. The first sub-question aims to clarify which aspects of the process, its commercialisation and its impact can be classified as a technology that falls under the concept of CE.

What qualifies pyrolysis processes to be classified as circular?

The basic idea of CE is to exploit fewer virgin resources by preventing materials already in use from a premature product-end-of-life and keeping them in circulation for longer by

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reintroducing them in one or another form. Throughout the application of this concept, it is essential to think in terms of material cycles. With chemical recycling, the polymer chains are split, and the chemical building blocks obtained are recycled by being re-polymerised into new products. The polymers are broken down into shorter hydrocarbons by exposing the product to heat, catalysts, solvents and hydrogen, and a partially oxidative atmosphere. As a result, monomers, petrochemical base materials and synthesis gas can be recovered from waste streams, with the classification depending on the forces acting to split the chains. In the case of pyrolysis processes, technology is introduced for processing waste plastic, undertaken under relatively high temperatures, above 300 °C, and in the absence of oxygen, in an inert atmosphere. The splitting and reassembling of the building blocks correspond in their fundamentals to the definition that was established for CE. On paper, it is certainly possible to refer to a cyclical venture.

Recalling the 9R model, it was found that recycling is located rather low in the waste hierarchy. Thus, it could be assumed that chemical recycling represents a relatively weak form of CE, closer to the linear economy than seven other strategies in the waste hierarchy. This argument is supported by the idea that chemical recycling or pyrolysis processes pretend that a technological solution to this major problem exists. At the same time, the status quo can be preserved, keeping up production and consumption patterns as per usual. Nevertheless, it must also be considered that chemical recycling not only reuses resources that are already in use but also reduces natural resources, especially fossil fuels, as new raw materials need to be extracted for further production of virgin material to meet the demand for plastic. Therefore, chemical recycling can also be interpreted to meet the objectives of the reduce-strategy further up the hierarchy.

From a purely technological point of view, several adjustments still need to be made before the process functions as smoothly and circularly as announced by several companies. Above all, the question of energy balance remains open due to the large amount of energy required for the cracking reaction. Further technical fixes are demanded to introduce mixed plastic types and the long-term operation of such plants. In addition, there are still environmental questions to be answered with regard to how emission-intensive the process is. Additional hurdles were identified in the economic, legal and logistical dimensions that currently prevent the frictionless closing-of-the-loop with the help of large-scale pyrolysis processes, thereby hindering it from being characterised as circular in practice. However, these will be dealt with in more detail in the answer to the next research question.

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The experts with whom interviews were conducted agreed that pyrolysis processes could be classified as circular by definition. P2C (personal communication, 2023) stated that they have already done enough tests in their small pilot bench scale plants to prove that they can achieve the specifications for off-takers to put some of the polymers back into the same application. This also applies to sensitive areas such as packaging material in the food sector. Simon also sees the circularity as a given, in contrast to some environmental organisations. He refers to the individual atoms, such as the carbon atom, and that it is kept in the cycle. However, he emphasises that the quantities are small and are not likely to become an enormous volume soon.

Another hallmark of CE is its blurred edges and unclear demarcation. Therefore, it is not easy to answer this question of what falls within the attribution range of CE with total certainty. Consequently, the criticisms of CE are now also included in the assessment as to whether they apply to pyrolysis processes. In this way, it can be ensured that pyrolysis processes are in line with the discourse about CE, are therefore part of the concept and are also representative of other developments and innovations in the spectrum of CE to a certain extent. For the first point of criticism, that CE initiatives promote economic growth and thus push the biophysical frontiers to their limits, it can be said that chemical recycling is a good example. Plastic waste is turned into a resource; hence it is commodified, more energy has to be used, and more material flows are in motion. What results from this is a further inflated economic output, without considering the slowly recovering environment. Referring to the butterfly model, the technosphere is growing disproportionately while the biosphere is being thrown out of balance. The second point of criticism, oversimplification, also applies to pyrolysis processes. Processes and chemical equations that appear simple on paper cannot be implemented without technical limitations. Significant uncertainty and ignorance about many processes in detail can only be anticipated with difficulty and are not addressed in the marketing of the technology. Furthermore, the social dimension is also not appropriately addressed in the discussion about the increased use of chemical recycling. Countries that are excessively hard hit by political instability and poverty tend to be less likely to have sophisticated waste collection systems and sorting facilities, and large-scale chemical recycling is unlikely to be an option for these countries. This problem is not considered, so these technologies become isolated solutions for wealthy countries with better waste management systems. Another relevant criticism of CE compared to pyrolysis processes is that sufficiency needs to be considered next to efficiency. Pyrolysis processes represent a technocratic solution to the plastic waste problem that takes the focus away from consumer behaviour change and

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propagates to be an already viable scientific answer when in reality, it is only implemented for an insignificant fraction of the total plastic waste as of today. If this problem is to be tackled, massive plastic production reductions must take place. This is the only way to counteract this problem. In addition to mechanical recycling, pyrolysis processes together with other forms of chemical recycling are likely to play a role in processing the overproduction of the past decades by extending their service lifetime. The utilisation of pyrolysis to enhance efficiency must be distinctly articulated from the promotion of sustaining current consumption levels by positioning it as a solution, thereby overlooking the importance of sufficiency.

In conclusion, several arguments can be applied to categorise chemical recycling in the form of pyrolysis processes as a technology that falls within the scope of CE. On the one hand based on positive characteristics, such as the extended lifetime of the basic building blocks of plastic, on the other hand also based on the prevailing criticism of CE, which can be applied analogously to pyrolysis processes. However, in practice, the implementation still lacks several technological and procedural improvements before it can be described as fully circular.

What is holding companies back from pursuing larger-scale implementation of the pyrolysis technology?

As can be seen from the assessment of current attempts to bring pyrolysis processes to market in section 4.2, not only are these efforts very diverse, but the majority of this brief list of companies processes relatively tiny fractions of the plastic waste generated. Still, efforts are becoming more substantial, and it must also be noted that the development is still in its infancy. Although there are obstacles to a smooth implementation and the impact of up-scaling pyrolysis processes on society needs to be considered, it could significantly contribute to tackling plastic waste in the future. To answer this sub-research question, an overview of the main stumbling blocks that must be overcome is presented.

Considered individually, as attempted in section 4.3, barriers to upscaling were identified in the technological, environmental, legal, economic and logistical dimensions. Starting with the technological aspects, some issues were highlighted that need more precision and can currently be seen as barriers to upscaling. While the process is well-researched for some types of plastics, there is still a lack of research on how to deal with others, especially mixed

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plastics waste streams. Furthermore, pyrolysis processes require vast amounts of energy, as the cracking reaction is an exothermic process by nature. Here, process setup and conditions need to be tested in which the energy burden can be reduced as much as possible. Altogether, many variables determine the outcome of a pyrolysis reactor, such as the introduced plastic, temperature, type of reactors, pressure, residence time, catalysts, type of fluidising gas and its rate. All these factors lead to varying end products and can produce unwanted by-products, which may cause clogging and increase maintenance time. The inconsistent processes and low transparency between the competitors imply that each pyrolysis project must be tested anew, which does not result in any generalisable findings. With regard to environmental barriers, first and foremost, the issue of Greenhouse Gas emissions must be addressed. Measurements in the form of LCAs are needed to clarify the global net sustainability of pyrolysis projects. In this way, a holistic picture can be drawn, covering the whole impact from the initial energy that enters the process, to the process itself, to the application of the products. In addition, more research and innovation are needed to capture the produced CO2 directly and not release it in the first place to prevent negative environmental impacts and guarantee more circularity. Another barrier is the lack of legal groundwork, causing uncertainty and restraint in the industry. In this context, it could help to switch from recycling quotas to recycling content targets, as well as to allow chemical recycling to contribute to recycling quotas, which is currently not included. The legal basis would also guarantee operators and investors more security, leading to more financial resources. The companies active in the sector are either trying to transfer their operations from oil and gas to a more sustainable business model or some start-ups. However, it is a costly undertaking as CAPEX and OPEX are high, and therefore the profitability of a pyrolysis plant is often only realised when oil prices are soaring. At a future date, as oil prices are set to rise, this could be a further incentive to produce more pyrolysis oil. In their report, Rubel et al. (2019) have identified four main factors for economic viability, which vary considerably by region and market. These factors are *"the addressable volume of plastic waste, feedstock acquisition and treatment costs, the capacity and operating expenses of pyrolysis plants, and potential revenues from the sale of pyrolysis gas and liquids"* (Rubel et al., 2019, 16). However, they also mention that several structural and environmental trends shape pyrolysis' economic potential. Moreover, to meet the quotas and capacities for which future pyrolysis plants will be created, a logistical system that works effectively and collects and, in the best case, sorts plastic after its use is also necessary. This will require investment in more efficient collection systems, better waste sorting, capacity for storage or pre-treatment facilities, and further improvement of the

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process. What is also not to be neglected is that a large part of the recyclability of the products is already decided in the product design. Therefore, circular thinking and operation should be implemented as early as possible within the supply chain. In the plastic industry, the different kinds of plastic should also be considered in the future, as some types are considered easier to recycle than others.

So, progress and efforts on many levels are needed to upscale pyrolysis processes. The endeavour is complicated by the fact that there are interactions between the dimensions presented separately within this paper. In some cases, one development serves as a prerequisite for others. For example, the legal situation may trigger a positive feedback reaction from the economic dimension, which may bring about more investment in logistical upscaling and thus counteract this issue. These interrelationships and other links are faced with a manifested factor of uncertainty arising from a prevailing lack of research.

5.2 Implications and Recommendations

As presented, there are two important factors for pyrolysis processes: the introduced plastic and the process settings. There seems to be uncertainty in the industry about what chemical recycling, including pyrolysis processes, should be used for. Hence, the first step is to determine which composition of plastic streams pyrolysis processes are best suited compared to other ways of treating plastic waste. For this purpose, LCAs and MFAs, including energy flows, should be carried out to create comparability. Once the application areas have been defined, the industry can focus on researching the best conditions (e.g., temperature, pressure, and residence time) in the appropriate reactors. This would allow resources to be pooled and concentrated on the important use cases without putting effort into other efforts where mechanical recycling or WtE are the more efficient solution. Pyrolysis processes can play a role in plastic waste management in the coming years, especially if they can overcome the abovementioned barriers. Assuming they are used properly and can continue to increase their efficiency, they will be the Best Available Technology (BAT) in certain scenarios and thus ought to be considered in these respective fields of application.

At the same time, however, it is crucial for the introduction of pyrolysis processes, just as for other new technologies, that this process is carried out with consideration for all stakeholders and with caution. Unforeseen problems can always arise, including side effects, which need to be taken into account. For example, the rebound effect is one of the potential unexpected concerns that may arise. There is increasing research on ways to explore various ramifications for the different stakeholders simultaneously and holistically. One idea

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discussed in this paper includes S-LCAs, which also integrate social aspects into the analysis of new projects and implementations of technologies. In the field of CE, it is important to note that pyrolysis processes, like other new circular technologies, are a tool to achieve the goal of waste management. This goal is to conserve resources and protect the environment. For this purpose, circular business models and market mechanisms can be used to have a positive impact on the achievement of the goal. However, it remains essential for the credibility of the CE concept and affected stakeholders that the goal is not lost sight of and abandoned for financial gains.

In their interviews, the experts, consisting of stakeholders from science and industry, jointly suggested that pyrolysis processes show considerable promise for the future, despite the fact that a number of adjustments need to be made. Schubert (personal communication, 2023) calls for an objective and honest comparison between the available technical options for the different materials. Only like this, transparency can be created in terms of material utilisation, but also in terms of cost-effectiveness and environmental impact. To this end, the lack of commitment to cooperation and shared development is another hurdle for the large-scale roll-out of pyrolysis processes. Simon (personal communication, 2023) also believes that it is technically feasible but it would demand the cooperation of large companies and more time. Many of the chemical and petrochemical companies that engage in pyrolysis processes made commitments and allocated resources as well as personnel to implement projects. These efforts will likely be communicated to relevant government ministries, such as the Ministry of Environment and the Ministry of Economy, to showcase their dedication and investment. Once these initiatives gain traction, they are expected to continue and expand. Lechleitner (personal communication, 2023) argues for a clear, shared plan that includes legislature, brand owners, waste management systems and recyclers. Legislators must lay the groundwork to remove more uncertainty, set a clear goal for other supply chain participants to work towards and push in the right direction; brand owners are, above all, responsible for designing their products for circularity; waste management systems must be prioritised and enhanced by decision-makers because reversed logistics, among other things, depends on them; and recyclers are responsible to invest more and conduct research to find optimal processes. To achieve progress, the entire supply chain must work together.

The main recommendations can be summarised as follows:

- It would be advisable to compare the most appropriate plastic compositions for pyrolysis procedures to other waste treatment methods via conducting LCAs and

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MFAs. This research makes it possible to identify key application areas and concentrate resources on the most effective use cases.

- Demonstrating concern for stakeholders and exercising caution when deploying pyrolysis processes is crucial. As with any new technology, this is necessary to prevent unanticipated challenges and negative side effects. S-LCAs that consider social factors are useful in analysing the effects of adopting a new technology.
- Pyrolysis processes and other circular technologies should be understood as tools to achieve waste management goals, including resource conservation and environmental protection. Circular business models and market mechanisms can be utilised to support these goals.
- The large-scale roll-out of pyrolysis processes requires cooperation among stakeholders. Companies, governments, legislators, brand owners, waste management systems, and recyclers must collaborate and develop a shared plan to overcome barriers, create transparency, set clear goals, and invest in research and development.

6 Conclusion

6.1 Summary of the Study

Three sub-areas have emerged throughout the study, whose results are summarised in the following section in a condensed version.

In the first section, examples of companies that are entering the market with pyrolysis technology are analysed with the help of statements sent by the companies, published reports and information found on their homepages. What becomes evident is, as mentioned by Simon (personal communication, 2023), there is no uniform approach that pyrolysis companies follow. The companies are more like *"soldiers of fortune"* (Simon, personal communication, 2023) trying to find a viable solution. What is certain is that some companies plan to process large amounts of plastic waste in the coming years. However, few are operational, and most are in the testing phase. Many companies are direct offspring or work closely with chemical or petrochemical companies. Others have a background in waste management or are relatively young, recently founded start-ups. To achieve higher capacity, two paths can be followed: The first is to build many small modular plants that are technically approved, can be built quickly, and can be placed close to the waste source. The second way is to scale up vertically, with companies trying to process plastics in the range of several 100,000 tpa of plastic waste

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in the future. Since pyrolysis plants are very similar to petrochemical plants and involve high CAPEX, larger units would provide more economies of scale and be more financially viable. However, the high CAPEX can also be an obstacle for smaller suppliers who forego large partnerships with corporations. Synergies and partnerships play an important role in establishing a successful project. In addition, the types of plastic introduced to the process are a key issue. These have a different number of process steps and different criteria that must be fulfilled by the plant, ultimately leading to different end products.

The second empirical section, a trend analysis, has shown that activities are spread across the three continents of Asia, Europe and North America, with the USA, Japan and the UK being the most prominent when looking at countries. Currently, most projects are designed for small capacities (< 10,000 tpa), and only eight are designed for capacities of over 30,000 tpa. The input materials are currently very inconsistent, come in different plastic waste streams and vary greatly in type and quality. Most companies fail to specify the input as more than plastic waste or unsorted plastic waste. Therefore, the level of transparency is not very high. The temperatures in the process range predominantly between 300 and 500 °C, although there are also outliers upwards. In so-called microwave-induced pyrolysis, temperatures above 1000 °C can be reached. This speeds up the process but requires a high energy input. Higher temperatures can also lead to more valuable outputs, which in most of the marketed processes consist of liquid hydrocarbons, often with by-products such as coke, waxes, and paraffin. Huge diversity in the processes prevails and leads to little synergies that can be tapped. In order to obtain additional know-how, more than half of the companies partner with chemical, petrochemical, energy companies or research institutions, universities, waste management or engineering companies. Nevertheless, many projects are in the research and development phase or only running a demonstration or pilot plant.

The third section used the interviews to derive five dimensions in which barriers prevent the large-scale use of pyrolysis processes. While the individual results were presented in section 4.3 and were included in the answer to the second sub-research question, they will be presented here for a more precise overview in Figure 18. The results are individually of interest, providing information on further areas for improvement and why the roll-out is stalled. Nevertheless, the problem is interwoven and complex, characterized by many feedback effects among the five dimensions. The situation is complicated due to the existing interrelationships being confronted with a tangible element of uncertainty due to an inherent dearth of research.

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Technological Barriers	Challenge of high energy consumption
	Lack of long-term research and understanding for small process-details
	Recycling contaminated, poor-quality mixed plastic waste
	Problems with keeping the process running over a long period
Environmental Barriers	Sourcing of energy for initial cracking reaction and polymerisation
	Close chemical proximity to combustion
	Leakages of CO2 during different process steps
	Lack of sufficient LCAs and MFAs
Legal Barriers	Sparse legal situation; lack of clear targets
	Different measurements (recycling quota vs. recycling content target)
	No acceptance of chemical recycling for recycling quota
	Uncertainties in accountability, classification, and waste management
Economic Barriers	High CAPEX and OPEX
	High upfront investment in research and development
	Financial profitability depends heavily on oil price
	Higher capacity would lead to economies of scale
Logistical Barriers	Provision and availability of usable feedstock
	Need for innovation along the supply chain
	Lack of efficient waste collection and sorting systems
	Losses of material in the various steps

Figure 18: Barriers to a large-scale implementation of pyrolysis processes (own graph)

The first sub research question established that chemical recycling through the technology of pyrolysis aligns with the principles of CE. Its aim is characterised by the extension of the lifespan of building blocks of plastic and therefore correlates with many of the definitions that CE are ascribed to. Moreover, the critical discourse on CE can be applied in a similar context to the management of pyrolysis processes to a large extent. However, it is important to note that despite these factors, practical implementation still requires significant technological and procedural advancements before pyrolysis processes can be considered truly circular. The technological specifications and many other aspects are peculiar to pyrolysis processes.

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Nevertheless, pyrolysis processes claim to be part of CE and can also be mentioned here as a notable example from which conclusions can be drawn for other initiatives.

6.2 Limitations and Future Research

The result of this work is an assessment of the current implementation status of pyrolysis processes in the context of CE initiatives in the field of plastic waste management. It was possible to obtain a general overview of the situation through various papers from different sources, obtaining company statements and conducting interviews. Nevertheless, the limitations of the approach and the informative value of this thesis should not be disregarded. A first limitation in connection with the assessment of the implementation status is that there is only limited transparency available. As companies are still working on improving their process, they tend to withhold a lot of information. In addition, it is difficult to assess whether companies do not want to share anything or are not yet ready to go public and break into the market. Furthermore, it must be pointed out that this qualitative research design allowed the interview partners and companies to disclose information they were willing to talk about in an open setting without asking for precise numbers. This issue could be addressed by using a more concrete questionnaire. Here, it is possible to speak of an information asymmetry that is difficult to overcome for external parties. Therefore, the research design of this thesis has tried to approach the issue in an explorative way but could not fully remedy this limitation. Furthermore, the interviews and the statements that can be found in the appendix, were only completed by people and companies who agreed to share information. The majority did not respond to the request to provide insight, which makes it impossible to depict a fully holistic state of the art. Like any assessment of the current situation, this work is prone to losing significance due to short-term changes, like changing laws or a spike in oil prices. Therefore, the analysis and monitoring should be repeated at regular intervals.

By revealing the limitations, opportunities for further research in this area have arisen. Building on this work, with more time and research resources, it is certainly possible to describe the implementation status in more detail and to elaborate the barriers in more detail. In addition, further research in the field is needed to confirm the collected qualitative results quantitatively. Besides the implementation status, primarily measurements such as LCAs and MFAs should be performed on the different pyrolysis processes compared to other plastic waste management options. Thereby, reliable results in terms of efficiency, environmental impact and economic viability can be concluded. Further research is also needed in the area of

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CE. As noted in section 2.1, there is no clear delineation of the concept, which complicates its scientific classification and measurement. Moreover, social science research on the impact of CE measures on society should also be conducted. In this context, the critical discourse on CE ought to be included to ensure an improved implementation. In this way, it is more likely that CE measures will meet their objectives.

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Appendix

A.1 Interviews

A.1.1 Dr.rer.nat. Franz-Georg Simon

Role: Researcher at the Department of Materials and Environment (Dpt.4), Bundesanstalt für Materialforschung und -prüfung (Germany)
Method: Personal Interview via Zoom
Date: 13 April 2023
Key: Interviewer- Felix Bruch (FB) / Respondent - Franz-Georg Simon (FGS)

FB: Wo sehen Sie das größte Potenzial von Pyrolyse Prozessen und welche Vorteile hat es im Vergleich zu anderen chemischen Recyclingvorgängen?

FGS: Also wenn Sie jetzt sagen, was sind die Vorteile von Pyrolyse oder anderen chemischen Recyclingverfahren, müssen wir zuerst mal zurückschauen: Was will man überhaupt machen? Also man will natürlich diesen großen Abfallstrom von Kunststoffen irgendwie in eine Bahn lenken, die es ermöglicht, eine Kreislaufführung zu erreichen. Die Kunststoffe sind beileibe nicht die größte Abfallfraktion. Das sind die mineralischen Abfälle, die sind da noch weiter vorne. Aber Kunststoffe stehen immer so ein bisschen im Fokus und da muss man im Grunde erst mal verstanden haben: Was sind das für Stoffe? Also erst mal bei Kunststoffen gibt es eben einige Produktgruppen, die da sehr, sehr prominent vertreten sind: das ist Polyethylen, Polypropylen, aber auch PET, das ist im Getränkebereich zum Beispiel ganz weit vorne, aber sicherlich Polyethylen und Polypropylen, also die einfachsten Polymere, die sind da sicherlich weit vorne. Und da muss man jetzt auch wieder unterscheiden in der Anwendung. Bei kurzlebiger Anwendung, wo wir nur eben kurz was verpacken für eine Weile, was im Verkauf ist, dann weggeworfen wird oder auch langlebige Produkte. Es gibt langlebige Produkte im Bereich Polyethylen, Polypropylen, wo Lebensdauer, wir nennen das Service Lifetime, also wie lang es im Einsatz ist, von 100 Jahren und mehr garantiert werden müssen. Und das erreichen diese Stoffe auch, indem sie ausreichend stabilisiert sind. Für diese Anwendungsbereiche, wo Kunststoffe 100 Jahre leben sollen, da wird man auf keinen Fall einen Recyclingkunststoff verwenden. Also wenn Sie jetzt beim Recycling so ein bisschen eingestiegen sind, haben Sie sicherlich gesehen, dass das meiste, worüber diskutiert wird, das mechanische Recycling ist. Also es geht in Europa häufig über eine getrennte Sammlung. Dann habe ich einen Behälter oder einen Sack voll mit gemischten Kunststoffabfällen, die ich heute schon relativ gut trennen kann. Und dann gehen die wieder zurück in irgendwelche Verwendungen. Meistens wenn sie aus dem Lebensmittelbereich kommen, gehen sie nicht mehr in den Bereich zurück. Oftmals ist das nachdem man sie so relativ gut sortenrein hingekriegt hat ein simples Aufschmelzen. Und das ist jetzt ein wichtiger Punkt: Man muss diese Substanzen stabilisieren. Also das reine Polymer ist eine Substanz, die sich innerhalb von wenigen Tagen bei Sonnenlicht und Sauerstoff komplett zersetzen würde in Wasser. Das brennt jetzt nicht richtig ab, aber das wäre innerhalb kürzester Zeit so spröde, dass man es nicht mehr verwenden kann. Das wird immer übersehen, dass da jede Menge Stabilisatoren schon drin sind, meistens auch für die Anwendungen, um die es da geht. Das heißt, wenn ich jetzt auf das mechanische Recycling zurückkomme, erwische ich ja meistens nie wieder genau die gleiche Applikation wieder, sodass ich generell wieder anfangen muss, neu zu stabilisieren. Deshalb ist das mit dem ganzen Recycling immer so eine Sache, die vollkommen anders läuft, als wenn ich Metalle betrachte. Wenn ich Metalle einsammle, habe ich immer das Metall, ich muss es nur wieder zurückführen auf die elementare Form. Ich muss allenfalls beachten, dass ich da Legierungselemente rausnehmen muss. Ich schweife jetzt ein bisschen ab.

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Sie wollten eigentlich wissen, was ist an der Pyrolyse so verlockend? Also erst mal gibt es, wenn Sie ein Polymer haben und sie wollen es in ein Monomer zurückführen, dann sind Sie eigentlich wieder an einem Punkt wo sie sagen können: Hier bin ich da, wo ich in der Herstellung in der Chemieindustrie schon mal gewesen bin. Ich mache wieder das Polymer und gehe dann in die Anwendung, wie ich sie haben will, mit der entsprechenden Stabilisierung. Bei der Pyrolyse gehe ich meistens nochmal eine Stufe weiter zurück. Also ich habe es noch nicht verbrannt zu CO2 und Wasser, aber es kommt zu so einem Pyrolysegas (CO und Wasserstoff) und manchmal zu einem Pyrolyseöl. Und aus diesem CO und Wasserstoff kann ich auf jeden Fall wieder Polymere machen, weil das nennt sich Synthese Gas in der chemischen Industrie. Damit können Sie Treibstoffe herstellen und können, aber auch jedes beliebige Monomer herstellen, um wieder Kunststoffe machen zu können. Das ist der Vorteil von der Pyrolyse, dass Sie relativ weit zurückkommen in dieser Kette und sind wieder relativ nah am Ursprung Stoff Rohöl. Aus dem Grund können Sie von diesen Pyrolyseprodukten eher mal wieder in jene Richtung Produkte gehen, wie das bei mechanisch Recycling möglich ist. Aber der Nachteil muss man sagen, das ist der wesentliche Nachteil: Sie sind schon relativ nah dran an der Verbrennung. Sie haben schon einen großen Teil oxidiert. Sie haben schon von dem Energieinhalt, wenn Sie jetzt nur die simple chemische Energie nehmen, die im Kunststoff drinsteckt, haben wir schon einen Großteil verbraucht und haben es auch oxidiert, deshalb ist es ja Kohlenmonoxid und nicht mehr Kohlenwasserstoff. Und das ist dann, wenn Sie so wollen verloren. Verloren ist es ja nicht, weil sie haben ja Energie gewonnen und können Prozesse betreiben, aber es ist nicht unbedingt sehr viel besser als die Verbrennung. Ich weiß nicht ob Sie sich schon Ökobilanzen angeguckt haben oder auch Stellungnahmen von Umweltverbänden zum chemische Recycling, die sind da ja sehr, sehr kritisch. Das ist eigentlich der Punkt, den sie kritisieren. Wir sind schon wieder fast bei der Verbrennung. Wir haben es schon fast verbrannt. Wir sind noch nicht ganz bei CO2 im Wasser, aber wir sind fast an der Stelle. Wir haben Wasserstoff, das ist gut und wir können viele Sachen damit hydrieren und können wieder in die Synthese einsteigen. Aber generell sind wir schon ziemlich weit zurück. Also einen Vorteil von der Pyrolyse sehe ich, wenn Sie das jetzt mal so wissen wollen, denn die Pyrolyse ist in der Lage, mit Stoffgemischen zurechtzukommen. Das können viele Produkte, viele Verfahren nicht. Die sind darauf angewiesen, dass es sortenrein ist. Das ganze PET Recycling, wo sie von dem Polymer wieder zum Monomer zurückgehen, das beruht darauf, dass sie reines PET haben. Sie können nur PET Abfälle drin haben, dann kommen Sie zurück zum Monomer. Die Pyrolyse ist in der Lage, auch mit Stoffgemischen zurechtzukommen, obwohl die da auch ihre Probleme hat. Pyrolyse und Vergasungsverfahren werden seit Jahrzehnten untersucht für Abfälle und es ist unglaublich schwierig, weil es inhomogen ist. Es ist beim Kunststoffabfall immer noch besser, als wenn ich den gesamten Haushalts Abfall dabei hätte. Aber es ist definitiv schwieriger, als wenn ich Kohle nehme. Also Kohlevergasung ist ein Prozess, der relativ gut läuft. Wird heute auch aber nicht mehr angewendet, weil man keine Clean Coal Technology mehr haben will. Aber wenn Sie so wollen, der Vorteil ist, die kommen mit Stoffgemischen zurecht.

FB: Sehen Sie den Pyrolyse Prozess als Verfahren das unter den Begriff der Kreislaufwirtschaft fällt?

FGS: Ich würde sagen, ich bin da nicht so kritisch wie die Umweltverbände. Also, wenn das einer machen will, kann er es machen. Und am Ende, wenn man sich die einzelnen Atome betrachtet, nehmen wir mal das böse Kohlenstoffatom, dann wird das tatsächlich im Kreislauf gehalten. Die Mengen sind natürlich klein, die werden auch nicht richtig riesengroß. Aber es ist ein Kreislauf, auch wenn die Mengen nicht so groß sind. Wie heißt denn diese große Raffinerie da in der Nähe von Wien?

FB: In Schwechat ist die von der OMV.

FGS: Genau in Schwechat. Wenn sie zum Flughafen rausfahren. Das sind so Unternehmen, die so was dann auch anfangen. Die machen das im Augenblick nicht, weil sie sich da wirtschaftlich was davon versprechen, sondern weil sie wissen, dass sie das in Zukunft machen müssen. Das wird nachher über Steuern, über Abgaben, über was weiß ich so geregelt, dass diese Verfahren sich wirtschaftlich so einigermaßen rechnen. Außerdem sind sie darauf angewiesen, Wasserstoffquellen zu haben, die sie für andere Zwecke auch brauchen. Aus dem Grund steigen die da ein. Aber definitiv ist es eine Chance da

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zu einer Kreislaufführung zu kommen. Aber man muss sich dessen bewusst sein, dass vom Kreislauf immer so schöne Bildchen gezeigt werden. Da muss ich auch wissen, dass es oft Bilder sind, wo der Kreislaufpfeil so dick ist, obwohl der relativ dünn ist. Die Kreislaufwirtschaft weltweit liegt bei 8 %. Der Rest geht einmal durch. In Europa ist es ein bisschen besser. 12 %, vielleicht 14. Bei Kunststoffen dürfte es übel aussehen. Das meiste wird verbrannt werden. Immer noch. Also im Artikel steht eine Zahl drin. 0,1 % gehen im Augenblick rein [in Pyrolyseanlagen]. Das ist ja nichts. Also 0,1 % von einer großen Menge ist immer noch etwas, jetzt in Tonnen gesehen. Das ist nicht ganz wenig, aber Prozentual gesehen ist das eben nicht sehr viel. Das dürfen Sie mich nicht fragen, wo ich das Potenzial sehen könnte, wohin könnte das gelangen in den nächsten Jahrzehnten. Aber als Kreislauf würde ich es definitiv ansehen.

FB: Aber eben wie Sie gerade angesprochen haben und auch in Ihrem Artikel, habe ich das ein bisschen versucht in Relation zu setzen, dass es diese 400 Millionen Tonnen pro Jahr von Plastikmüll in 2015 gab. Und eine verschwindend kleine Zahl kann da bearbeitet werden mit Hilfe von Pyrolyse. Finden Sie das unverhältnismäßig, dass das so viel Aufmerksamkeit bekommt? Auch natürlich in Anbetracht dessen, dass diese Öl und Gas Firmen sich selbst in einem anderen Licht darstellen wollen.

FGS: Ja, ohne die Aufmerksamkeit würde es nicht vernünftig laufen. Also die größeren Unternehmen haben es ein bisschen leichter. Die können da so eine Entscheidung treffen, dass sie eine Pilotanlage bauen für paar 1000 Tonnen, um dann mal anzufangen, um die grundsätzliche Machbarkeit des Prozesses zu zeigen. Wenn die Aufmerksamkeit so nicht da wäre, würde sich das alles nur auf dem Forschungslevel abspielen. In Forschungseinrichtungen werden dann kleine Pilotanlage bzw. kleine Laborreaktoren laufen gelassen. Das heißt die Aufmerksamkeit, die wird auch benötigt Und wir brauchen auch nicht nur diese Start-Ups, sondern die Industrie muss da mitmachen. Wenn die Industrie da nicht ein Commitment abgibt, dass sie also sagt, wir stellen diese Polymere her und wir versuchen die auch so weit wie möglich wieder im Kreislauf zu führen, indem wir eine Pyrolyse Anlage zum Beispiel, die eben viel annehmen könnte, aufbauen, und zwar mit der großen Kapazität. Man muss anfangen mit 10.000 Tonnen pro Jahr, aber das muss sich steigern auf das Zehnfache. Also wir haben es im Artikel jetzt ein paar Mal drin. Wenn ich in den Bereich 100.000 Tonnen komme, dann ist das eine industrielle Anlage, die sich sehen lassen kann. Und dann brauche ich von denen eben nur genügend verteilt übers Land. Und ich habe das, was ich dann auch erreichen kann.

FB: Offensichtlich gibt es ja Schwierigkeiten beim Upscaling, um das so groß auszubreiten. Aber wo sind denn da die größten technischen Schwierigkeiten?

Darüber wird natürlich ungern berichtet, was da so die Schwächen sind von den Verfahren. Es sieht immer so idealisiert aus: Wenn ich die Pyrolyse mache, dann nehme ich diese Kohlenwasserstoffe, das sind es ja schließlich, erhitze die, habe wenig Sauerstoff dabeiund komme dann halt zu einem Gasgemisch. Aber es sind eben auch Öle unterschiedlicher Konsistenz. Es ist aber auch Koks, reiner Kohlenstoff. Das führt zu Verstopfungen. Die Ausbeuten ändern sich. Also das sind vielfältige Probleme, an denen die immer alle gescheitert sind. Das sieht so verlockend aus, wenn ich es auf dem Papier hinschreibe, diese Reaktionsgleichung. Es ist auch alles thermodynamisch in Ordnung, aber der Teufel steckt da eben im Detail. Also das sind alles Anlagen, die auch bei Temperaturen laufen, bei mehr als Raumtemperatur und man setzt dem eben alles Mögliche zu. Ich habe selber auch mal, ganz andere Welt, an Schmelzverfahren von […] gearbeitet. Was da alles schiefgehen kann, da kommen sie gar nicht drauf, wenn sie so mit den Leuten sitzen und jetzt so ein Brainstorming machen, darüber was da so schiefgehen könnte. Die bauen die Anlagen alle auf, alles schön sauber und setzen die in Betrieb. Und dann funktionieren die auch erst mal eine Weile, aber eben dann irgendwann nicht mehr. Und das ist so ein bisschen die Krux, dass das nicht richtig am Laufen gehalten werden kann. Dann kommen dann auch immer wieder Störstoffe rein. Ich weiß nicht, wie die mit so was alles umgehen. Am Ende bleiben die im Reaktor und da muss dann einer rein, das Zeug rausholen. Im simpelsten Fall sind das ja Metalle, die irgendwo an den Kunststoffabfällen noch dran gewesen sind. Und irgendwann müssen sie raus aus dem Reaktor.

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FB: Das heißt, da braucht es auch noch Forschung und Entwicklung in diesem Bereich. Können Sie sagen, wo es noch am meisten Bedarf gibt, um diesen Prozess zu optimieren?

FGS: Als wir diese Übersicht geschrieben habe, war ich ein bisschen erstaunt, dass das die ganzen Ansätze sind. Ein paar von denen habe ich mir dann auch mal ein bisschen genauer angeguckt. Was schreiben die auf ihren Internetseiten? Das ist ja alles so ein bisschen geschönt. Die Ansätze sind eben vielfältig, was ich für einen Nachteil halte, dass da nicht alle an einem Strang ziehen. Sie machen alle irgendwie ein Geheimnis daraus, was sie so machen. Und das führt am Ende dazu, dass vielleicht gar keiner erfolgreich ist. Das müsste eigentlich mit einer stärkeren Förderung einhergehen, wo man aber auch die Beteiligten an einen Tisch bringt. Aber am Ende sind das alles Glücksritter, die da unterwegs sind, denken, sie könnten das große Geld machen. Sie müssen immer sehen, die ganze Sache fing damit an, dass eine Tonne Treibstoff, sag ich mal, der Preis stimmt jetzt nicht mehr ganz, dass der so ungefähr 1000 bis 2000 € gekostet hat und dann hat einer sich gesagt, wenn ich jetzt eine Tonne Kunststoffabfall habe dann ist das ja auch 1000 bis 2000 € wert, weil ich könnte ja Treibstoff draus machen aus sowas. Der braucht den Kunststoff ja nur annehmen für 100 € und hat schon einen Gewinn von 1000 €. Das funktioniert natürlich so nicht, weil die Anlagentechnik sehr, sehr teuer ist. Die brauchen auch Leute, die da dranhängen. Die Personalkosten sind hoch. Also ich sehe da auch noch nicht, wer da wirklich die Nase vorne hat mit dem Verfahren, was die Praxistauglichkeit im großen Stil da bewiesen hat, mit Ausnahme von PET, das ist da schon wirklich gezeigt worden, dass die da ordentlich Recycling hinkriegen.

FB: Aber auch in Ihrem Artikel haben Sie geschrieben, abgeleitet von einem Bericht von der BCG, dass das wirtschaftlich ja bereits feasible ist und auch umsetzbar in unterschiedlichen Märkten. Aber trotzdem hat man den Eindruck, dass es doch noch Zurückhaltung gibt in der Umsetzung, vor allem eben auch im großen Einsatz dieser Technologie.

FGS: Der Arkadi Maisels hat meistens auf den Ölpreis verwiesen. Wenn das Öl teuer ist, dann lohnen sich diese Verfahren auf jeden Fall. Das Öl könnte in der Zukunft teurer werden. Ich denke, dass das schon der Schlüssel dazu ist. Wir sind da nicht auf irgendwelche anderen Länder, vor allem nicht bei den Erdölproduzenten, darauf angewiesen die eigenen Abfälle umzusetzen. Es ist nur so, dass ich vernünftige Mengen zusammenbringen muss. Wenn ich eine 100.000 Tonnen Anlage bauen will, dann muss ich auch 100.000 Tonnen Kunststoffe da rein liefern. Und das muss ich organisieren.

FB: Also ist ein logistischer Aufwand damit verbunden.

FGS: Der ist enorm.

FB: In der EU haben wir Recycling Vorgaben. Das heißt, wenn wir ein europaweites oder auch globales logistisches System aufbauen können, dann kann auch der Pyrolyseansatz zu den Recycling Targets beitragen in der Zukunft?

FGS: Ich denke schon, dass das funktioniert. Ich hatte ein Gespräch zum gleichen Thema mit zwei Leuten von einer Unternehmensberatung. Da habe ich gefragt, wen sie denn beraten in der Chemieindustrie und sie haben gesagt, sie beraten im Augenblick gar keinen. Sie wollen das so im Background haben, falls mal einer kommt. Sie wollen sich mit dem Thema befasst haben und dann denen sagen, der chemischen Industrie sagen, was sie machen sollen. Also wir haben da auch über die Mengen gesprochen und über die Qualitäten. Die guten Qualitäten, die sind ruckzuck weg. Die will jeder haben, weil es einfach ist, was daraus zu machen. Und mit den guten Qualitäten können Sie auch mechanisch nochmal einen Durchlauf durch die Schleife erreichen. Das heißt, da müssen Sie nicht gleich in Pyrolyse Verfahren gehen. Die schlechte Qualität will keiner haben. Und die könnten sie haben und an denen muss man letztendlich arbeiten. Am Ende geht es, weil das ja in diesem Bereich so ein bisschen immer mitschwingt, mittels politischer Instrumente. Da muss man sich Gedanken machen. Eine Kunststoffabgabe, irgendsowas in der Richtung, dass diese relativ teuren thermischen Verfahren, es sind ja thermische Verfahren, dass die trotzdem wirtschaftlich bleiben.

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FB: Regulierung ist bestimmt auch ein wichtiges Thema. Gibt es da schon aktuell Regulierungen oder ist das noch im Entstehen? Oder sind es, wie Sie gesagt haben, nur Glücksritter, die vor sich hin probieren?

FGS: Also die Vorgaben, die wandeln sich ein bisschen. Also, was wir bisher immer hatten, waren diese Recyclingquoten. Ihr müsst 90 % oder 75 % von den Kunststoffabfällen recyceln. Das wurde aber berechnet auf das, was in die Anlagen reingeht und eigentlich schon nicht mehr auf das, was rausgeht und schon gar nicht mehr, was in die Produkte reingeht. Also die Forderung ist: wir wollen Substitutionsquoten haben. Ja, dass man sagen muss, in jedem Produkt muss mindestens 20 % Recyclinganteil drin sein. Das ist viel wirkungsvoller, als Recyclingquoten vorne vorzuschreiben. Dann haben sie direkt den Markt eröffnet und sie haben natürlich die Qualitätsstandards festgelegt. Wenn 20 % in einem Kunststoff Produkt ist, das im Baubereich verwendet wird, muss es die und die Stabilität haben. Und das erreichen ja die Firmen auch. Das kriegen die ja hin mit Zusätzen, mit Stabilisatoren. Aber es muss eben auch so sein, dass man sagt, ihr müsst jetzt hier eine Substitutionsquote nachweisen, ihr müsst da 20 % Recyclingmaterial reintun. Und ich denke mal, dass das der Door Opener ist für überhaupt die Kreislaufwirtschaft, dass ich das vorschreibe und nicht eine Recyclingquote. Und dann liegen die nachher irgendwo rum oder ich mach irgendwelche minderwertigen Produkte. Gehen Sie mal im Baumarkt und gucken an, was da alles aus Kunststoff gemacht wird. So komische Zaunpfähle, da kriegen sie auch Masse unter, die Dinger sind ja schwer. Aber das ist ja nicht Sinn der Sache. Eigentlich wollen sie ja zurück in die Anwendung, wo sie hergekommen sind. Sie füllen so eine Blase mit Recyclingkunststoff. Wenn die voll ist, dann müssen sie sich wieder was Neues suchen. Kreislaufführung heißt, die Kunststoffe, die wir verwendet haben, werden wieder in eine ähnliche Anwendung reingebracht und es wird nicht immer nur neues Material produziert und das geht nur über Substitutionsquoten.

FB: Und wenn das dann aber so lange im Kreislauf auch drin ist, dann muss man ja wieder neue Stabilisatoren, Additive hinzufügen. Und gibt es da noch andere Nachteile, die für die Umwelt entstehen, wenn man das länger im Kreislauf führt?

FGS: Erst mal sind natürlich die chemischen Recyclingverfahren da ein bisschen robuster, weil ja viele von diesen Stabilisatoren bei der Pyrolyse wieder verschwinden. Die werden ja auch umgesetzt zu den Produkten, die da wieder stattfinden. Diese Stabilisatoren sind vor allem ein Problem im mechanischen Recycling. Und da muss man auch wissen, die Substanzen, die wir ausschleusen wollen, also gewisse Weichmacher. Nehmen wir das als Beispiel, wir nehmen gewisse Weichmacher, die wir ausschleusen wollen, dann können sie kein mechanisches Recycling machen. Da sind schon einige Verfahren letztendlich eingegangen. Die EU hat beschlossen, im PVC Bereich einige Weichmacher zu verbieten. Das hat letztendlich dazu geführt, dass PVC Recycling, zumindest für weiches PVC, praktisch zum Erliegen gekommen ist, weil das können sie nicht mehr heraus sortieren, weil sie das nicht mehr erkennen, was ist da drin ohne eine aufwändige Analyse zu machen. Deshalb hat das chemische Recycling den Vorteil, dass es mit den Schadstoffen eher umgehen kann als die anderen Verfahren. Das ist ja der Vorteil eigentlich. Und deshalb erwarte ich da für die Umweltauswirkungen keine Gefahren, weil sie fangen eigentlich wieder bei einem relativ jungfräulichen Material an und können die normal stabilisieren, wo sie natürlich heute auf die verbotenen Additive verzichten, die seit Jahrzehnten eben nicht mehr im Umlauf sein sollten, weil nicht mehr in Gebrauch sein sollten. Aber im Recycling sind natürlich alte Kunststoffe immer wieder anzutreffen.

FB: Und von der CO2 Belastung her?

FGS: Da bin ich nicht so gut wie beim mechanischen Recycling. Das ist der Hauptkritikpunkt der Umweltverbände. Die CO2 Bilanz ist nicht so toll, sie ist besser als bei der Verbrennung, aber sie ist nicht so gut wie beim mechanischen Recycling. Wenn ich mechanisches Recycling kann, sollte ich es tun. Wenn ich jetzt nur Treibhausgase mir anschaue, muss ich nur den Energieverbrauch der Maschinen da einberechnen, mehr nicht. Beim chemischen Recycling habe ich, weil ich ja schon

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oxidativ bin, habe ich schon CO2 gemacht und das müsste ich abscheiden, dann taucht es nicht auf. Aber es ist ja irgendwo entstanden. Also das ist dann ein Nachteil. Das ist ganz klar.

FB: In welchem Bereich wird es noch Innovation geben und in welche Richtung wird sich das chemische Recycling bewegen? Welche Rolle wird das Pyrolyseverfahren darin einnehmen?

FGS: Diese Verfahren sind ja uralt. Da muss man ja mal sehen. Das ist ja jetzt nicht eine Innovation, wenn ich Kunststoffabfälle pyrolysiere, das ist state-of-the-art. Da kann ich bisschen was am Reaktordesign machen, aber eine richtige Innovation ist das ist.

FB: Dann vielleicht anders gefragt: Wird es dann jetzt mehr eingesetzt werden? Glauben Sie, dass es geschafft wird, bis 2030 zu vervierfachen, wie im Artikel angesprochen?

FGS: Ja. Wissen Sie, ich bin schon ein bisschen älter und manchmal bin ich da auch ein bisschen pessimistisch geworden. Ist aber vielleicht nicht berechtigt. Ich habe auch nicht geglaubt, dass wir so schnell so viele Elektroautos kriegen. Aber ich glaube, dass es technisch möglich ist. Es müssen die großen Unternehmen mitziehen. Also bei uns in Deutschland sind es vor allem BASF. Aber ich weiß, die haben da auch ein Commitment. Haben wir, glaube ich, irgendwo auch geschrieben. Die haben da ein Projekt, die haben da Mitarbeiter abgestellt, die werden wahrscheinlich den Leuten in den relevanten Ministerien da, Umweltministerium, Wirtschaftsministerium auch mal erzählen, dass sie das machen, wie viel Geld sie da ausgeben und dann werden die sicherlich auch die entsprechenden Mengen produzieren. Und wenn das erst mal dort zum Laufen gekommen ist, dann setzt sich das fort. Aber wie gesagt, es ist der Druck von außen gekommen. Die haben das nicht von sich heraus gemacht, die Welt besser zu machen oder für ein Riesengeschäft. Es lohnt sich eben nur beim hohen Ölpreis und bei den sich verschärfenden Randbedingungen mit Recychlingquoten und Substitutionsquoten und so weiter. Dann fängt man damit an. Aber es ist machbar, weil eben die Industrie aufgesprungen ist.

FB: Aber trotzdem auf den Druck von außen?

FGS: Ja es war der Druck von außen.

FB: Also das ist interessant, weil ich habe auch mit jemanden gesprochen von einem von diesen Unternehmen und die hatten gemeint, dass wenn die Industrie nicht auf ihre eigene Initiative gestartet hätte, wäre gar nichts passiert.

FGS: In der chemischen Industrie arbeiten ja Chemiker, so wie ich jetzt auch einer bin und da wird ja auch, obwohl das natürlich trotzdem hierarchische Organisationen sind, diskutiert und da kommt immer mal einer sagt: Wollen wir nicht unser eigenes Öl gewinnen aus Kunststoff Abfällen. Dann fangen die im Labor an und dann sagen die ja gut, das ist ja vielversprechend und wir sind ja nicht blöd, wir kriegen das ja zum Laufen. Und dann kommt von außen noch so ein Anschub und dann läuft so was irgendwann. Und die haben begriffen, dass es ihnen ein gutes Image verschaffen kann. Die chemische Industrie hat immer wieder mal ein schlechtes Image, jetzt sind es die Perfluorierten Verbindungen und so weiter. Da kommt immer viel Zeug und da kann man sich da so ein bisschen ein grünes Image verschaffen. Es wird ja von den Verbänden, von den Umweltverbänden kritisiert, das sei Greenwashing, was sie machen. Glaube ich nicht ganz. Also ein gewisser Rückenwind ist da auch, glaube ich, aus den Konzernleitungen zu spüren, dass sie sagen: Wir wollen das machen. Es geht nicht ewig so weiter, wir müssen da mal sehen. Der von der Unternehmensberatung, hat noch gefragt, ob ich was mit Bio-basierten Kunststoffen sehe. Nein, sehe ich nicht. Die sehe ich überhaupt nicht. Die Biomasse ist gar nicht da. Aber diese Kunststoffe sind da, das Öl ist da. Und wenn ich Kunststoffe habe, die aus Öl gemacht sind, dann kann ich da eigentlich immer einen ganzen Teil auch zurückführen und damit den Verbrauch schon ordentlich senken.

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A.1.2 Erik Moerman M.S. M.Eng. (P2C)

Role: Director of Sales and Development (Plastic2Chemicals – Indaver Group)
Method: Personal Interview via Zoom
Date: 13 April 2023
Key: Interviewer- Felix Bruch (FB) / Respondent – Erik Moerman (EM)

FB: So as I understood, Plastic2Chemicals is a company of the group of Indaver. And you're specifically pursuing a pyrolysis process. What is for your company the advantage from a pyrolysis process to other chemical recycling approaches and mechanical recycling as well?

EM: It's still an emerging business and technology and process and supply chain. So, there's still a lot of work to do it. But that's how it goes in companies. You see something, you think there might be an opportunity, you do it step by step. And of course, not directly investing in the big treatment units, but doing it step by step, but sufficiently for us that we already invest in the first step, which is a demonstration plant of €50 million based in Antwerp and then another pre-treatment plant which is preparing material for this plant of another 30 million. So, it total €80 million. So, we're spending already quite a bit of money because there is some believe that this will work. And why pyrolysis, because we believe that for some polymers not for all, but for some polymers it's likely to be the best option to transform post-consumer plastic waste back into, let's say, the high-quality feedstock that can be used again for the same application because that's for us crucial. We do not have a background in the company in the mechanical recycling of plastics. We don't because that is more or less called down cycling. I mean, it's still a perfectly good way to recycle it, but it's less our thing. So, we really want to step in where very specific processes and technologies are needed with a high purification potential. So, you can actually close the loop and you recycle within the same application level. That's key. So, with this condition, basically we believe for polystyrene and polyolefins, which is polyethylene and polypropylene, we believe according to the current status of technological developments in the pyrolysis. For other polymers it might maybe not be a technology, but for these two we believe that it's a good technology.

FB: Is this pyrolysis approach meeting your definition of circularity and for a circular economy that can be implemented?

EM: Yes. Because we did already a lot of tests, we have our own small pilot bench scale plant, where we see that we can actually match with the product we are making, the intake specifications of our off takers, who are bringing it back into the same application. So, most of the cases, it's a packaging material, it's used for food packaging. And on the tests that we did, we've seen that we can match the specifications and close the circle. Of course, there are still some challenges because there will be losses in the system.

FB: Where are fields of research and development which still need to be looked at?

EM: Maybe I'm simplifying it a little bit. But I think in general, you can say that pyrolysing plastics is not so innovative. I mean, the basic process is not innovative. I mean, you can go to India and, for example, there are pyrolyzing installations, working at maybe not the same safety conditions that we are used to in Europe, but they work and convert it in a plastic soup like they call it, which is then used as a fuel. But I mean, that transition is that process to transform the plastics into such a soup, that's not so innovative. So, I think the innovation is slightly more in changing the business model, changing the markets. And because we are used to work in a linear market and not in the closed loop market. So, it's very interesting as we are doing this on a contract basis that we close contracts to do so and okay, we still need to start off the plants that we are building now. But it's very interesting to see how business wise things are different. And parties need to get used to this, partnerships will be different, and collaboration will be different, pricing structures are going to be different. So that's something which is, I think, also innovative in a way. And then the innovation will be in the optimisation of the system where you have supply chain. So, logistics, storage, you name it, where you have pre-treatment, where

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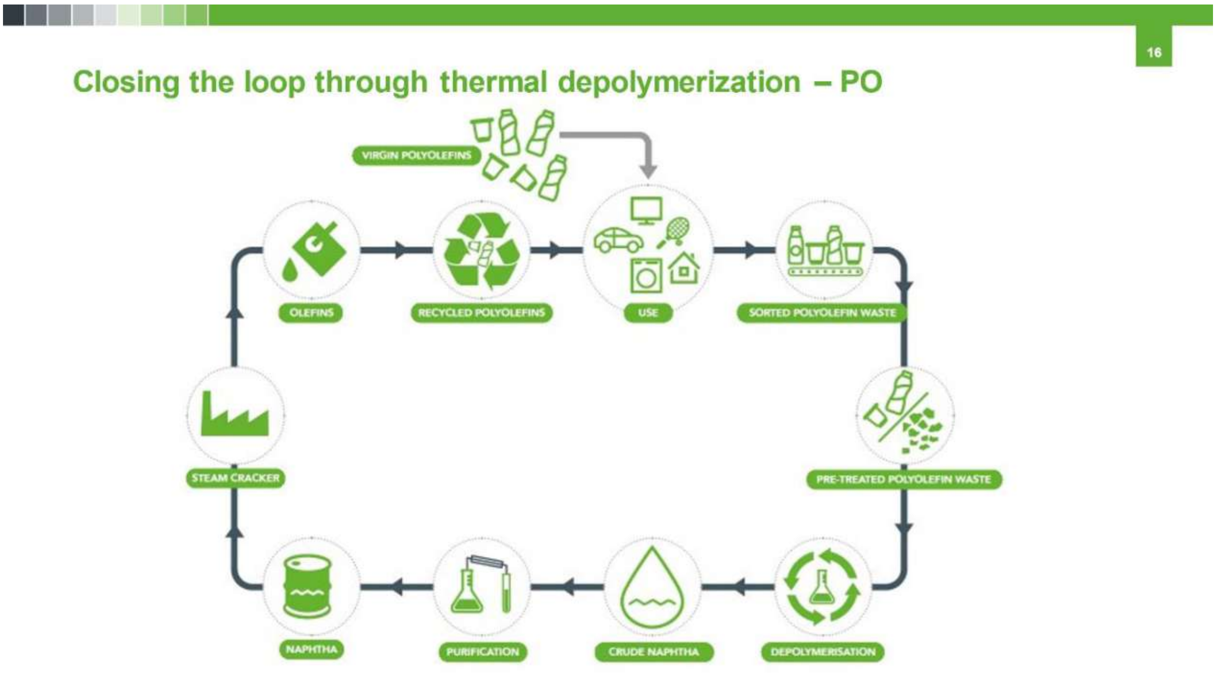
you have then the, let's say, the pyrolysis itself, where you can do things more efficiently by having more efficient pyrolysis reactors, by having less losses and higher yields. And innovation will be in this specific domain. So, to have like a robust process where things are not optimal. Okay. I think that's doable. But then to optimise it further, to bring it down to the lowest possible cost per ton with the highest yields, that where still a lot of work is needed and where innovation is needed.

FB: And we need that innovation also for upscaling. But what are the current limitations that are still hindering companies in really achieving that on a large scale?

EM: There's a legal part in the story which is missing. It's coming, but it's still missing as a real regulation and a very important factor, there is the recycled content. So, if you look at the draft, which is an official draft proposal for the new packaging and packaging waste regulation. It used to be a directive, but now it will be a regulation. That includes now also recycled content and this is the first time that there is any regulation or common regulation that will include the recycled content and that's going to be a major driver towards what I call advanced recycling and it does not matter if it is pyrolysis or another approach. And if you put it on the market, this packaging on objects, like on a Mars bar, will need to have a certain percentage of recycled content. So, that means that these companies, that they need to buy material with recycled content, that means that there needs to be recycled feedstock available at a quality which is the same as the fossil based material today, exactly the same quality. That means that you need to have this recycling processes with a very high purification level. And very simply speaking from the moment that you have this regulation implemented, there will be demand, which is huge for recycled material at very high quality, and this will drive the markets in Europe. I mean there's still some other things that will be important in terms of how you calculate, let's say, your amount of recycled material. Because today there's this some discussion also going on at the European level that let's say, you have different steps. And actually if you want, I can share a slide with you that supports my explanation here.



This is the circle for the polyolefines. And as you can see, there are a lot of steps. Each of these steps they have losses so you have a lot of steps with losses. It's only here that you have actually the ethylene and the propylene, the olefines which are then used again for the polymerization and the production of the recycled plastics before they are used again. And here losses are neglectable but here in sorting you have losses, in pre-treatment you have losses, depolymerization you will have also losses, purification step, you will have losses limited and then you get naptha in the steam cracker you have losses. There's still a lot of debate and discussion going on in the European Commission too,

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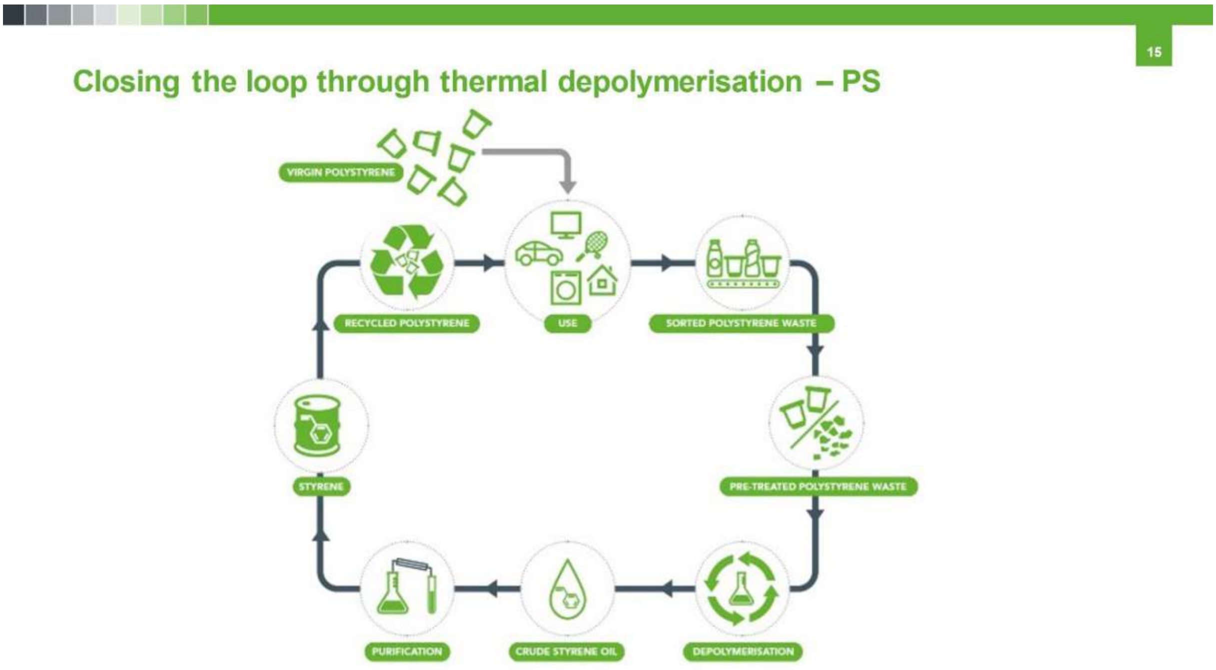
because they want to use the mass balance principle, which is a bit the same thing as with green electricity. If you have a contract at your home to buy in green electricity, you can buy 100% green electricity. But it's not that these electrons are green, that physically they have been made on solar or wind basis, but they have been attributed as green and this whole attribution process and the rules for that, they are in the discussions and depending of that, it can have quite a high impact on the yield because some of these processes have losses and that's still an important factor. There are a lot of companies now who are looking for the outcome of these discussions, and this is specifically the case for example, in some plastics like polyolefins because they pass through a steam cracker and they have losses.



If you look, for example, at polystyrene, because we decided to work on both polymers because we want to spread the risks as there's also a business side of this, but also because the polymers are quite different in terms of how they behave in such a recycling process. And for the polystyrene, you see if we pyrolyzed, we have basically depolymerisation directly into the styrene monomer, so you produce immediately a styrene, and then you need to distil it during a purification/distillation process and then you have fewer styrene immediately. This can go immediately into the polymerisation process, so you have less steps, that means less losses. And this was one of the main reasons that we are working on polystyrene. However, it only has limited applications like yoghurt pots, but they are used in many cases. It's limited, the volumes are limited and let's say the market is looking to polystyrene as a not important polymer. It is very small and so on, but it's a very good and circular polymer. The world will change, towards the advantage of circular polymers and I think polystyrene is [...] yeah let's talk in five years from now, we see what the market share of polystyrene will be compared to what it is today. That's why we are working on that. With polyolefins, you have more steps. More steps are more losses, but it's a much broader used polymer. There is enormous amounts and volumes of that in the markets. And that's the reason why we are working on that one also. We know there are more losses and it is a challenge to make it cost efficient and the yield high enough and so on. But it's very broadly used. We believe that something needs to happen, and the polyolefins are very hard, actually impossible to recycle mechanically back towards the same application level. You can recycle it into other applications which are lower. But the same application level is not possible. So that's the reason why we are looking at Polyolefins also for our project.

FB: Okay, so you see a shift in the future from Polyolefins to polystyrene.

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EM: Well, I haven't said this. Maybe not polyolefins to polystyrene. Maybe some other polymers. Because polyolefins, they are used for flexible packaging, films. Polystyrene, I don't think it's the ideal polymer for that. It's possible, but it's much more costly to use them. To substitute yoghurt pots you can make them also in PP, polypropylene or maybe even PET. For that, I think it might come to some shift maybe from PET again towards PS because PS lost market share to PET in the last couple of years. Because it's so-called not good recyclable, which I think is not correct.

FB: Alright. And if we look at the environmental aspect, we often hear that in terms of CO2, chemical recycling is not the ideal way to go. How is this different for different types of polymers?

EM: The more losses you have, the higher your carbon footprint is. That's really the big driver of your carbon footprint in your process. Because if you have a loss in the process, most likely that means that the losses will need to go to waste-to-energy or cement or other types of thermal treatment. But that means you will be producing CO2. So that's the big driver. I think it's also a given, if you compare mechanical recycling with, chemical recycling or pyrolysis, mechanical recycling will be better in terms of carbon footprint. There's no need to deny that. That will be better. But you always need to reflect also towards what the final product will be useful. And there, it's always the same. Today, you can recycle polyethylene films, you can recycle it, but not back into films for food grade, but you can make, for example, for the sewer systems and the houses the big pipes that are used. In many cases they are made from Polyolefins, and in many cases, that's based on recycled material. But if you want to use that film again by mechanical recycling back into a food grade film, then you will see it will become also worse because you need to clean it up much further and you will have much more losses. The more you clean, the more losses you will have. So, I think today we need to be very careful with comparing recycling technologies without taking into consideration the final use of the recycled products. We cannot decouple that from each other and in many cases, they don't couple these two to each other and then they just make the wrong conclusions. So, it should be coupled. And then let's say the difference between mechanical and chemical recycling process already becomes a lot smaller. I think that's still a bit of guess work that we are doing there because it's hardly done. There are only a few percentages of plastics which are recycled at the same application level. So that needs to be proven further.

FB: The lifecycle assessment is definitely important in this case.

EM: Something that could help you in your work. There is quite some work that has been done by a professor in the University of Gent in Belgium. By Stephen Demeester. So, you should check on his publications. And he's also doing a lot of consulting for that joint research centre at the European Commission. And also from the JRC, you will find reports there which are giving quite some information also on LCAs and things like that.

FB: I would like to ask you about the business side. I have read some reports, including from BCG, and they found that today already it is commercially viable in different markets. Still, we haven't seen large scale projects. Do you see a roll out of the commercialisation also from other companies in this field and what are the obstacles?

EM: Let's say that we are definitely not the only one that was doing this. There's others, there are already working installations today. We are building ours, but their installation is already working. Maybe not always in the optimal condition, but still. Plastic Energy is very well known. They have a long, long track record already in pyrolysis towards fuels. There is a plant in Spain that they are building and plants in different countries, but always related to a petrochemical company. They do it specifically for a petrochemical company, that's their business model. We have another business model. We are a waste company. We just say, okay, we do it, we invest, we operate, we do everything and more on a neutral basis. I mean, the petrochemical industry, they are also investing themselves based on technology, for example, in plastic energy. But in each of the cases, the plants are rather small. I think the biggest one is probably Exxon Mobile in France, in Notre-Dame-de-Gravenchonnshore which is 30,000 tonnes per year input capacity and then there are a lot around

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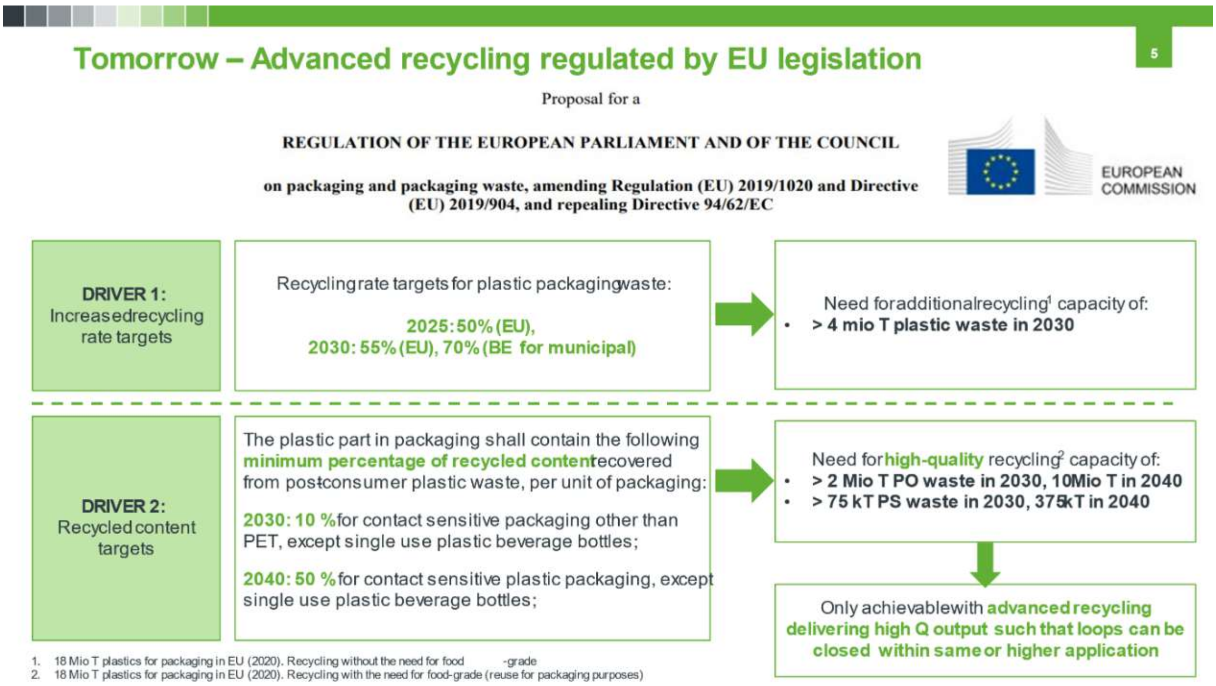
15000. There's not a single company today who is really building or has a very concrete plan to install a big one. And the thing is, with the pyrolysis plants, you have a bigger advantage in terms of economies of scale than with a mechanical recycling plants. That's typical because a chemical recycling plant is more like a petrochemical plant. And then these are units which have a bigger advantage on the basis on economies of scale. Until today, there's no concrete plan of any that I know of in Europe that they say, okay, we're going to build 200,000 tonnes per year. They're waiting. Waiting for this clarification on the legislation. And another important factor is that, if you just have a straightforward pyrolysis, the product you make is not capable to be substituted in, for example, a steam cracker at high volume. Small volumes, yes and then it is blended. But bigger volumes, it's still too impure. So, you need a purification step. And for one year, companies are working very hard on this purification step so that when you have this extra step, you can actually match also for the bigger volumes, the pyrolysis oil, with the input of a steam cracker. And again, what I'm seeing now is for polyolefins. For polystyrene, it is much more straightforward. There are less constraints in terms of that polymer if you want to depolymerize it.

FB: For the future, let's make a short outlook keeping in mind the recycling targets from the European Union, for example. What are in your opinion the innovations and trends that will happen in chemical recycling? And what role will pyrolysis play in that?

EM: I think an important part will be this, what today is missing, this upgrading or purification step that needs to be installed at the high capacity. You cannot build this for like ten or 20,000 tonnes per year. You need that really at high capacity. So that's something that's important for the further upscaling that these are installed. That combined with a clear regulation on recycled content. I think for the Polyolefins, this is what is missing for the next step. The next step is a first upscaling. I'll share one more slide.



If you look to recycled content. That's what I already mentioned to you today. The legislation on draft is mentioning that you need by 2030, 10% of recycled content for what they call the contact sensitive packaging. So that's food, for example. And you need only 10%. In 2040, they talk about 50%, I mean, that's insane. I don't think it's possible. To be honest, there's not enough material for that. But if you need 10%, if you start translating that back into waste because you have losses also, that means that by 2030, you need more than 2 million tons of polyolefin waste that will need to be recycled in this, let's say, chemical or advanced recycling process, 2 million tons of waste. It's an enormous amount already only for the polyolefins. Today, it's not available in the market as such. So also a big constraint is the

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availability of the waste. It should be there because if you look to the fresh products that are put on the market, it's around 10 million tons. It should be there, but it's not. I mean Europe is in terms of waste management and recycling a front runner. But even as a front runner, there's still little material available for recycling. There's a lot of material which is lost by citizens who are not sorting, bad collection systems, collection system which are not even in place. Still a lot of this material going to waste-to-energy even to landfilling in Europe. 30% of plastic packaging is still going to landfill. So, all this needs to be tackled. And if that's done, then, I think in 2030 there will be a necessity because of the demand side. The ones who want to have recycled content of 2 million tonnes of processing capacity in advanced recycling. And we are far off that today. So, legislation is crucial. You are not doing that just because they think it's important, it's because of the legislation that this will happen. And companies are pushing it a bit because they see that some, let's say, of their customers, we, the citizens, we found it's important that we buy something where there is recycled material in the packaging but at the end it's legislation that is making the changes.

FB: Do we know when this when this legislation is coming?

EM: There's now a draft on the table. It's not 100% sure when it will be now finally voted. So, it has to go to do different stages in the European Parliament. And, yeah, it's difficult to predict. But maybe after summer or so.

FB: So hopefully sooner than later.

EM: I hope, before the end of the year.

A.1.3 Dipl.-Ing. Dr.mont. Andreas Lechleitner

Role: Senior Expert for Circular Economy Innovation at OMV
Method: Interview in written form
Date: 9 May 2023
Key: Interviewer- Felix Bruch (FB) / Respondent – Andreas Lechleitner (AL)

FB: What are the main advantages of pyrolysis over other chemical recycling methods for plastic waste?

AL: Pyrolysis is a well-known process and capable to accept a more impure feedstock (=post-consumer plastics) than other methods. Chemical recycling is supposed to broaden the recyclability, so we do not want to use feedstock which can be processed in mechanical recycling plants. Therefore, a lot of impurities need to be considered, from big stones to exotic molecules. Pyrolysis uncovers all of them and can separate them by using methods which are usual for refineries. A further big advantage of pyrolysis is the scalability of the process. Our own proprietary ReOil® technology can be upscaled to 200 kta and more easily.

FB: Does pyrolysis-based recycling meet your definition of a circular economy?

AL: Yes, definitely. I would even say that chemical recycling is inevitable for a true circular economy. Every mechanical recycling process always entails a certain quality loss, which results in a so-called “downcycling” of products. Therefore, it would make sense to use chemical recycling as a “reset button” after a couple of mechanical recycling cycles and by that keep the hydrocarbons in the circle. Additionally, there are quite some fields of application, where mechanically recycled plastics are not allowed, because the quality requirements are so high. Examples of such strictly regulated industries are food packaging or medical products. Chemical recycling however enables produce materials of virgin-like quality, which are fully comparable to fossil-based materials.

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FB: What are potential environmental and economic benefits/drawbacks of using pyrolysis to recycle plastic waste?

AL: In my opinion chemical recycling is absolutely necessary to reach a true circular economy. Pyrolysis is probably the most efficient and easiest way to do so. But of course, every pyrolysis process forms coke and also the impurities, non-hydrocarbons, in the feedstock need to be separated. This would be a possibility for optimization, but the time is not ready to extract for example noble metals out of coke.

FB: What kind of research and development is needed to further advance and optimize pyrolysis processes for plastic waste recycling?

AL: I personally see the challenges less on the technical side. A clear, united path forward between legislation, brand owners, waste management systems and recyclers would be desirable. Defined recycling targets with clear implementation timelines form the basis, while brand owners play an important role when it comes to the right design and material selection for products, so that they are easier recyclable. Waste management systems need to provide appropriate waste collection systems and the recyclers need to invest in the development and construction of the required recycling capacities. Regarding capacity, we produced about 400 Mio. t/y of plastic waste in 2015 and pyrolysis can currently process approximately 1 Mio t/y, according to this article (https://doi.org/10.1002/cite.202100115). Even if it increased by the factor of 4 by 2030, why should we discuss a solution that is only capable of recycling less than 1% of our plastic waste? Our first commercial ReOil® plant will be upscaled to a size of up to 200 000 t/y. This might not sound as much compared to the total amount of plastic waste in the world, but we are just at the beginning. Further, also the synergy to mechanical recycling needs to be considered. Pyrolysis plants alone do not need to cover the whole amount of plastic waste, but the full circular economy systems should.

FB: What is the impact of pyrolysis processes in achieving our recycling targets?

AL: There are two kind of recycling targets: the first one is the so-called “recycling quota”, which refers to the amount of plastic waste that is recycled, while the second one is the so-called “recycling content target”, which refers to the amount of recyclate in products. The upcoming Packaging and Packaging Waste Directive (PPWD) suggests recycling content targets for contact sensitive applications (non-PET). These targets will only be achievable when using chemical recycling technologies that ensure virgin quality. As already mentioned, chemical recycling addresses waste streams that cannot be mechanically recycled and therefore are currently sent to waste incineration (e.g. sorting residues from sorting of light-weight packaging (yellow bag)). Chemically recycling these waste streams will add to the recycling quota. So either way, chemical recycling plays a very important role in achieving any future targets.

FB: What are the current limitations and challenges facing a widespread adoption of pyrolysis technology for plastic waste recycling (upscaling)?

AL: One challenge is that there are currently still some uncertainties in legislation regarding chemical recycling. Another challenge, that I see, is the sourcing of appropriate feedstock. In order to ensure that there is enough feedstock of the right quality available, also waste management systems will need to develop their collection systems and invest in further waste sorting capacities.

FB; BCG found that pyrolysis is a commercially viable solution in mature, moderately developed as well as in nascent markets. What are obstacles in the commercialization of pyrolysis projects? (https://www.bcg.com/publications/2019/plastic-waste-circular-solution)

AL: First of all, the EU needs to advocate pyrolysis or chemical recycling in general and ensure a harmonized legislation . Without fundamental regulations, no sustainable market can be formed. Also, the recycling targets and implementation timelines should be fixed as this has a strong influence on the

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market demand for recyclates and subsequentially also on the supply, hence investments in recycling capacities.

FB: How do regulations and policies impact the development and implementation of pyrolysis processes for plastic waste recycling?

AL: Regulations and policies give the direction to develop the right processes. In case of chemical recycling this is a very important topic. If there are no clear targets for contact-sensitive applications and no acceptance of chemical recycling for the recycling quota, it's rather unlikely that a market will be established and subsequentially, no chemical recycling plant will be built, no matter if based on pyrolysis or some other technology.

FB: What are some future trends or innovations that you foresee in the field of chemical recycling? Will pyrolysis play a role in the future of recycling?

AL: I definitely see a trend towards design for eco-efficiency and design for recycling. This means: producing goods, which can be reused more often, recycled more easily or simply have a longer life span, all due to the right design and material selection. Pyrolysis will still play an important role, simply because of the already mentioned virgin-like quality and all the benefits and possibilities that come along with it

A.1.4 DI. Dr. Teresa Schubert

Role: Senior Research & Development Specialist at Wien Energie GmbH, Researcher on Chemical Recycling
Method: Interview in written form
Date: 24 April 2023
Key: Interviewer- Felix Bruch (FB) / Respondent – Teresa Schubert (TS)

FB: What are the challenges associated with processing different types of plastics?

TS: In mechanical recycling, different types of plastics lead to significant challenges since simple re-melting of plastic mixtures gives lower quality products due to different melting points and mechanical properties. Therefore, it is necessary to sort waste plastics by type to obtain high-value recycling products. In chemical recycling, the feedstock requirements are lower, depending on chemical recycling routes. Especially pyrolysis is tolerant of mixtures and impurities because the polymeric material is broken down thermally into its building blocks. The depolymerization mechanisms of different types of plastics vary, leading to for example different degradation temperatures and, for example in the case of PVC, multistage decomposition behaviour. On the other hand, some sources of literature point out a beneficial effect of plastics mixtures, because low degrading types give radicals at lower temperatures, which enhance the depolymerization of more stable plastic types. The generated gaseous and liquid (intermediate) products are further processed and refined, and the necessity for further treatment due to mixed plastics depend on the final utilization.

FB: What are the main characteristics of the pyrolysis process and what are its key stages?

TS: The mechanism of plastics pyrolysis for the most common plastic types, for example of polyolefins, usually can be described as radicalic chain reaction. The main reaction steps can be found in literature. Other types degrade by other reaction mechanisms.
Industrial pyrolysis processes can be designed in many different ways, depending on targeted plastic type and product fraction. Usually, such process consists of feedstock preparation and feed-in systems.

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Afterwards, the – usually molten plastics – is depolymerized by thermal energy, whereas this step can take part in various reactor types without or with catalysts like tubular reactors, stirred tanks or fluidized beds. Afterwards, the products are separated from unconverted material and further processed, upgraded and refined.

FB: What are the main advantages of pyrolysis over other chemical recycling methods for plastic waste?

TS: In comparison to solvolytic chemical recycling, pyrolysis processes do not necessitate solvents, which can reduce complexity and costs. Furthermore, a broad range of types can be processed thermally in comparison to solvent-based processes.
Compared to gasification as chemical recycling, the process conditions in absence of oxygen lead to intermediates and products without additional oxygen, which can be beneficially energetically.

FB: What are some of the potential environmental and economic benefits of using pyrolysis to recycle plastic waste?

TS: Pyrolysis as chemical recycling route enables the recovery of material flows which cannot be recycled mechanically and leads to higher circularity in material utilization, lower primary resource consumption and valorization of waste streams.

FB: In terms of energy flows, what kind of energy budget can be achieved through pyrolysis processes?

TS: Pyrolysis processes are by nature exothermic since the cracking reactions require energy. Due to the broad range of products, which are generated during plastics pyrolysis, the option to cover energy demands by internal usage of for example short hydrocarbons and therefor, the overall energy balance depend largely on the types of plastics as well as the process conditions and setup. Furthermore, it has to be noted that to achieve circular material cycles, the energetic utilization of the obtained products shall be reduced as far as possible.

FB: What are the current limitations and challenges facing the commercialization and widespread adoption of pyrolysis technology for plastic waste recycling?

TS: Besides technical challenges, which have to be addressed to enable the implementation of stable and reliable processes, the main challenge of the commercialization of pyrolysis processes is economically. Due to cheap fossil product equivalents, the still high costs (CAPEX, OPEX) cannot be covered by the product revenues. Furthermore, open questions in the legal framework lead to uncertainties in accountability and classification, and in waste management, there is already a war for suitable fractions, whereas the pathways with the highest value creation have the best chances to be supplied with feedstock rom the market.

FB: How do regulations and policies impact the development and implementation of pyrolysis processes for plastic waste recycling?

TS: Yes, especially recycling routes represent a major motivation for new recycling and recovery routes. Furthermore, as already stated, the acceptance of pyrolysis products for various obligations is important for further roll-out activities.

FB: What kind of research and development is needed to further advance and optimize pyrolysis processes for plastic waste recycling?

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TS: Due to the complex reaction mechanisms of depolymerization, further research is required to fully the fundamental reactions and interactions, especially in plastic mixtures and in interaction with impurities and contaminants, under varying process conditions. Furthermore, the used materials and therefore, the resulting waste materials will change. The effect of pyrolysis on novel materials like bio-based plastics and high-tech compounds must be investigated in more detail to enable sufficient process development for these future waste streams.

FB: What is the impact of pyrolysis processes in achieving our recycling targets?

TS: Pyrolysis enables to recycle material streams which cannot be recycled mechanically, because mixed and contaminated waste fractions can be processed.

FB: How can stakeholders in the plastic waste management and recycling industry work together to promote the use of pyrolysis technology for a more circular plastics economy?

TS: In my opinion, it is necessary to work together and enable objective and honest comparison of various technology options for each material flow, in regard of value creation but also in regard of material utilization and ecological factors.

FB: What are some future trends or innovations that you foresee in the field of pyrolysis-based plastic waste recycling?

TS: Compound materials represent a major challenge in waste plastics materials, for example carbon fibre reinforced plastics from wind turbines. Due to an increase in usage of these materials due to their advanced properties, it will be necessary to recover these materials. Pyrolysis bears the potential to recover not only the building blocks of the plastics but could be used to recover other components.

A.2 Company Statements

A.2.1 Resynergi (14 April 2023)

We know that Resynergi is just one piece of the puzzle when it comes to circularity. Not all plastics can be processed with Resynergi's technology, and chemical companies need the right infrastructure to synthesize new polymers from the liquid products that we produce. With that said, Resynergi's technology is uniquely positioned to advance plastic circularity as it addresses many of the large problems the industry faces today.

A number of pyrolysis companies are in the scale-up process or are building their first 200 ton-per-day (or larger) plants across the world. This is a generally good thing, but there are a lot of issues that present themselves during scale-up that cause plants to shut down, and feedstock sourcing becomes an issue at such large volumes. Resynergi's angle is to modularize the pyrolysis technology, allowing us to scale horizontally rather than vertically. Through horizontal scaling, no additional engineering has to be done, and the technologically proven modules function independently of each other. Another advantage of modularization is the speed at which pyrolysis systems can be deployed. While many larger plants take months or years from groundbreaking to operation, Resynergi's modules can be deployed and started within weeks. Starting with a module that can process at 5-tons-per-day, systems can be multiplied to meet the feedstock availability, and modules can be deployed as close to the point-sources of plastic waste as possible, eliminating cost and energy intensive transportation.

Resynergi's system produces high quality hydrocarbon oils, as corroborated by some of the largest chemical and oil companies in the world. Our partners in chemical refining and plastics manufacturing have set specifications for oil quality such that their equipment can easily convert the oil into fresh

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plastics or other chemicals, and our product easily meets those specifications using contaminated HDPE, LDPE, PP, and PS feedstocks (post-consumer and post-industrial).

The combination of rapid deployment, modular design, and high-quality products makes Resynergi's system a great solution for the plastic waste problem as it is now. It may take decades for policy to minimize the plastic waste problem (reduce use, material engineering, better collection and environmental protection), so offering a solution that can have an impact now is certainly valuable.

Some of the major roadblocks for the establishment of large-scale pyrolysis include historical technology failures and logistics regarding plastic sorting and transport. Many pyrolysis companies have failed to deliver on their promises, making the industry wary of new pyrolysis efforts. This wariness makes it difficult to expediate efforts through funding and get support from local governments. Feedstock can be difficult to source in high volumes, especially at the quality necessary for existing pyrolysis companies and their offtake agreements, so high efficiency sorting systems are in development to solve that labor intensive problem. There are a number of robotic sorting companies that are getting closer and closer to high throughput systems, so the issue may not exist in the near future.

A2.2 Bioland Energy Ltd. (3 April 2023)

Our company has developed a methodology and a strategy that will both recycle materials and produce electricity from end-of-life tyres (ELTs) both in Cyprus and in the future in other countries worldwide. Please note the following however:

- That the first plant (to be built in Cyprus) is under development and is not yet been built.
- We have spent many years and resources in R & D and in obtaining the required permits.
- Our intension is not to recycle plastic but ELT (End of Life Tyres).
- That our project can be considered bot a "waste to energy" and a "recycling" project (circular economy project)
- The project aims to have no waste and meet the strictest emissions standards.
- The project has been designed to be both economically viable and have significant benefits to the environment.
- Our first planned which we hope will be operating by 2026 , will process 67 000 tons of ELTS per year.

1.Legislation: Quality Parameters and standards for using RCB (Recovered Carbon Black) on many applications i.e. for new tyres have not been developed and create a constrain in the marketing of RCB.

2.Green agenda: The Green agenda/ sustainable agenda has a number of objectives that are not practical and restrict integrated initiatives. Consider the following points:

a.Waste to energy is not encouraged and the approach is to motivate and encourage 100% recycling or reuse.

b.This is not practical for many waste products and a more feasible and practical approach is to balance both objectives (recycling and waste to energy).

c.The green agenda / strategy needs to recognise the opportunities of integrating several other parallel strategies. For example, our approach to ELTs combines objectives of the following strategies:

i.Waste to energy
ii.Recycling – Circular economy
iii.Reducing waste deposits / landfills
iv.Renewable energy

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Instead of encouraging integrated projects such as this, the Green agenda regards them as inadequate in any of the specific objectives.

3. The current ELT strategy in Europe does not fully embrace the true potential value of ELT's and instead promotes its use in low energy efficiency usages i.e. as a fuel in cement kilns and as a product used in the manufacturing of cement. This strategy is effectively against the principles of circular economy and recycling.

(Please note the contradiction of points 2 and 3 above, on the one hand "waste to energy" is not promoted but on the other hand the accepted strategy in Europe for ELTs is use ELTs in cement kilts. Similarly circular economy principles are ignored in the current strategy of ELTs.)

A.2.3 Neste (28 March 2023)

Our goal is to advance chemical recycling. We consider the technology an important contributor to higher recycling rates and to replacing fossil resources in the manufacturing of plastics. As of today, only 9% of plastic waste is recycled globally. Some 90% of plastics are still made from fossil resources. We want to change that and enable the industry to increase recycled content (and renewable content, by the way - but that's not part of your topic here).

By 2030, we want to process more than 1 million tons of plastic waste in our refinery. Already today, we are processing otherwise hard-to-recycle plastic waste in a series of trial processing runs, which we started in 2020. In these runs, we are processing liquefied waste plastic into high-quality feedstock for new plastics. To do that at large scale, we will require additional capacities for pre-treatment and upgrading of liquefied waste plastic. A project to build those (Project PULSE) at our Porvoo refinery has recently received 135m€ funding from the EU Innovation Fund. We also recently announced a cooperation with Uponor, Borealis and Wastewise on the chemical recycling of PEX pipe production waste that would otherwise end in incineration or landfill.

When it comes to liquefaction of waste plastic, Neste is cooperating with various partners. We are a minority shareholder in US-based Alterra Energy and we have also acquired the rights to Alterra's technology in Europe. Together with our partner Ravago, we are planning a joint venture to build a liquefaction site based on Alterra's technology in Vlissingen (NL) with a capacity of 55kt per year.

In general, we believe that chemical recycling will play an important role in getting to circularity. It can complement mechanical recycling by making additional, otherwise hard-to-recycle, waste streams recyclable. It can also allow recycled content in even sensitive applications such as food-contact or medical.

A.2.4 Rudra Environmental Solutions India Ltd (3 May 2023)

The focus of Rudra has always been to recycle traditionally non recyclable thin plastic waste. This has no recyclability nor the monetary value and mostly ends up in landfill or in nature. In the short term there is emphasis on creating awareness on the useability of plastic vs the ill effects of the waste. And in long run we look at this to be established in smaller towns and in a decentralised manner, as collection of segregated waste is such a huge problem. The collection is another costly affair. If the plastic is segregated and collected as segregated waste at source the recycling and the quality of product is much better.

In the long run we are aiming this to be a viable option alongside mechanical recycling.

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The basic bottleneck is getting segregated plastic (In India its difficult as there is not much segregation and its contaminated. We believe in decentralised models for India. For large scale in terms of capacity we require either waste from landfill or fresh segregated waste.

We have developed model where smaller machines can work in line to increase capacity

The capex for larger quality is very high and we see this as barrier as not many governments are ready for investment. We need financial support for that in terms of wither grant or low interest loans

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